Learning in Clinical Practice:

Findings from CT, MRI and PACS

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I hereby declare that this thesis has not been and will not be submitted in whole or in part to any other university for the award of any other degree

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Tanja Sinozic

To my parents and grandparents.

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Learning in Clinical Practice: Findings from CT, MRI and PACS

SUMMARY

This thesis explores learning in clinical practice in the cases of CT, MRI and PACS in UK hospitals. It asks the questions of how and why certain evolutionary features of technology condition learning and change in medical contexts.

Using an evolutionary perspective of cognitive and social aspects of technological change, this thesis explores the relationships between technology and organisational learning processes of intuition, interpretation, integration and institutionalisation. Technological regimes are manifested in routines, skills and artefacts, and dynamically evolve with knowledge accumulation processes at the individual, group and organisational levels. Technological change increases the uncertainty and complexity of organisational learning, making organisational outcomes partially unpredictable. Systemic and emergent properties of medical devices such as CT and MRI make learning context-specific and experimental. Negotiation processes between different social groups shape the role and function of an artefact in an organisational context. Technological systems connect artefacts to other parts of society, mediating values, velocity and directionality of change. Practice communities affect how organisations deal with this complexity and learn. These views are used to explore the accumulation of knowledge in clinical practices in CT, MRI and PACS.

This thesis develops contextualised theory using a case-study approach to gather novel empirical data from over 40 interviews with clinical, technical, managerial and administrative staff in five NHS hospitals. It uses clinical practice (such as processes, procedures, tasks, rules, interpretations and routines) as a unit of analysis and CT, MRI and PACS technology areas as cases. Results are generalised to evolutionary aspects of technological learning and change provided by the framework, using processes for qualitative analysis such as ordering and coding.

When analysed using an evolutionary perspective of technology, the findings in this thesis suggest that learning in clinical practice is diverse, cumulative and incremental, and shaped by complex processes of mediation, by issues such as disease complexity, values, external rules and choice restrictions from different regimes, and by inter-disciplinary problem-solving in operational routines.

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Chapter 1

Introduction

1.1 Background

Medical innovation is central to the advancement of human health, wellbeing, and increase in life expectancy (Ackerknecht 1982; Jennett 1986; Pickstone 1992; OECD 2008). While advancements in diagnostics, therapeutics and devices have moved quite quickly, innovation in healthcare delivery systems have taken place much more slowly (NRC, 2002:12).

A large variety of products and treatments are associated with medical innovation, such as immunisations, antibiotics, vaccines, aspirin (Vane et al. 1990), intraocular lenses (Apple and Sims 1996), hip replacement technology (Anderson et al. 2007) and diagnostic devices (Gelijns and Rosenberg 1999). Many of these innovations have direct benefits to individuals such as the eradication of certain diseases, early diagnosis, the reduction of the duration of illness and increase in longevity (Pickstone 1992). Medical innovation also benefits social and economic development more generally by supporting a healthy and productive workforce (Jennett 1986).

While positive relationships between medical innovation and health outcomes are often undisputed, the translation of medical innovations via hospitals into effective and efficient services for patients is found to be wrought with complexities and difficulties (Kaluzny 1974; Kaluzny et al. 1974; Greenhalgh et al. 2004; Webster 2006). Hospitals are sometimes described as intractable and inefficient contexts for innovation and change (Plsek 2003). Healthcare sectors have a high degree of organisational and professional heterogeneity and regulation (Kaluzny et al. 1974; Scott et al. 2000). Healthcare sectors differ in their regulatory conditions from private industry[1]. The high degree of regulation of processes,

[1]Regulatory conditions are sometimes considered as a central characteristic differentiating the public healthcare sector from private industry (Gelijns and Rosenberg 1999).

products, inputs, investments, and outcomes at the organisational, regional and national levels makes hospital decision-making relatively unpredictable and structures difficult to change (Scott et al. 2000).

Hospital organisations are different from each other and they are different from firms, making planning and prediction of innovation outcomes difficult (Djellal and Gallouj 2005). Hospitals are organised in complex ways, with many connection points and differences in local, regional and institutional links and interdependencies between them (Mohr 1992; Fitzgerald et al. 2002).

Hospitals are highly specialised with a large and growing diversity of medical professionals and medical specialties. For example, NRC (2002) notes that in the US between the 1950s and 2001 the number of different medical specialists increased from approximately 10-12 to 20, and the number of different medical specialties from 6-8 to over 100. These and other characteristics of the production process (such as interrelationships between specialists that may differ from service to service) mean it is very difficult to ‘scale-up’ service provision in this sector, for example to achieve an increase in the production and quality of services by investing in inputs (NRC 2002).

Hospitals face a highly differentiated customer base compared to other organisations. Patient needs and their health outcomes are challenging to measure and understand (Kaluzny 1974). Patients and biological diseases are diverse and change continuously over time, making it difficult to ‘customise’ services and make predictions about future requirements (NRC 2002).

Healthcare sectors such as the UK National Healthcare Service (NHS) are closely monitored and scrutinised by the public and the media, sometimes more so than any other industry (Roberts 1987). Close public attention makes it difficult to pre-empt directions, opportunities, drivers and consequences of change (Roberts 1987; Epstein 2000; Robertson and Jochelson 2006). For example, patients are supported in voicing their clinical demands, and have the ability to exert pressure on healthcare services and shape the degree of clinical autonomy (Sitzia and Wood 1997).

Healthcare has in recent years attracted a lot of policy attention, especially in the area of innovation and change. For example, since the 1990s the UK NHS has invested over £350 million[2] in the formulation and implementation of programmes to make hospital services more 'high-tech'[3] (NHS 2000; NHS 2003).

Despite the considerable amounts of investments and efforts that have been focused on innovation in the NHS, policies for change have been criticised for the centralisation of decision-making and underestimation of contextual complexity (NAO 2005; Clegg and Shepherd 2007; Eason 2007). For example, innovation policies in the UK NHS can be based on an understanding of successive steps between advancements in science and industry, followed by evidence of efficacy through clinical research and trials, followed by formulation of medical guidelines and their implementation, which are expected to lead to changes in clinical practice (Granados et al. 1997; Grimshaw et al. 2004). This suggests a linear relationship where medical innovation is viewed as a natural outcome of implementation of guidelines with predictable results in their translation in clinical contexts (Granados et al. 1997).

Centralisation of decision-making and its separation from application contexts (for example in large-scale implementation programmes) result in problems of implementation 'on the ground' (Collins 2003; 2007). Hospitals differ in important aspects such as the availability of staff, types of patients, and decision-making structures, meaning that innovation via the implementation of medical protocols may be possible in one hospital and impossible in another (Granados et al. 1997).

Researchers have long argued that hospital and healthcare contexts are too complex and too diverse for policies informed by a narrow and linear view of innovation (Pickstone 1992;

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[3] This is large by international comparison for the time period and also compared to previous investments in the NHS (OECD Health 2005).

Metcalfe et al. 2005; Greenhalgh et al. 2004; Metcalfe and Pickstone 2006). Previous research has explained innovation in hospitals through concepts associated with diffusion (Rogers 1962; Coleman et al. 1966), communication (Rogers and Kincaid 1981), and as organisations innovating via evidence-based medicine (Ferlie et al. 2001; Van de Ven and Schomaker 2002). Diffusion approaches have tended to conceptualise hospitals as adopting organisations, and to give importance to aspects such as how the adoption decision is made, and the roles that specific individuals have in mediating information on ideas and products to decision-makers in hospitals (Rogers 1962). These perspectives have added greatly to our understanding of the process of diffusion of products and ideas into clinical environments.

Further important perspectives have been provided by research on change processes more strictly within organisational contexts. Using perspectives of organisational behaviour and management, studies of innovation processes in hospitals have found specific organisational features of innovation outcomes such as routinisation of products and solutions to organisational problems (Kanter 1988; Van de Ven et al. 1989).

While research on innovation in hospitals is both rich and vast, less has been said about the role of technological accumulation in underpinning and sustaining hospital innovation processes, such as suggested by neo-Schumpeterian evolutionary perspectives on the role of technology in organisational and economic change (for example, Rosenberg 1976; Freeman 1982; Dosi et al. 1988). Neo-Schumpeterians argue that underlying innovation processes are incrementally accumulated ‘bundles’ of technology components such as knowledge (for example, individuals, artefacts, systems) and regimes (for example, structures within which knowledge components are organised, learning conditions shaped, and learning constrained) (Dosi 1988; Bell and Pavitt 1995).

Sociological notions of innovation in organisations suggest that technological evolution is a social process of negotiation between social groups who over time ‘construct’ the meaning of, for example, a technological artefact in an organisational context (Pinch and Bijker 1984; Blume 1992). In sociological perspectives the innovation process is shaped by the meaning of the technology arrived at through the negotiation process, formed by social norms and structures, which may take a very long time (Bijker 1995; Williams and Edge 1996).

This thesis aims to add to existing literatures on medical innovation by exploring novel empirical areas of innovation in the UK NHS with existing evolutionary theories of technological learning and change. In supplier-dominated service sectors such as healthcare, innovation is characterised by processes of organisational change (Pavitt 1984) and that is why this thesis focuses on organisational change occurring in hospital practices.

An important area of rapid technological advance that has attracted much investment in modern healthcare sectors since the 1990s and 2000s is that of diagnostic imaging technologies (Lazaro and Fitch 1995; NHS 2000; DoH 2007). Since their emergence in the 1890s, medical imaging devices[4] have revolutionised medical practice (Kevles 1997; Gelijns and Rosenberg 1999). Diagnostic imaging devices have dramatically transformed diagnosis and treatment of diseases, both since the discovery of X-rays by Wilhelm Roentgen in 1895, and more recently through advancements in data processing and computing technologies in the 1970s, 1980s and 1990s and the creation of Computed Tomography (CT) scanners, Magnetic Resonance Imaging (MRI) machines and Positron Emission Tomography (PET). Devices such as CT and MRI, in addition to providing images of anatomy, provide data on organ functionality and chemical and physical cell properties to a virtually unlimited degree (Kevles 1997).

Medical imaging devices can be life-saving. In its first widespread applications in the 1980s, CT was reported to have saved many lives because it provided 3-D images and much more information about what was going on in the patient's body, unlike any other previous device or diagnostic technique (Sochurek 1987). Their high capacity and

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[4] Medical imaging devices are a group of diagnostic devices. Gelijns and Rosenberg (1999:313) suggest a grouping of diagnostic devices in five categories: (1) non-invasive imaging devices such as X-ray, CT scanners, MRI machines, and ultrasound, (2) invasive imaging devices such as angiography and cardiac catheterization, (3) invasive direct visualisation technologies such as endoscopes, (4) electrical devices, such as electrocardiograms, and (5) "enhancing" technologies such as Picture Archiving and Communications Systems (PACS) which are software based.

sensitivity to detect tiny abnormalities makes modern digital imaging technologies very important in the early detection of severe and common diseases such as cancer[5], which may be difficult or impossible to treat if they are not detected early enough (DoH 2001)[6].

Medical imaging devices can be cost-saving[7], especially in the medium to long term (Mitchell 1988; Trajtenberg 1990). The costs of maintaining and using medical devices tend to fall over time and over the course of treatment, in contrast to therapeutics costs which tend to rise[8] (NRC 2002). CT is considered to be welfare-enhancing (Trajtenberg 1989). The early detection of diseases often makes them easier to treat, and medical devices such as CT and MRI, in addition to providing information on the type and condition of the disease provide information on its size and spread, which helps in the accurate planning of treatment (DoH 2001).

Medical imaging devices are preferred by patients to other diagnostic techniques. CT and MRI, which are both non-invasive imaging devices, are often favoured by patients to invasive diagnostic techniques, which require insertion into the body[9] or removal of tissue (Jennett 1986). With time, people have become less and less tolerant of invasive treatments and more apprehensive about their efficacy making non-invasive technologies more popular (Jennett 1986).

In addition to hardware advancements in CT and MRI there has been a tremendous increase in computing software technologies in medicine. PACS[10] produces digital images which can be enhanced, reconstructed, processed, displayed, archived, and analysed improving

[5] It is predicted that 1 in 4 UK residents will contract cancer in their lifetime (NHS 1999).
[6] The diversity of diseases that can be detected with medical imaging is increasing quickly. For example, recently, MRI is making advancements in the detection of brain conditions such as dyslexia (MNT 2012).
[7] More generally, advancements in medical innovation over the period 1970 to 1990 have contributed to increased life expectancy as much as improvements to material wealth (NRC 2002). On the other hand, increasing technology costs are a key factor in rising health expenditures (Porter et al. 2006). Yet others state that they affect each other, and are differentiated by treatment and technology. For examples, vaccines have been very cost-effective, but progress in organ transplants has been costly but with little overall welfare gain (Djellal and Gallouj 2007).
[8] Furthermore, the economic value of disease reduction increases over time (as the wealth of the population increases the value of disease reduction rises) and the value of progress on one disease rises as progress is made on other diseases (NRC 2002).
[9] For example angiography, cardiac catheterization, and endoscopy are all invasive diagnostic devices.
[10] PACS, like other computer-based information management systems, is highly software dependent.

image quality and lowering transaction costs by enabling instant transmission of images to computer screens, between radiology departments, the operating suite, the bedside, portable communication devices, or anywhere else (Kevles 1998; Wolbarst 1999). For example, once an image is digitised, it can be enlarged or reduced, rotated or inverted, stretched or transformed to help the recognition of clinically relevant patterns and features that can dramatically improve accuracy in diagnosis (Huang et al. 1988; Strickland 1996; Bryan et al. 1999). Moreover, PACS can combine images from very different medical imaging devices, such as CT, MRI or PET, and make them comparable on one screen (Huang et al. 1988; Bryan et al. 1999). It can also produce real-time images on a screen during surgery so that the surgical team can actually see their instruments inside the body as they perform operations (Kevles 1998). These are all differences from X-ray technology where images were printed on film providing a static image that could not be manipulated, enhanced or digitally transmitted.

A large variety of factors affect the development of medical imaging devices (Gelijns and Rosenberg 1999). The following sections briefly review industrial advancements in medical devices and conditions affecting their supply in healthcare systems. The history of these technologies is described in more detail in Chapter 4 of this thesis.

The medical imaging devices industry is rapidly advancing into different technology areas, and it is dominated by a handful of very large firms[11]. Since the emergence of computer processing technologies and their application to X-ray and the development of the CT scanner, the diversity, quantity and power of medical imaging devices have increased tremendously. At the time of its innovation in the early 1980s, the prototype CT scanner went through several generations within three years of its development (Kevles 1998). In the 1990s and 2000s for devices such as MRI and PET this was even shorter.

[11] Unlike other medical devices industries which are composed of many small firms, the medical imaging devices industry is dominated by the large firms Siemens, Philips, Toshiba, and General Electric (GE) (Gelijns and Rosenberg 1999). These firms also dominated the X-ray industry in the 20th Century and continue to do so today.

CT, MRI and PACS are part of a group of technologies that have evolved with the clinical specialty of radiology. These technologies originated largely outside of medicine, with complex operating principles based on the integration of knowledge of physics, mathematics, chemistry, engineering, electronics, computation and software. Very briefly, CT was developed in the early 1970s by EMI[12], a firm specialised in recording, broadcasting and entertainment equipment which branched out into electronics after WWII. Their employee and engineer, G. Hounsfield, who specialised in pattern recognition and computing techniques is credited with having manufactured and patented the CT scanner[13]. The CT scanner quickly spread into the US, European and Japanese markets in the 1980s (Gelijns and Rosenberg 1999).

Unlike CT which uses ionizing radiation combined with computing technology, MRI is based on principles of radio waves and magnetic fields and computing. MRI development is even more strongly connected to computing because, unlike X-rays which can produce an image without computers, magnetic resonance data requires much higher signal processing power to be processed into images. MRI development is attributed to close cooperation between UK-US universities and industry (Kereiakes 1987); the most notable academics credited for its development are P. Mansfield, R. Damadian, P. Lauterbur and J. Mallard. Industry research intensified in the mid-1970s with firms such as EMI and Philips. Development was difficult at first because, briefly, the computer algorithms were more problematic, the strong magnets created problems in hospitals, and up until the 1990s examination time for full-body scans was up to an hour (Young et al. 1982; Kaufman 1987). The market for MRIs grew rapidly and between 1985 and 1993 the number of machines in the US grew tenfold (Gelijns and Rosenberg 1999).

PACS is an information management system for diagnostic images in digital format which replaced traditional X-ray film, and was developed in the early 1980s. PACS is traced back to US efforts in the field of medical informatics, mathematics and physics, and the development of computer interface standards DICOM (Duerinckx and Pisa 1982; Wiley

[12] Electrical and Musical Industries Ltd.
[13] Godfrey Hounsfield and Allen M. Cormack won the Nobel Prize in 1979 for the CT scanner.

2005). The first PACS system is said to have been built in the University of Kansas in 1982/83 with support from a private company. Simultaneously, at UCLA, the pioneer B. Huang was employing his graduate students to digitise X-rays in paediatric radiology. In the early 1990s DICOM was completed and the harmonisation of standards made it easier for PACS systems to be created and connected in hospital settings (Huang 2003).

Most hospitals in developed countries today have CT, MRI and PACS[14] devices and systems. Their importance in the early detection of diseases and their cost-effectiveness in the long run make them very attractive investments. Table 1 shows the change in distribution of CT scanners for selected countries over time.

Table 1: Distribution of CT scanners by country, 1979, 1990, 2000 and 2005

Country	Scanners per million population 1979	Scanners per million population 1990	Scanners per million population 2000	Scanners per million population 2005
United States	5.7	24.5	28.7	34.4
Germany (W)	2.7	11.9	11.9	14.4
Austria	n.a.	12.3	26.2	29.8
United Kingdom	1.0	1.89	5.5	8.3
France	0.6	7.2	10.0	10.4

Source: Author’s own calculations based on OECD Health Data (2001; 2007; 2008).

Table 1 shows that in the period 1990 to 2005 the amount of CT scanners in the UK increased from 1.89 to 8.3 CT scanners per million inhabitants. A large proportion of this increase is attributable to extensive government programmes for the diffusion of CT scanners in UK hospitals during this period (NHS 2000; NHS 2003; NPfIT 2004) and the increase in guidance for CT scanning (for example, NICE 2003). The table also shows that countries differ in the distribution of CT scanners in their population. For example, in 2005 Germany had 73% more CT scanners per million population than the UK.

[14] Imaging devices are also used in other sectors, such as archeology. However healthcare forms the largest part of the market for these devices (Gelijns and Rosenberg 1999).

Explanations for the variations over time and between countries are attributable to technical advance and government policy[15] for the procurement of medical devices (Lazaro and Fitch 1995; OECD 2008). In publicly financed healthcare systems such as the UK, the government plays a central role in the planning and regulation of resources such as hospital facilities, technologies, and staffing (Hutton and Hartley 1985). Other important factors are the degree of clinician specialisation, types and size of hospitals, patients, clinician accountability to patients and the public, as well as cultural predispositions towards invasive medical treatments (Yoshikawa et al. 1993; Herzlinger 2006).

Technical change in diagnostic imaging is partially reflected in changes in usage of 'high-end' CT and MRI scans compared to 'low-end' traditional X-ray scans. Table 2 shows growth rates in the UK NHS in the period 1995 to 2005. Both CT and MRI have high growth rates compared to X-ray which is relatively stable and slightly declining. CT and MRI are very different medical devices compared to X-rays, and the fast-paced changes in supply, demand, and technical changes are creating innovation challenges in the UK NHS (NPfIT 2004; Hendy et al. 2005; Clegg and Shepherd 2007).

Table 2: Average annual growth rate of CT, MRI and X-ray scans NHS England 1995-2005

X-ray	-0.2%
CT	9.2%
MRI	11.6%

Source: Author's calculations based on UK Department of Health Hospital Activity Statistics (1995 to 2005).

[15] In public healthcare systems the procurement and implementation of medical devices is largely centrally funded, although many hospitals acquire their scanners themselves through, for example, local charity and "Scanner Appeals". In private healthcare systems such as the US hospitals buy their own scanners. In such cases, the high profitability of scanning make them lucrative investments, and many more hospitals have them (Blume 1992:8).

1.2 Aims and research questions

The aim of this thesis is to understand learning in clinical practices in the diagnostic imaging technology areas CT, MRI and PACS through a theoretical perspective informed by evolutionary theories of technological change. Some authors consider scientific research, advancements in private industries and evidence-based medicine as important developmental motors of change in the medical sector (Granados et al. 1997; Grimshaw et al. 2004). This thesis suggests that additional conceptual relationships are revealed when medical innovation is analysed through an evolutionary perspective of knowledge accumulation and social change (Morlacchi and Nelson 2011; Nelson et al. 2011)[16].

To fulfil these aims, this thesis addresses the following research questions and sub-questions:

> ***RQ1: How do technical change processes in diagnostic imaging technologies (CT, MRI and PACS) affect learning in clinical practice?***
>
> - *What is the role of technical accumulation processes internal and external to the hospital with respect to learning in clinical practice?*
> - *In what ways do cognitive features at the individual, group, organisational and sectoral levels support or constrain learning?*

[16] NRC (2002:2) state: "[…] innovation in diagnostics, therapeutics and devices are important but are not the whole story. Corresponding innovations in the health care delivery system have not taken place and are badly needed if the full benefits of innovations in diagnostics, therapeutics and devices are to be achieved". Nelson et al. (2011) suggest three different pathways to medical progress: (1) biomedical research, (2) the development of new modalities through the advancement of technological capabilities, and (3) learning in clinical practice.

RQ2: How do social processes of technical change in diagnostic imaging technologies affect learning in clinical practice?

- *What is the role of social features of technological systems and communities internal and external to the hospital with respect to learning in clinical practice?*
- *In what ways do social features at the individual, group, organisational and sectoral levels support or constrain learning in these technology areas?*

RQ3: Why do some technologies in clinical practice develop more easily than other technologies?

- *For what reasons are CT, MRI and PACS more easily routinised in some clinical practice settings than in others?*

To answer these questions, this thesis uses a case-study approach and over 40 interviews with clinical, technical, managerial and administrative staff in five hospitals in the South East region of the UK. The cases examined in this thesis trace changes in hospital learning conditions and processes in CT, MRI and PACS technology areas in the period 2003 to 2005.

The findings in this thesis suggest that medical innovation is underpinned by processes of knowledge accumulation that are complex, incremental, iterative, and unpredictable, and which co-evolve with artefact characteristics, social norms, practice communities, experience and learning relationships constrained and supported by interactions with processes of social agency.

The research in this thesis uncovers important questions in the area of medical technology policy. The incremental, complex, partly tacit and uncertain nature of processes underpinning innovation suggest that policies guided by scientific evidence which mask the emergent and systemic nature of technological learning in healthcare may need to be changed. The complex issues of creating learning conditions to lower technological uncertainty in the healthcare sector may need to be addressed in medical innovation policy, their complexity perhaps being a reason why they may have been neglected in the past.

1.3 Thesis content and structure

This thesis has seven more chapters. Chapter 2 provides a literature review of some of the main approaches to hospital innovation with the objective of identifying contemporary themes and frameworks addressing the topic. The chapter then reviews the main approaches to organisational learning, with the objective of finding a suitable framework for learning in clinical practice. The literature on evolutionary approaches to technical change is then reviewed, with the aim of identifying the rationale for the thesis. The theoretical framework and research questions are developed, explaining and justifying the exploration of hospital innovation through a neo-Schumpeterian viewpoint.

Chapter 3 explains the research design and methods used. It discusses and justifies the choices for generating contextualised theory using novel qualitative empirical data. It presents the reasons for choosing clinical practice as the unit of analysis, and CT, MRI and PACS technology areas as cases. The chapter also describes the use of interviews for data collection, the selection of hospitals, and the use of qualitative analysis techniques for interpreting the data. The shortcomings of the research design and methods are discussed, as are the steps I took with the aim of lessening their negative impact on the study.

In Chapter 4 the background history, technology, and policy of CT, MRI and PACS are presented. The beginnings of diagnostic imaging in medicine and the historical evolution of X-ray technology are described. The chapter then provides developmental histories of CT, MRI and PACS, to inform the reader of the factors that have shaped the organisational technological contexts of the cases examined. The chapter concludes with a description of the policy context of these technologies in the UK NHS where the empirical study was carried out, and aims to inform.

Chapter 5 analyses changes in learning conditions and operational routines in two hospital cases of CT innovation. The first case highlights changes in conditions for knowledge coordination and exchange in cancer diagnosis in a large urban teaching hospital. Changes in medical guidance, diagnostic information, and disease complexity influenced the processes by which clinicians solved complex cancer cases. The creation of departmental CT capabilities was supported by the formation of a community of practice characterised by inter-disciplinarity in problem-solving. The second case explores the development of departmental capabilities in CT scanning in a medium-sized town hospital. Social norms for change in departmental roles, mentoring and participation underpinned the creation of CT capabilities in a small radiology department. Painstakingly acquired departmental know-how formed the basis for medical guidance in CT scanning for other hospitals in the region.

Chapter 6 analyses innovation and change in MRI clinical practices in two hospital cases. It describes how the learning environment for hospital institutionalisation of a novel MRI procedure for dementia imaging was enabled by individual imagination, experience and commitment, hospital strategic shifts changing resource availability, and changes in patient population. The second case examines the process of formulation of a regional MRI protocol for breast imaging. Differences in MRI devices, incremental processes of user configuration, and changes in patient preferences transformed the conditions within which clinicians solved medical problems and learned.

Chapter 7 analyses changes in learning conditions for PACS integration in a city and in a town hospital. The first case traces the transition from a paper-based X-ray regime to a digital diagnostic regime shaped by the development of hospital-wide PACS capabilities. It shows how incremental, step-wise behavioural restrictions of technical choices, the inclusion of specialists with diversified skills, and organisational goals informed by the healthcare regulatory authority helped hospital staff change operational routines and unlearn. In the second case emergent and unplanned learning processes are found and examined, which support the incremental creation of hospital PACS capabilities. It shows how the external imposition of rules can be in conflict with internal changes in learning, how the making of decisions on aspects of emergent and systemic technologies such as PACS far away from the organisational locus of learning increases technological uncertainty, and the activities individuals and groups engage in to help reduce it.

Chapter 8 summarises the main findings of the research study and presents the central aspects of medical innovation based on the individual case studies. It highlights the main theoretical implications of the research, and discusses how the results have supported and how they have contradicted existing theory on medical innovation and technological change. It also presents the limitations of the study and suggests some options for future research. Policy inferences derived from the research evidence are discussed as are suggestions for changes in health technology policy.

Chapter 2

Innovation in hospital organisations: Literature review and theoretical framework

This chapter first provides a literature review of some of the main approaches from the social sciences that have addressed hospitals as innovation contexts. It does this with the objective of identifying the state of the art of the literature on innovation in hospitals, along with the main research gaps, and finds the subject of learning processes in hospitals to be an important but relatively understudied area warranting further enquiry.

Section 2.2 reviews the main approaches to organisational learning, with a specific focus on learning processes, and the factors underpinning them with the objective of developing a suitable framework for exploring learning processes, and the factors influencing them, in hospitals. This section establishes that Crossan et al.'s (1999) learning process model provides a workable framework to apply to the exploration of hospital learning processes, learning levels, and learning outcomes. In terms of the factors affecting learning, this section argues that a focus on technology offers a fruitful direction for the exploratory study.

Section 2.3 presents how technological change has been explained in the literature, with the objective of arriving at an identification of the role of technology in organisational innovation, to be used as a set of factors in the exploration of hospital learning and innovation processes. It is used to supplement the organisational learning model introduced and defined in the previous section, and to provide the rationale for the thesis framework and research questions.

Section 2.4 develops the theoretical framework and research questions guiding the study. In doing so, it introduces, explains and justifies the exploration of the interrelationships between learning in hospitals and evolutionary aspects of technology. It proposes a model of hospital innovation that is defined by interactions between '4I' organisational learning processes (intuiting, interpreting, integrating, and institutionalising) and certain knowledge and social features of technology.

2.1 Hospital innovation: a review of existing approaches to the topic

Hospital innovation has been approached from a large and diverse range of perspectives. Hospitals have been conceptualized, for example, as demand-side organisations innovating via diffusion (Rogers 1962; Coleman et al. 1966), or communication (Rogers and Kincaid 1981), as organisations innovating via evidence-based medicine (Granados et al. 1997; Ferlie et al. 2001; Grimshaw et al. 2004), and as those innovating through product and process improvement and integration (von Hippel 1988; Van de Ven 1991; Lettl 2005). The following sections briefly review these approaches to hospital innovation, focusing on their conceptualisation of the hospital innovation process, factors influencing it, and some points of critique.

2.1.1 Rogers' diffusion approach to the analysis of hospital innovation

In Rogers' (1962/1995) diffusion approach, hospital innovation processes were defined as the adoption of new ideas and products from outside the hospital organisation. Rogers conceptualized innovation in hospitals as stages in the spread and adoption of new products or ideas by medical practitioners (Rogers 1962/1995). He considered a rich array of factors such as the social connectedness between doctors (see next paragraph), individual characteristics and agency, the 'fit' of the novel product to the adopting context, and contextual characteristics, as antecedents to innovation diffusion (ibid.). Different factors assumed differing degrees of importance in various stages (invention, development and adoption by users) of the innovation diffusion process (ibid.). The outcome of a successful diffusion process was adoption by users in hospitals.

Social connectedness referred to the personal relationships between doctors (Rogers 1962; Coleman et al. 1966; Burt 1973; Rogers and Kincaid 1981). Personal relationships supported communication and information exchange, and increased the propensity for imitation (Burt 1973). Well-connected individuals were more likely to become aware of new products through communication with other doctors, and therefore were more apt to purchase and adopt them.

In addition to social connectedness, heterophily (differences in individual knowledge bases and culture) was important in the first stages of the process, for a novel product to enter the adopting context (Rogers 1962/1995). In later stages, homophily (similarity in knowledge bases and culture) was important to simplify communication between individuals in the adopting unit and thereby facilitate product or idea integration into existing operational processes (Fennell and Warnecke 1988; West et al. 1999; Fitzgerald et al. 2002; Becker et al. 2005).

Individual agency increased the propensity to adopt an innovation. In the early stages, the existence of individuals who engaged in and influenced opinion formation within the adopting unit was important (Rogers 1995:5-6; Locock et al. 2001; Fitzgerald et al. 2002). Opinion leaders informed, communicated and pushed forward the adoption process by assuming a mediating role between the buyer and the seller. At a later stage and after the decision to adopt had been made, individuals who engaged in changing context-specific processes (‘change agents’) facilitated further steps in product adoption.

Structure influenced process. Rogers defined structure as the “patterned arrangements of the units in the system” (Rogers 1995:24). Structure had three main aspects. First, it determined the decision-making roles at different stages in the adoption process. For example, the level at which the decision to adopt an innovation was made (optional at the individual level, collective at the group or organisation level, a decision made at the authority level of the organisation or above, or a decision that was contingent upon other innovation decisions) was important in influencing innovation spread and integration. The closer the innovation-decision was to the individual adopter, the greater chance it had for integration into working processes (Rogers 1995). Second, structure was important for communication patterns between individuals. As communication influenced the spread of ideas, the structure of communication networks co-shaped their spread (Coleman et al.

1966; Granovetter and Soong 1983; Scott 1991). Third, structure was closely related to social norms defined as the established behaviour patterns of individuals in the organisation (Rogers 1995), such as the degree of individual opinion leadership or change agency.

Despite its widespread appeal and importance in identifying factors affecting innovation adoption, Rogers' approach did not take into account contextual differences and differences that exist across innovations. Moreover, Rogers did not address innovation processes and outcomes that occur post-adoption. The diffusion process was seen to end with product adoption and to be the same as imitation. This was later criticized in other literatures for reasons such as the inseparability of the diffusion and innovation process (Bell and Pavitt 1995), and the fact that the adoption of products does not necessarily mean that it has diffused within the organisation or transformed its processes (Van de Ven et al. 1989), and that innovation diffusion is more complex than imitation (Greenhalgh et al. 2004).

A further criticism is that the product or idea that was being adopted was viewed as static and unchanging (Greenhalgh et al. 2004) and as atomistic. Products change over the course of time in their composition, application, and connectedness to other parts of the hospital organisation and the wider system (Barley 1986). The idea that products are dynamic and interconnected with other parts of the organisation and system was later examined in detail, for example, by Hobday (1998) in his study of 'complex products'. This topic has also been analysed from a sociological perspective in connection with the role of IT in healthcare systems and its changing relationship to healthcare workers, patients, their perceptions and their interrelationships (Henwood et al. 2003; Jones et al. 2003; Hart et al. 2004). Dynamic aspects of products will be described in later sections of this chapter and form an important part of the chosen conceptual framework.

Adopting contexts such as hospitals are not passive adopters but more active, complex and dynamic than Rogers implied (Kaluzny et al. 1974; Van de Ven 1991; Djellal and Gallouj 2005). For instance, their internal structures are found to differ in terms of a greater number of aspects than those described in the diffusion approach (Djellal and Gallouj 2005). For example, hospitals have a diverse range of activities; doctors have a diverse range of specializations and their role in hospital structures and the wider healthcare system changes over time (Djellal and Gallouj 2005), which may affect adoption processes in more differentiated ways than suggested by Rogers.

The view of the innovation process as occurring in stages (invention, development and adoption by users) was found to be deterministic and in some ways flawed (Rothwell et al. 1974). For example, it did not take into account interactions of processes and factors within and between the stages, the iterative, multi-organisational, multi-institutional and interdependent nature of the innovation/diffusion process, and the change in importance of different factors over time and context (Lundvall 1992; Edquist 1997). Several historical studies have pointed out the importance of multi-organisational interdependencies in innovation, and their partial unpredictability (Pickstone 1985; Pickstone 1992; Metcalfe et al. 2005; Metcalfe and Pickstone 2006).

The diffusion approach nevertheless was a very important analytical approach to understanding adoption as socially mediated processes, and influenced other innovation approaches such as quantitative studies to hospital innovation adoption[17], and information and communication studies approaches to hospital innovation, reviewed in the following section.

2.1.2 Communication studies approaches to the analysis of hospital innovation

Communication studies approaches developed from the sociological perspective of diffusion, building on the notion of innovation as ideas that spread through the social process of communication (Rogers and Kincaid 1981; Kincaid 1987). Innovation as

[17] The emergence of quantitative techniques beginning in the 1970s and 1980s influenced many quantitative studies on the determinants of hospital innovation (for example, Kimberly and Evanisko 1981; Tornatsky and Klein 1982; Damanpour 1991; 1992; 1996; Nystrom et al. 2002). These studies do not focus on innovation processes and are therefore not reviewed here. They form a large volume of the literature on hospital innovation and to a large extent the studies ask very similar questions and come up with similar answers. In many cases the variables whose relationships are modelled (for example, size and innovation adoption as in Damanpour 1992) have a positive relationship to each other. These studies have been criticized for not being able to explain differences across hospital organisations, for treating the variables as atomistic, and for the unrealistic assumptions that their effect can be isolated from other effects and that these effects are quantifiable (Greenhalgh et al. 2004).

communication implied “a process by which individuals share information with one another to create a shared understanding” (Rogers and Kincaid 1981:63). An individual or organisation was more likely to adopt an innovation if other organisations and individuals they communicate with had already done so (Burns and Wholey 1993; Westphal et al. 1997).

Communication of innovations was found to have network features that shape the direction of information flows between people (Granovetter 1973; Granovetter 1995). Social networks were vehicles for the flow of information via social ties, detectable through the frequency and intensity of the information exchanged through them (Granovetter and Soong 1983; Wasserman and Faust 1994). Information flow frequency and intensity between members determined the structure of the network and its operation (Granovetter 1973).

Social network structure was characterised, for example, by individuals assuming different positions in the network because of the volume, content and reach of the information that flowed through them (Wasserman and Faust 1994). Individuals with a relatively large number of social ties to other network members had central positions in the network and were experts or ‘stars’ (Wasserman and Faust 1994). Stars had power over the network because they could, to a greater degree than the other network members, determine the type, content and receivers of information (Granovetter 1973).

Information content was also determined by the connectedness of members to other networks. Individuals who had ties to other networks had access to different types of information, and acted as ‘boundary spanners’ in the network (Tushman 1977). Boundary spanners were important because through them new information could spread within the network.

The strength of social ties between network members and members outside the network was important for information novelty and innovation. Weak social ties were more useful in bringing in new information to the network than strong ties, because strong ties implied repeated information exchange with the same network members, increasing the propensity that the same kind of information was circulated within the network (Granovetter 1973). Over time this approach was further developed by differentiating between network models for innovation diffusion (Valente 1995) and the relationship between network features and network dynamism (Watts 1999; Kossinets and Watts 2006).

These theoretical principles were built upon with other, more nuanced concepts asking the question of why information or knowledge flowed more easily between some members than between others. The characteristics of the message transferred, the quality of the source, the recipient[18], the channel of communication, and the characteristics of the context within which messages are flowing were all found to be important (Teece 1977; von Hippel 1994; Szulanski 1996).

On the other hand, many empirical studies that drew on these approaches simply created new terminology out of what Rogers and Granovetter already had said. For example, the empirical study by Goes and Park (1997) on hospital innovation found that inter-organisational links affected hospital innovation positively, emphasising the importance of structure and links without adding new information about these concepts or their effects on innovation.

2.1.3 Evidence-based medicine approaches to the analysis of hospital innovation

Evidence-based medicine evolved from the discipline of clinical epidemiology and focused on medical innovation as the spread of medical research that had the best evidence of treating diseases effectively[19] (Granados et al. 1997). Clinicians were to innovate in their clinical practices by staying informed and changing their behaviour in accordance with new information about which drug, device or technique was most efficient and effective for patients[20] (Grimshaw et al. 2004).

[18] Such as their absorptive capacity (Cohen and Levinthal 1990).
[19] Health technologies are heavily evaluated and assessed before they are allowed to enter the market (Granados et al. 1997).
[20] Evidence-based medicine has been important in shaping health technology policy in the UK (NICE 2001).

Medical innovation was seen as a linear technical process at the level of the individual (Green 1998; Green 2001). Recently many scholars using this approach realised that the implementation of guidelines was not as straightforward as individuals changing their own practice, but required more complicated hospital-level and systemic changes (Dopson et al. 2002; Grimshaw et al. 2004). Clinicians were embedded in specific structures, their behaviour was connected to other parts of the hospital and healthcare system, and changes to their own practices required other changes that were difficult to anticipate (Dopson et al. 2002). The evidence base for certain practices was often ambiguous and contested and needed to be continuously interpreted and reformulated to fit the practice context (Ferlie et al. 2001).

Changing clinicians' behaviour through research evidence has been critiqued (Dopson et al. 2002; Gurses et al. 2010) for neglecting factors such as clinicians' autonomy and the fact that its implementation in clinical settings often involves power struggles (Ferlie et al. 2001). Moreover, Dopson et al.'s (2002) study on how research evidence is created and evaluated in healthcare settings suggests that before research evidence can be assimilated, the requisite knowledge must already exist within the organisation.

The diffusion, communication and evidence-based approaches tended to focus on hospitals and clinical contexts as part of the 'demand-side' – individuals and organisations were seen as passive receivers of products or information, and whose main innovation process is that of adoption. The models assumed that their main premises were applicable to other clinical contexts (Greenhalgh et al. 2004). These critiques have, to a certain degree, been subsequently built upon by Van de Ven and colleagues (Van de Ven et al. 1989; Van de Ven and Grazman 1999), who explored hospitals as diverse innovation contexts engaged in organisational innovation processes that carried on, or began, once the innovation was adopted.

2.1.4 Organisation and management approaches to the analysis of hospital innovation

A broad variety of factors, their interactions with each other and with contextual characteristics are found to constitute different hospital innovation processes in this literature (Van de Ven 1991). Hospital innovation processes are conceptualised as organisational-level processes defined as the integration and routinisation of products within the hospital organisation (Kanter 1988; Van de Ven et al. 1999), the improvement of products and processes through user innovation (von Hippel 1988; Lettl 2005), the solution of organisational problems (Grilli and Lomas 1994), or the creation and change of hospital organisational practices (Van de Ven et al. 1989).

The diversity of these approaches and the factors that they attach to hospital innovation make it difficult to derive generalisations. However, broadly speaking, hospital innovation is considered to be a complex process that cannot be traced back to single entrepreneurially minded individuals, single inputs, or single innovations but instead arises from combinations of various factors, sometimes specific to the case, context, and time-period under observation, that interact to push the innovation process forward (Van de Ven 1999).

These processes are represented by trial-and-error and experimentation (Van de Ven 1991). Organisational factors such as effective leadership, flexible bureaucratic style, management of relationships between people, and an organisational culture that is open to risk were found in hospital case studies to positively affect the opportunity for hospital members to ‘try things out’ and find solutions to their problems (Grilli and Lomas 1994; Yetton et al. 1999; Plsek 2003). The degree of contextual complexity was also found to be important (Kanter 1988; Nystrom et al. 2002). Kanter (1988) showed that organisational complexity in structure, such as different and complicated departmental and organisational boundaries, has the potential to increase the generation of ideas in the hospital context. On the other hand, too big an organisational size increases complexity and bureaucratic procedures, slowing innovation processes down (ibid.).

Process studies from these literatures also found that hospital innovation is supported by staff involvement in decision-making. A dichotomous relationship between decision-making and implementation existed in many hospitals, hindering innovation (Van de Ven 1991). If staff were involved in the decision to adopt innovations, they could translate these decisions into clinical practices more effectively (ibid.). Good communication between different groups of people in the hospital facilitated innovation, especially because medical practitioners are often disparate and disconnected (ibid.). The inclusion of top management had innovation-enabling effects, as well as encouraging harmonious work groups, and low turnover of staff (ibid.).

Innovation processes in hospitals depended upon the use and improvement of existing products. Von Hippel (1988), addressing the role of medical practitioners in product and process improvement of medical devices through their medical usage of them, found that in his sample of devices over 80% were conceived, developed or improved by doctors and technicians working in hospitals (ibid.). Lettl (2005) and Lettl and Gemuenden (2005) suggested that the high level of education and professional use of medical devices by doctors, the high pressure to solve proximate problems, and user openness to new technologies were all important supporting factors in hospital innovation.

Hospital innovation outcomes in these studies are varied and mixed. They can range from the creation of new products or their radical improvement (von Hippel 1988; Lettl 2005), to incremental and piecemeal changes to existing hospital processes and practices that emerge from hospital adaptation to new technologies (Van de Ven, 1999). Overall, these studies highlight the importance of hospital innovation processes, but tend to envision the hospital as a closed organisation, and do not refer to external factors (apart from products) affecting innovation. Moreover, organisation and management approaches have tended to treat hospitals much like firms (especially the US literature on healthcare innovation) and do not take into account the differences between hospitals and firms in innovation (such as regulatory aspects specific to the healthcare sector).

The table below summarizes the main conceptualizations of hospital innovation reviewed here, along with the associated processes, factors, and some areas of critique.

Table 3: Summary of approaches to hospital innovation: Process, factors, and critique

	Diffusion approaches	**Communication studies approaches**	**Evidence-based medicine approaches**	**Organisation and management approaches**
Innovation process	Adoption of ideas or products (from outside) by medical practitioners (Rogers 1962).	Ideas that spread through the social process of communication (Rogers and Kincaid 1981).	The adoption of medical research that had the 'best' evidence of treating diseases by clinicians (Granados et al. 1997).	Changes in hospital organisational practices (Van de Ven 1998; 1999), changes in medical products (von Hippel 1988; Lettl 2005), solving organisational problems (Grilli and Lomas 1994), and many others.
Factors affecting the innovation process	Social connectedness (personal relationships between doctors), heterophily, 'innovation-system 'fit', individual agency and roles such as change agency and opinion leadership, structure (of units in the adopting system) (Rogers 1962/2003; Coleman et al. 1966; Burt 1973). Factors assume different degrees of importance at different stages of diffusion.	The structure and operation of social networks (Granovetter 1973; Rogers and Kincaid, 1981), the strength and degree of social ties measured, for example, by the degree and intensity of information flow (Granovetter 1973; 1976), 'boundary spanners' (Tushman 1977). More recent studies focused on more nuanced characteristics of the message transferred, the source, the recipient, and the context (Szulanski 1996).	Evidence of clinical efficiency and effectiveness of products, devices or techniques (Grimshaw et al. 2004).	A broad and diverse array of factors which are context-specific, and cannot be traced back to single individuals or processes but instead arise from a combination of factors, their interactions, characterised by trial-and-error experimentation (Van de Ven 1991). Few empirical studies using this approach explicitly focus on hospitals. Factors such as: the relationship between decision-making and implementation, opportunity for hospital members to experiment (e.g. Yetton et al. 1999), hospital complexity, good communication and inclusion of hospital management in the innovation process (Van de Ven et al. 1999).
Critique (shortcomings as analytical approaches for the study of innovation in hospitals)	Does not take into account contextual differences (Kaluzny et al. 1974; Djellal and Gallouj 2005; 2007), and differences across innovations, 'the innovation' is considered to be static and atomistic, the process is deterministic (e.g. Rothwell et al. 1971; Metcalfe et al. 2005); and the approach does not provide a framework for understanding what happens post-adoption.	The main focus is the individual, difficult to bound the network, that the characteristics of the innovation or the individual do not change over time, and that the frameworks are applicable to other contexts (Greenhalgh et al. 2004).	Medical innovation is seen as a linear technical process of changing behavioural practices by clinicians without the need for other changes in the practice context or wider healthcare system (Green 1998); evidence of certain practices is often ambiguous and contested and needs to be adjusted to fit the context (Ferlie et al. 2001); neglects that for a practice to change the requisite knowledge needs to be available in the adopting context (Dopson et al. 2002).	No coherent framework, unclear what underpins organisational transformation and change, hospital viewed as a closed organisation.

Source: Author's own summary. The selection of approaches partially draws on the extensive and detailed review by Greenhalgh et al. (2004).

To sum up, hospital innovation is a topic studied from a variety of perspectives providing a rich and detailed conceptual background to the diversity, complexity and importance of hospital innovation. However, the main approaches reviewed have several shortcomings in their direct application as frameworks for studying innovation processes in hospital organisations.

First, the diffusion approach is not suitable because it does not offer a comprehensive framework for studying organisational processes following adoption; it does not take into account contextual differences, adoption by units other than individuals, and changes in ‘the innovation’ over time (Greenhalgh et al. 2004). Second, the communication studies approach is not directly applicable to hospital innovation because it, too, limits innovation to adoption and passive spread, and it is difficult to bound the network, especially in exploratory studies as in this thesis. Third, the evidence-based medicine approach sees medical innovation as a linear technical process of changing behavioural practices at the individual level following the acquisition of information (a narrow view of innovation), and neglects the changing and ambiguous nature of what counts as evidence, and the fact that the contextual changes required to modify clinical practices are much more complex and involve many more actors, both aspects being largely unpredictable and different from context to context. Finally, the organisation and management approaches, although the unit of analysis moves away from the individual to the organisational level allowing for the inclusion of more variables, processes and actors, the studies are too few to provide a comprehensive framework. Overall, it is difficult to frame which processes trigger and underpin organisational changes, and as a result it remains unclear how and why hospitals learn (Van de Ven et al. 1999; Djellal and Gallouj 2005).

The following section provides a review of the organisational learning literature with the aim of finding a suitable and comprehensive framework for studying learning processes that underpin hospital innovation.

2.2 Organisational learning: literature review and hospital learning framework

2.2.1 Seminal works: Herbert Simon and James March and their followers

Since Simon's (1957) seminal contribution, many conceptual advances have been made in understanding organisational behaviour and change. Simon (1957) argued that organisational behaviour is dependent upon decision-making processes. Organisational decision-making processes were seen as a combination of individual cognitive capacities and how individuals in the organisation made choices about what to do (ibid.). Decision-making was determined by individual cognitive capacities and the individual's role in the organisation (which influenced where to look for information, which roles to pursue and how to do what they needed to do) (ibid). Simon described individual cognition as boundedly rational, emphasizing the limits to what people learn, and what they know, and the uncertain outcomes of their learning (ibid.).

March and Simon (1958) further developed Simon's work and created what was to be a ground-breaking analysis of organisational behaviour, decision-making and choice. March and Simon (1958) stated that organisational processes are influenced by rules that guide and control individual behaviour. Organisational rules served to transform the different knowledge bases, perceptions, attitudes, and interests into actions that were predictable and stable, and ensured that, despite the internal differences between individuals, organisations still met their goals[21]. Changes in rules were processes by which organisations changed.

Organisational rules changed only gradually because they were made up of a broad and complex range of components (such as storylines, traditions, common beliefs, goals, loyalties, standard practices, and interpretations), with the result that control over them was problematic (March and Simon 1958; Lindblom 1959). March and Simon (1958) challenged the notion that organisational hierarchies determine what organisations do, by

[21] Organisational behaviour was not entirely rational, but guided by what was known to work in the past to meet desired organisational outcomes (March and Simon 1958).

highlighting that organisational processes were often not hierarchical, but were made up of flows of information and actions that went in many different directions.

Following this intellectual trajectory, Levitt and March (1988:320) stated that organisations achieve their goals through the establishment of routines, a richer concept, defined as: “forms, rules, procedures, conventions, strategies, technologies, around which organisations are constructed and through which they operate. [Also including] the structure of beliefs, frameworks, paradigms, codes, cultures and knowledge that buttress, elaborate, and contradict the formal routines.” Organisational behaviour was conditioned by routines which were stable and predictable processes that allowed organisations to achieve their goals. They were also independent of the individual actors who carried them out, and continued to exist even when individuals left the organisation (Cyert and March 1963/1992).

Routines were dependent upon what happened in the past (Simon 1955; Siegel 1957). Based on systems of socialisation and controlled behaviour, and on inferences and knowledge about what worked previously, routines emerged as stable patterns of conduct (Cyert and March 1963/1992). Retention processes were part of how an organisation created its own memory (Simon 1955). Organisational memory contained the cognitive and behavioural processes and targets of the organisation, and remained when individuals left it, or when the organisation merged with others.

Organisations behaved the way they did because this is what they had learned to do (Simon 1957; Cangelosi and Dill 1965). Organisational learning was an experiential process by which individuals, alone and in interaction with others, created knowledge, and applied this knowledge to their actions. Learning processes preceded the creation of routines, through testing and experimentation, and integration with other processes and structures, to become routinised actions. Learning was found to be incremental (Lindblom 1959). It was gradually improved upon as new information was obtained (Quinn 1980) or through re-examination about what worked and did not work (Argyris 1982). The incremental nature of learning made change difficult, slow, and uncertain, less rational and more a process of ‘muddling through' (Lindblom 1959). Individuals were said to have different cognitive capacities and abilities for interpretation, influencing learning and routines in organisations (Loasby 1976).

To behave differently, organisations first had to unlearn (Hedberg 1981; Nystrom and Starbuck 1984). Hedberg (1981) defined unlearning as "a process through which learners discard knowledge" that was no longer accurate or suitable. Unlearning made room for new knowledge and behaviour. Unlearning was difficult because routines were a form of specialisation of the organisation. It was the areas within which the organisations were competent, and enjoyed increasing returns to scale (Arthur 1994). As conditions or organisational targets changed, existing routines were often no longer optimal modes of behaviour, and organisations became locked-in to sub-optimal processes (David 1985).

Zaltman et al. (1973) and Argyris and Schoen (1978) stated that the extent and degree of learning was important. The degree of learning determined whether an organisation is really learning or merely adapting (Fiol and Lyles 1985). Lower-level learning (single-loop) occurred through routine operations and was reflected in changes in behaviour within the prevailing norms and structure. Higher-level learning (double-loop) changed the organisational structure, defining new problems, heuristics and strategy (Argyris and Schoen 1978).

During the same period of time, advances in the relationships between knowledge and economic change were being made by Solow (1957) and others, who put knowledge at the centre (of economic change). Arrow (1962) stated that different process of learning such as 'learning by doing' was how economies accumulated knowledge, and augmented their productive capacities. Learning-by-doing and learning-by-using (Rosenberg 1982) differentiated between the forms of knowledge acquisition in practice.

A landmark contribution was Nelson and Winter's (1982) suggestion of routines as a locus of learning in organisations, and their explanation for why some organisations performed better than others. Nelson and Winter (1982) defined routines as repeatable patterns of organisational processes that may “range from well-specified technical routines for producing things through procedures for hiring and firing”. Organisational routines defined the organisation’s areas of competence and its learning outcomes (Nelson and Winter, 1982). Routine change was an observable change in behaviour preceded by learning processes. Learning processes occurred at multiple levels. Sometimes learning processes were implicit and did not lead to routine change (Argyris and Schon 1978; Huber 1991).

Many studies on organisational learning that followed continued to add more and more concepts, sometimes in a more and sometimes in a less integrated way (Dodgson 1993). Many approaches were developed without empirical testing (March and Simon 1958; Huber 1991; Dodgson 1993) making it difficult to understand how they may be more systematically organized in an empirically testable framework without losing their richness and complexity, and how they may be expressed and recognizable in organisational practices. To make the exploration of analytical approaches to learning more manageable, following Crossan et al. (1999), I have used an organizing principle of concepts that addressed respectively organisational learning levels, learning processes, and learning outcomes. The following section presents the analytical approaches reviewed and the organisational learning process framework I decided upon.

2.2.2 Approaches to the analysis of organisational learning processes

The literature on organisational learning reviewed so far has focused on the seminal concepts and definitions. This thesis explores learning processes in hospitals, drawing on the organisational learning literature and the literature on technology evolution. This section draws on more recent organisational learning literature to explore organisational learning processes, levels and outcomes in hospitals.

Individual level

Learning processes such as comprehension, gaining insights and new ideas, and other cognitive processes, occur at the individual level (Argyris and Schon 1978; Huber 1991;

Simon 1991; Nonaka and Takeuchi 1995). Conscious and subconscious processes in individuals enable them to perceive, understand and recognise patterns, and to draw conclusions (Underwood 1982). Their capacities are dependent upon what they learned in the past (Simon 1991). Through learning in practice and processes such as learning-by-doing and –using (Rosenberg 1982), individuals gain competencies and expertise in specific areas that enable them to recognise patterns, and to apply what they have learned to similar situations. Over time, knowledge that is acquired through experience becomes tacit knowledge, applied intuitively without conscious effort and planning, but as an unconscious spontaneous process (Polanyi 1966).

Tacit knowledge is difficult to transfer, but individuals may be able to express what they know tacitly using imagery and metaphors (Nonaka and Takeuchi 1995). Metaphors link individual intuition with mutual interpretation (Crossan et al. 1999). In order to be able to express tacit knowledge, individuals must also possess a language capacity. Shared language enables individuals to express what they may only ‘feel’ as an insight or a new idea if the language is not yet known or does not yet exist (Tsoukas 1991). Metaphors may also be useful when what is tacitly known becomes harder and harder to express by the individual over time, as the codified elements are transformed into tacit elements (Nonaka 1994). The metaphors and kinds of language used can become an important basis for the learning trajectory, and what happens as a result (Crossan et al. 1999).

Individual-level learning also includes conscious processes, such as interpreting (Weick 1979). The process of interpretation involves making explicit what is known, and making cognitive connections to an existing environment, as well as the creation of a ‘cognitive map’ of a knowledge space (Weick and Bougon 1986). The more connections the individual can make with a particular knowledge area, the better equipped they are to learn more, and to increase the complexity of what they do (Crossan et al. 1999).

Similar to the expression of what is intuitively known, interpretation involves language capacities. Individual interpretive capacity differs according to the degree of precision with which they can express what they know (Weick and Bougon 1986). There is a relationship between individual cognitive capacity and the existing language and knowledge domain. Individuals' cognitive maps differ and they will interpret the same events and information differently. The degree of ambiguity that is attached to a piece of information or event will differ across individuals, sometimes independently of the quality of information.

Individuals make interpretations on their own and as part of a social process. Through interaction and communication with others, individuals clarify their understandings, make new connections, and refine their language (Brown and Duguid 1991). The process of collective interpretation may foster a shared understanding and a shared language, becoming an integrative process occurring at the group or community level.

Individual knowledge is created through interactions between codified and tacit knowledge (Nonaka 1994). Similar to what was explained before with reference to Polanyi, individuals internalise knowledge through practice, by transforming codified knowledge into tacit knowledge, which becomes 'embodied' in the individual. As well as through individual practice, tacit knowledge is increased through social processes of interaction (Nonaka 1994). People learn to imitate others through interaction and face-to-face observation. A further learning process is externalisation, or the transformation of what is known tacitly to explicit knowledge (for example, through publications, or the issuing of standards and guidelines). Through the process of combination, individuals integrate codified knowledge with other codified knowledge (Nonaka 1994). Externalisation and combination also occur at the group and organisational levels.

Group level

Learning processes occurring at the group level involve integration. Integration processes are expressed in the coordination of collective actions amongst individuals. Groups or communities make individuals interact with one another and collectively get better at doing the activity (Lave and Wenger 1991). Integration is facilitated by shared language reinforced by continuous interaction and involvement in similar tasks. Belonging to the same group reinforces a similar identity and culture, reinforced by the application of individual knowledge and actions to similar tasks (Brown and Duguid 1991; Lave and Wenger 1991). Through collective application of its knowledge to similar tasks and goals, the group evolves into a community of practice (Lave and Wenger 1991).

Communities of practice are loci of learning. Shared understanding creates a mutual understanding that crosses formal departmental and organisational boundaries. Shared language makes it easier for knowledge to flow (Brown and Duguid 1991). Learning can also occur between groups and communities (Cohendet and Llerena 2003) via, for example, individual 'boundary spanners' knowledgeable in the language of several communities at the same time (Huber 1991). Learning processes in communities are underpinned by a common language that retains what has been learned in the past (Brown and Duguid 1991).

Learning processes in communities of practice have a strong degree of informality (Wenger 2000). 'Hybrid' characteristics of communities, made up of a diversity of specialties, professionals, academics, that have (in the short or long term) converged in one area make it easier for problems to be solved because of the diversity of knowledge and experience that the group can draw on (Cohendet and Llerena 2003).

Communities of practice are defined by agreement on certain principles of collective action, which if unreflective can evolve into 'groupthink' (Janis 1982). Repeated interaction and engagement in similar activities makes what was once a conscious process an unconscious and unquestioned one in which the heuristics of the activity are accepted and taken for granted. In such a condition, learning and change may be difficult and 'double-loop' learning (Argyris and Schoen 1978) is required to enable the group to adapt to changing requirements.

Organisational level

Learning processes observable at the organisational level involve routinisation (or institutionalisation) (Nelson and Winter 1982; Dosi 1988; Crossan et al. 1999; Feldman 2000; Cohendet and Llerena 2003). The routinisation process differs from individual and group learning processes, and it remains part of the organisation even when individuals and groups leave it, i.e. they are retained in the organisational memory (Nelson and Winter 1992). Routines are composed of an organisation's knowledge in the form of operational procedures, rules, behavioural codes and norms that are formalised and define the organisation's structure and competencies. Routines are a locus of organisational learning (Dodgson 1993).

Routinisation is characterized by a high degree of mutual consensus and by the stabilisation of organisational processes (Greenhalgh et al. 2004). Learning at this level is more linear and involves less trial-and-error experimentation, than learning at the individual and group levels. It takes a long time for learning outcomes from the individual and group levels to be institutionalised, and when they are, they may no longer fit the context (Crossan et al. 1999).

Institutionalising learning processes is a way of making informal knowledge explicit and usable to the organisation (Crossan et al. 1999). By forming structures around individual and group practices, an organisation can make use of its internal knowledge bases. Creating a context within which behavioural processes may occur more easily and repeatedly is a way of creating the right conditions for achieving desired organisational outcomes.

Routinisation is a way of achieving desired goals more efficiently and effectively. Over time, the organisation increases the proportion of individual and group behaviour that is regulates, and learning becomes less experimental and more directed and target-oriented. Practices that become institutionalised have achieved a form of approval from members high in the organisational hierarchy and often last for a long time (Crossan et al. 1999). The organisation moves more towards modes of knowledge exploitation than knowledge exploration (March 1991).

2.2.3 Hospital learning framework

Crossan et al. (1999) provided a broad and integrated organisational learning process framework that captured the depth and richness of organisational learning processes analysed in the early approaches, as well as later approaches based on communities of practice (Lave and Wenger 1990; Brown and Duguid 1991), and complexity (Lant and Mezias 1990). This thesis uses Crossan et al.'s framework for opening the 'black box' of organisational learning in an exploratory study of hospital learning. The following section defines the learning processes and organisational levels that this thesis uses as a framework based on Crossan et al.'s '4I' learning processes.

Intuiting

Crossan et al. (1999:526) define intuiting as a subconscious process by which individuals learn and comprehend something new. It is considered as a process of "past pattern recognition" based on the knowledge that the individual accumulated throughout their lifetime. It is based on what the individual experienced and internalized through both explicit and tacit knowledge acquisition (Polanyi, 1966). Intuition is difficult to express because it is 'felt' subconsciously. Its expression may be helped with imagery and metaphors that enable the communication of intuition to others. The language people attach to their intuition has important consequences for how an idea is developed or a problem solved because it influences processes of intuiting within others (Crossan et al. 1999:527).

Interpreting

According to Crossan et al. (1999:528), interpreting is defined as a conscious process of developing cognitive maps and making connections within the area that they are knowledgeable in. It is expressed in an individual's understanding as well as in their actions. Attaching a vocabulary to what is known allows individuals to make connections between what they intuit and the external environment. The language connections individuals can make affects their comprehension, and the actions that they will take. The outcome of interpretation depends upon the language that already exists 'out there' as well as the individual's cognitive map. Interpreting is not exclusively a process that occurs at the individual level, but can also be a social process involving dialogue and discussion until an understanding and agreement upon what action to take is reached (Daft and Weick 1984 as cited in Crossan et al. 1999:528).

Integrating

For Crossan et al. (1999:528), integrating is defined as “coherent and collective action”. The process of developing and mutually adjusting towards joint group behaviour requires a collective understanding of what is going on (Brown and Duguid 1991). Group learning is characterized by a shared language and common tasks, and defined by a collective identification with a common goal or set of beliefs or domain of knowledge and action. Developing a shared language co-evolves with the development of shared meaning (linking integration with interpretation). Engagement with similar practices and the desire to reach a common goal make people adjust their behaviour and learn.

Institutionalising

Lastly, Crossan et al. (1999:529) define institutionalising as the formalisation of what is learned at the individual and group levels into procedures, rules, and organisational routines. It is the process by which the organisation exploits what has been learned at the individual and group levels to achieve its desired goals. Routines provide the context for stable and repeated action and remain active in the organisation when individuals leave it. Routines are composed of elements such as formal practices, with rules and sequences that are embedded in the organisation and arise from the formalisation and stabilisation of organisational processes, emerging as predictable and certain rather than experimental and uncertain learning processes occurring at the individual and group levels.

According to Crossan et al. (1999), organisational learning starts at the individual level and works its way up to the organisational level and the creation of organisational routines. The processes are not linear (from individual to group to organisational level) but interrelated with feedback loops between the different processes and levels. Not every process occurs distinctly at each level, apart from intuiting which occurs at the individual level and routinisation which occurs at the organisational level. Table 4 presents a summary of the various processes and levels. For concepts of technology, I drew upon the literatures on technological evolution reviewed and defined in the following section.

Table 4: Hospital learning processes as suggested by Crossan et al. (1999)

Level	Process	Inputs/Outcomes
Individual	Intuiting, interpreting	Practice, imagery, metaphors, cognitive maps, dialogue and communication
Group	Integrating	Collective action, common language, shared meaning, understanding and identity, spontaneous adjustments to thinking and behaviour
Organisation	Institutionalising (routinising)	Routines, rules, procedures

Source: Crossan et al. (1999:525)

2.3 Evolutionary approaches to the analysis of technological change in organisations

Two central assumptions of this thesis are that the understanding of the organisational learning literature would be enriched by concepts of technology evolution[22], and that a greater understanding of which organisational learning processes affect technology evolution in organisations would be useful for the technological change literature. These assumptions are a guide to develop the exploratory framework through which to address the questions of how and why hospitals innovate in different technology areas. To structure the contributions of this rich literature and make it usable for an exploration of learning in CT, MRI and PACS clinical practices, I focused on knowledge and sociological features of technology evolution inside and outside the organisation.

2.3.1 Knowledge aspects of technology evolution inside the organisation

Nelson and Winter (1982) view technology as dynamic, differentiated by sector, time period, and organisation, and embodied in ‘technological regimes’ which are specific and manifested in routines, skills, artefacts and organisational and sectoral structures. Organisational learning is not a homogeneous set of processes occurring to the same degree across organisations, but idiosyncratic and differentiated by regimes and technology areas

[22] The concept of ‘knowledge accumulation’ links the organisational learning literature with the literature on technology evolution.

outside and inside the organisation. As such, technological regimes play a central role in organisational learning and change (Nelson and Winter 1982; Freeman and Perez 1988), making the accumulation of technical knowledge central in an organisation's productive work (Rosenberg 1976).

Technological change is not something that organisations "buy-in" from outside, but it is rooted in a specific set of change-generating resources (or routines and capabilities) which are located within the structures of the technology-using organisation (Bell and Albu 1999). These resources are composed of a variety of dynamically evolving and inseparable 'elements' in organisations, such as "knowledge embodied in artefacts, people, procedures and organisational arrangements… [including, *at least*] product specifications and design; materials and component specifications and properties; machinery and its range of operating characteristics, together with the various kinds of know-how, operating procedure and organisational arrangement needed to integrate these elements in a production system" (Bell and Albu 1999:1717) (emphasis added). Elements of technology are highly interconnected so that changes in one area may be linked to many other elements of the technology bundle (Bell and Albu 1999).

In organisations, technical knowledge is systematically ordered and stored in organisational routines. According to Nelson and Winter (1982), routines store technical knowledge that has been made operational. Operationalising technical knowledge occurs through learning, the embodiment of knowledge in individual skills, their application, and their expression in 'solutions to problems' (Teece et al. 1994). Technical knowledge, like all knowledge that is partly tacit (Zollo and Winter 1999), needs to be accumulated via learning processes such as learning-by-doing and learning-by-using (Rosenberg 1982). As such, complex technologies that are integrated in organisations in the form of products, processes, knowledge and skills cannot simply be 'transferred' but need to be learned in order to be incorporated into existing structures and processes (Attewell 1992).

Technological change increases the uncertainty and complexity of organisational learning (Rosenberg 1976). Knowledge accumulation underpinning routine creation and change is characterised by experimental and trial-and-error processes of change. The types of problems and possible solutions that may occur in changing organisational contexts are unpredictable; if the tacit knowledge required to solve them is unavailable, then processes of experimentation and trial-and-error will prevail (Rosenberg 1976; 1982). Technical change processes in organisations are diverse, the importance of different technological processes is believed to vary over time, and at any given time multiple technologies, their mechanisms, and modes of organisation, may co-exist in any given context (Rosenberg 1976). Technical knowledge is applicable in similar contexts, but because it interacts with many other resources and organisational characteristics it is difficult to say which contexts are similar, making the evolution of technology areas in organisations partially unforeseeable and different from context to context (Rosenberg 1976).

Technical change in organisations is path-dependent (Dosi 1982). Organisational routines are reliant and dependent upon existing resource contexts. In particular, they are reliant upon the localised tacit knowledge, which also explains heterogeneity in technical change across sectors and organisations (Pavitt 1984; Bell and Pavitt 1993). These factors also give rise to diversity in organisational routines and the degree to which they are able to change (Pavitt 1998). Moreover, technical knowledge is cumulative. The degree to which an organisation adapts to technological change depends on skills and knowledge it has accumulated from the past (Nelson and Winter 1982).

Organisational routines are underpinned by solutions that have been found for problems on the one hand, and new problems and problem-solving on the other. Rosenberg (1976:17-18) states: “Dynamism refers not only to learning but to the successful application of that which is learned. This often happens where the highest level of problems and problem-solving exist”. Knowledge, in order to lead to change and be learned, must therefore be applied to solve problems, which in turn generates new knowledge. If the same kinds of problem-solving skills are useful in one context as in another, then one technology will generally be applicable to both (Rosenberg 1976). Knowledge accumulation through problem-solving is also dependent upon an individual’s commitment to solve the problem (Rosenberg 1976).

Technical knowledge differs in importance and complexity for organisations over time (Dosi 1988). As technologies and their conditions evolve and change, certain kinds of knowledge become more important (Dosi 1988). Over time, the complexity of what was once radically new and difficult to comprehend and use, becomes less complex and more widely known. For example, at the beginning of the 20th Century knowledge of corrosion processes was poor and developed by few, while in the 21st Century it is very well known and exploited by many.

Learning under conditions of technological change is incremental (Rosenberg 1982). The knowledge requirements of different technology areas and their interactions with existing contextual conditions are non-obvious and difficult to predict. A further factor making learning in different technological areas incremental and slow is the partial tacitness of knowledge. Nelson (1998) suggests that technical knowledge has two interacting modes. The first consists of ‘bodies of understanding’ which comprise knowledge in a particular technological area that is easy to codify and transfer. Bodies of understanding contain knowledge that has evolved into general knowledge. The second comprises ‘bodies of practice’ which have been incrementally acquired within a particular context and are specific to the problems, experience and skills that have been accumulated through tacit learning.

Knowledge accumulation in an organisation’s ‘bodies of practice’ is what an organisation depends upon to carry out its productive processes. The limits to what an organisation can and cannot do are partly defined by what it knows and does not know (Pavitt 1998). If components of technological processes are relatively novel in organisations, there may not be enough individuals to ‘observe’ and the required tacit elements may be lacking, thereby constraining learning and routine change (Zollo 1997).

Technological knowledge is not only created in universities and firms but in other organisations such as hospitals in the form of “Mode-2” knowledge (Gibbons et al. 1994; Nowotny et al. 2001). Mode 2 processes indicate a shift from traditional, linear and disciplinary forms of knowledge generation to knowledge that is created from interactions across specialisations and is directly applicable to current problems (Gibbons et al. 1994). Knowledge generated ‘in the context of application’ suggests a role for organisations and practice settings in which knowledge is generated where problems arise and where its application is direct and proximate. Hospitals are increasingly considered as such organisational contexts (Gibbons et al. 1994; Hopkins 2004). Instead of being organisations narrowly recognised for their medical services, hospitals are portrayed as contributing to the generation of knowledge that solves healthcare problems. In addition to internal problems and requirements for Mode-2 knowledge, Martin (2003) suggests external drivers of Mode-2 such as higher complexity in products, technologies and skills.

Technology comes in different forms, one of which is its embodiment in products. Products can be highly complex and contain a diversity of knowledge and multiple technologies, making them difficult for organisations to absorb (Granstrand and Sjolander 1990). Technological diversity in products, or ‘capital goods’, may be underpinned by specific disciplines such as physics or engineering which the organisation may or may not be proficient in (Patel and Pavitt 1997; Pavitt 1998). Technologies embodied in products change over time and affect an organisation’s learning and production processes (Patel and Pavitt 1997). Technologies in products tend to increase (rather than decrease) specialization and complexity in the organisation (Pavitt 1998).

Products differ according to the degree to which they are autonomous, systemic, emergent and complex (Hobday 1998). The degree of autonomy or systemness of a product has an important impact on organisational learning (Rosenberg 1994). Autonomous products are defined as ‘hardware’, equipment, or instruments that possess ‘stand-alone’ qualities in terms of their connectedness to other parts of the organisation (Barley 1986; Zuboff 1988). Autonomous products tend to be easier to integrate in organisational processes than systemic products. Systemic products, on the other hand, are connected to other parts of the organisation and the wider technological systems influencing organisational and socio-economic structures (Hughes 1987; Davies 1996). Such connections to ‘large technical systems' (LTSs) involve important interactions with the internal structure of the organisation such as its learning and production processes (Davies 1996).

The degree to which a product is emergent is also important for organisational learning. For example, mass-produced commodity goods that have 'stabilised' in their organisational functions and roles are easier for organisations to integrate than products that are in the process of finding their role (Hobday 2000). Moreover, the relationship between the properties of complex products and their stabilisation or routinisation in organisations is not straightforward or predictable. Aspects of technological complexity of products evolve in organisations at different rates; where one aspect or functional demand may be met in the organisation, other aspects may not (Wang and von Tunzelmann 2000).

Hobday puts forward the notion of 'complex product systems' (COPS) to denote products that are technology-intensive, typically high cost and customised, including capital goods, control units, software packages, and services (Hobday 1998; 2000). COPS encompass a broad range of products that are characterised by systems and sub-systems, sub-components, network attributes, and emergent properties that require complex processes of coordination, integration, and design (Hobday 1998). COPS fall into different categories (e.g. IT networks, train engines), change with processes of customisation in sectors and organisations, and entailed a high degree of user involvement in their evolution (Hobday 1998).

The extent to which a product may dynamically co-evolve with their environment is partially dependent upon the degree to which it is 'locked-in' to specific roles, functions, and relational configurations in the organisation and the wider system (David 1985; Cowan and Gunby 1996). Learning and change is more complex when technologies are embedded in the organisation and 'compete' with different technologies for similar functions (Arthur 1989).

2.3.2 Knowledge aspects of technology evolution outside the organisation

Important aspects of learning in organisations are shaped by external changes. Freeman and Perez (1988) explain that organisational structures both shape and are shaped by new technological paradigms. Technological paradigms define the bodies of knowledge external to an organisation (Dosi 1982). Dosi (1982) applied Kuhn's (1962) interpretation of scientific paradigms to suggest that organisations are not led by a technological development path that they govern internally, but that they are part of a growing body of knowledge external to the organisation which influences its internal processes and direction. This growing body of knowledge is also considered to constrain it along a path dependent on what has occurred in the past (Dosi 1982). Nelson et al. (2011) put forward the notion of a 'practice paradigm' linking external knowledge with internal organisational practices, suggesting important influences of organisational conditions under which skills can be improved across practices, and technical knowledge can be acquired, retained and applied.

Schumpeter (1939) first stated the importance of considering the flow of resources (information, knowledge, people) across organisational boundaries. Knowledge comes into the organisation from different sources, such as external organisations, firms, research institutions, government support conditions, regulatory conditions, and users (Rothwell 1986). Organisational knowledge is created through processes of interaction, with other types of organisations, and via linkages between organisations, people, user/producer links and other systems integrator elements that enable knowledge flows within and outside the organisation (Lundvall 1992). It emerges from feedback, application, and change in different parts of the system (von Tunzelmann et al. 2008).

Medical knowledge is advanced through hospital interactions with other parts of the 'medical innovation system' (Metcalfe et al. 2005). Historical studies of medical products and techniques have shown that hospitals are part of the innovation and production process of medical technologies, with varying degrees of involvement over time and technology area. Medical practitioners, for example, played an important role in scientific advancements and product improvements in the areas of prosthetic hips and intra-ocular lenses via their interactions with other parts of the innovation system (Pickstone 1985; Pickstone 1992; Metcalfe and Pickstone 2006).

Pavitt (1999) states that flows and creation of knowledge between and within organisations are not random but have important structural dimensions. In more traditional manufacturing firms, it is important for R&D departments to be connected to production (Pavitt, 1999). In cases where knowledge is not produced in R&D departments but elsewhere, network connections between people and organisations are important, connections which can exist along supply, production and distribution channels as well (Bell and Pavitt 1993; Sutton 1998). Organisational innovation emerges within a 'system of innovation' in which governments and institutions play an important role (Freeman 1988; Lundvall 1992; Edquist 1997).

Organisational learning processes are affected by the differing rates at which external knowledge progresses (Rosenberg, 1982; Cohen and Levinthal, 1990). Knowledge progress is not easily recognisable or acquired in forms that can be conveniently applied (Pavitt, 1999). Instead, it relies on tacit knowledge embodied in competencies, routines and capabilities to be assimilated and absorbed (Dosi 1988; Zollo and Winter 1999). The ability to deal with changing external knowledge is dependent upon a firm's 'absorptive capacity' (Cohen and Levinthal, 1990). As knowledge outside the firm is continuously growing, the firm's absorptive capacity, a relative concept, needs to be increasing at least a similar rate to keep up (Cohen and Levinthal 1990; Zahra and George 2002).

An organisation's ability to assimilate and innovate with external technologies is not solely dependent on science-based knowledge, but also requires engineering forms of knowledge and other "lower" types of knowledge useful in problem-solving (Rosenberg, 1982). More important than 'higher' types of external knowledge are technologically useful knowledge and information, and conditions that encourage and enable their acquisition and assimilation. Internal learning is dependent upon a variety of external knowledge bases, but if very different from internal knowledge bases they are difficult to absorb and apply (Pavitt 1999). An important constraint in the production, application and use of complex products is the reliance upon an increasing diversity of knowledge principles and disciplines (Granstrand and Sjolander 1990; Pavitt 1999).

Sometimes what is developed in research and development is not suited for practice. Medical treatments, for instance, need to be evaluated in humans in trials examining their clinical effectiveness. They are not, however, examined on criteria related to the context within which they will be applied, administered and transformed into healthcare services (Nelson et al. 2011; Morlacchi and Nelson 2011). Organisational context includes the equipment, memories, and work environment, and the information that is processed by other members, whose interactions with the technology are impossible to predict (Nelson and Winter 1982:105). In a similar vein, Rosenberg (1982:143), drawing on Kuznets (1972), points out that "a product innovation in one context may be a process innovation in another", suggesting that contextual specificities may be definitive in determining the role of an innovation in an organisation or sector, rather than it being given from outside.

2.3.3 Sociological aspects of technology evolution inside the organisation

Technological evolution in organisations is a social process of negotiation between social groups (Pinch and Bijker 1984; MacKenzie and Wajcman 1985; Bijker et al. 1987; Blume 1992; Williams and Edge 1996). Instead of being driven by the evolution of knowledge as defined previously, technology in the sociological perspective is part of the evolution of social processes, perceptions and decisions regarding technology (Pinch and Bijker 1984; Blume 1992). Over time, social processes 'shape' or 'construct' the role the technology plays in the social system, stabilizing its functions and rules for the organisation (Pinch and Bijker 1984; Bijker 1987; Wynne 1988). Social features of the organisational context such as social groups, negotiation processes, social norms and structure, play a dominant role in the evolution of technology in the organisation (Williams and Edge 1996).

Social contexts are heterogeneous and have multiple social groups at the same time that may have radically different interpretations of, for example, the technological artefact, and thereby exert a different influence on the evolution of its 'meaning' (Pinch and Bijker

1984). Interpretations may change over time and interact with one another (ibid.). By possessing ‘interpretative flexibility’ in the use and functions of the artefact in their social context, social groups such as ‘users’ for example, in turn, are shaped themselves, and assume different roles in the organisation or social system (Kline and Pinch 1996).

The different technical options and choices surrounding the artefact in the organisation are outcomes of social choices throughout the negotiation process (Clark et al. 1988). Social choices are affected by the social structure (for example, the distribution of power between social groups) in the organisation, the technological problem, and the solution (Pinch and Bijker 1984; Orlikowski 1992). Each social group may have a different position in the organisational hierarchy, may perceive a problem differently, and have a different solution. The acceptance of the solution may depend upon the position of the social group in the hierarchy (Pinch and Bijker 1984; Blume 1992).

Social negotiation processes are not smooth and predictable but often problematic. One reason is that they may challenge existing power structures in the organisation. For example, Barley (1986), in his analysis of the negotiation process of the CT scanner in two hospital departments, found that technicians (lower in the organisational hierarchy) had different solutions to the problem to radiologists (higher in the organisational hierarchy), which challenged the structure between them.

Organisations may have similar hierarchical structures but differ in their behavioural norms, which may affect the negotiation process (Barley 1986). For example, Barley (1986) found that the social norms or ‘scripts’ that predefine the ways in which different members of hospital departments interact have an important influence on the speed and direction of technology evolution in the organisation. The hospital department with norms that supported horizontal interaction across social groups allowed for faster problem-solving than did the department that maintained a vertical and uni-directional form of exchange (ibid.).

Negotiation can take a long time and indeed it is often impossible to know how long it will take. The meaning of the artefact is intertwined with which social groups are involved in gradually giving meaning along its technological trajectory (Latour and Woolgar 1979; Williams and Edge 1996)[23]. Social processes are unpredictable, and relevant social groups, their perceptions and their roles in shaping meaning, may only be recognisable in hindsight (Pinch and Bijker 1984).

Negotiation can come to an end when artefacts are 'stabilised' (Barley 1986; Blume 1992). Stabilisation is also sometimes described as routinisation or institutionalisation (Greenhalgh et al. 2004). This occurs when the main problems with the artefact have been solved and the solutions have been accepted (Blume 1992). Routinisation occurs incrementally throughout the negotiation process, and is characterised by the artefact assuming a role and function within the social system that is, relative to previous periods, unchanging (Blume 1992). Over time, a further negotiation process for the same artefact may occur when new uses are found (Pinch and Bijker 1984). Empirical studies on routinisation processes of technological artefacts within hospitals are, apart from Barley's exemplary (1986) study, quite scarce (Greenhalgh et al. 2004).

During the negotiation process, the relationships between social groups change (Barley 1990; Nettleton and Hanlon 2006) and their relationship to the technology changes too (Green et al. 2005). Healthcare environments in particular are considered as diverse and complex with complicated decision-making structures, and it is unclear which social group is driving the stabilisation process and which group is subject to its outcomes (Henwood et al. 2003; Berg 2004).

[23] The social negotiation of the bicycle (Pinch and Bijker, 1984) is considered to be shaped by the differential social forces that varied and prevailed over 19 years before it was stabilised, shaped by the differential preferences and roles of different social groups (e.g. cyclists, anti-cyclists and female cyclists), their differential perceptions of problems, and their solutions.

2.3.4 Sociological aspects of technological evolution outside the organisation

Organisations are part of wider socio-technological spaces, and sociologists and historians of technology have suggested several important organising themes within which processes and features can be questioned, subsumed and analysed. Of these, the main ones which I will discuss here are Hughes (1983; 1987) work on technological systems, Constant's (1980; 1987) work on technological communities, and Bijker's (1987) work on technological frames. I will also repeat some important aspects of Pinch and Bijker's (1984) work on negotiation and closure because these processes occur in the social systems of which organisations are part and affect the evolution of technology and the role and processes of artefacts within the organisation.

Technological systems connect artefacts to different parts of society, they develop through stages, and each context or locality has its own technological style (Hughes 1983). The connectedness of artefacts to different parts of society (for example, to inventors, engineers, entrepreneurs and consumers) means that defining features which are established in one part of the system (for example, the building of an artefact and their characteristics such as power systems by engineers and entrepreneurs) influence the role of the artefact in another part of society (for example, the role of electric power in households) (ibid.).

The evolution of technological systems is characterised by stages defined by reverse salients (Hughes 1983). Reverse salients are disruptive situations or problems that focus problem-solving efforts on them and over time create specific groups of problem-solvers (Constant on Hughes 1989:229). Cultural aspects of technologies such as values (for example, what is considered most important about the technology the time, such as efficiency), institutions, and ideas change through these stages (Hughes 1983).

Evolution of technological systems has momentum, which is derived from the components of systems, their interactions, and their goals and directionality, and velocity with which they spreads and are created (Hughes 1989:76). Velocity can create conditions of radical technological changes, which can be disruptive to the organisation via for example deskilling, and making previous investments wasteful (Hughes 1989:59). Systems evolve and expand, and over time they become less flexible, but they do not simply disappear; instead, systems layer over one another (ibid).

Localities and organisations have their own contextualised technological style which arises from interactions with the economy, geography and politics of which they are part (Hughes 1989). Hughes (1989:70) provides the example of a copper shortage in Germany after WWI, causing power plant designers to install larger and fewer generators to save copper, which persisted after the copper shortage passed. Such learning experiences and localised design modifications can help explain the regional style of the Ruhr area (Hughes 1989:70). Diagnostic imaging technologies in Japan diffused rapidly because of the cultural value of non-invasive medical examinations in Japanese culture (Yoshikawa et al. 1993).

Organisations are embedded within communities of technological practices (Constant 1980; 1989). Defined by “the adherence to a tradition” (Constant 1989:224), practice communities are composed of individuals and organisations that incrementally develop their tradition through shared normative values, common problem themes, and testing procedures (Constant 1980). The community changes by changes in constraints to what can be usefully done while continuing the conventions (Constant 1989:225).

Organisations and artefacts change within evolving technological frames which structure communication between social groups (Bijker 1989). The technological frame explains how a social environment structures the design of an artefact. A problem (e.g. scarcity) and several solutions, the solution which is chosen creates the frame within which other solutions are searched for and chosen as the technology evolves. The frame includes goals, problem-solving strategies, and practices of use (ibid.). Depending on the technological frame that is described, different factors will play different roles (ibid.).

A member of a social group can have different degrees of inclusion in a technological frame, which will change over time and influence the negotiation process (Bijker 1989:174). Users and their practices, for example, can influence the design of the artefacts (ibid.). The technological frame notion can help explain the role of social processes in ‘closing’ the definition process of an artefact by specifying the role of different social groups, their problems, and the solutions to the problems that are agreed upon in society (Pinch and Bijker 1984).

Table 5: Summary of evolutionary approaches to technological change in organisations

	Knowledge approaches	**Sociological approaches**
Conceptualisation of technology	Knowledge embodied in artefacts, people, procedures, routines, capabilities and organisational arrangements, product specifications and design; materials and component specifications and properties; machinery and its range of operating characteristics, together with the various kinds of know-how, operating procedure and organisational arrangement needed to integrate these elements in a production system (Bell and Albu 1999:1717).	Social process of negotiation between social groups (MacKenzie and Wajcman 1985; Bijker et al. 1987).
Factors affecting technology evolution inside the organisation	Changes in the technological regimes, and the technical knowledge stored in routines (Nelson and Winter 1982; Freeman and Perez 1988), changes in the complexity and diversity of technical knowledge in the different technology areas examined (Rosenberg 1976; Dosi 1988), path dependencies in technological trajectories (Dosi 1982), cumulativeness in technical knowledge bases (Nelson and Winter 1982), individual commitment to problem-solving (Rosenberg 1976), changes over time in technical knowledge embodied in products (Patel and Pavitt 1997), internal practice-based knowledge regime (Nelson et al. 2011), changes in the multitude of technologies embodied in the products (Granstrand et al. 1992), changes in the emergence and systemness of products (Hobday 1998), and the competition between technologies with existing technologies for similar organisational functions (Arthur 1989).	Social features of the organisational context such as social groups, negotiation processes, social norms and structure (Pinch and Bijker 1984; Blume 1992).
Factors affecting technology evolution outside the organisation	Changes in the external practice paradigm (Nelson et al. 2011), feedback and interactions with other organisations (Lundvall 1992), different rates of change in external technical knowledge (Dosi 1982), the suitability of external products and technologies for organisational practices, and the absorptive capacity of the organisation (Cohen and Levinthal 1990; Zahra and George 2002).	Technological systems, specifically connectedness, reverse salient, momentum, expansion, inflexibility, layering of systems, and contextualised technological style (Hughes 1983; 1989). Technological practice communities and adherence to tradition characterised by shared normative values, common problems, testing procedures, and constraints Constant (1980; 1989). Technological frames (Bijker 1989) and notions such as social environment, social group inclusion and exclusion, problems, and closure upon a solution shaping the role of the artefact in the organisation and in society (Pinch and Bijker 1989).

Source: Author’s own summary of literature reviewed.

2.4 Conceptual framework and research questions

The literature reviewed in section 2.1 suggested that hospital innovation is a complex and heterogeneous process of product and information adoption (Rogers 1962), and communication within social networks (Rogers and Kincaid 1981), determined by research evidence (Ferlie et al. 2001) and an outcome of organisational and managerial adaptation processes (Van de Ven 1991). This review also highlighted that a conceptualisation of hospitals as 'passive adopters' is misleading and that hospitals are, like firms, active participants in the medical innovation process (Greenhalgh et al. 2004). Section 2.2 then reviewed the organisational learning literature, to establish a framework to help uncover elements and underpinnings of hospital innovation processes. The exploratory nature of the study and choice of empirical context led me to choose the open, flexible but systematically integrated organisational learning framework suggested by Crossan et al. (1999). This also provided the definition of 'hospital innovation' as introduced in section 2.4.1 below. Moreover, the literature review of organisational learning showed that these perspectives are rather vague as to what drives the process of change in organisations (Dodgson 1993), and provided a reasoning for focusing on technology, and thereby the grounds for the thesis. Section 2.3 reviewed several perspectives on technology evolution, focusing on aspects of neo-Schumpeterian approaches and sociological approaches, to arrive at a comprehensive and detailed list of factors for their application to a novel empirical area.

Based on the theoretical contributions and their exposition, this section introduces the original research questions guiding the study. Section 2.4.1 defines hospital innovation based on the definition of routinisation provided by the organisational learning literature reviewed in section 2.2.3. Section 2.4.2 draws on the literature on knowledge approaches to technological evolution to suggest knowledge factors that may play a role in hospital innovation, and proposes the first research question of the study. Section 2.4.3 draws on the literature reviewed on sociological approaches to technological evolution to suggest social factors affecting hospital innovation, and introduces the second research question in the study. Section 2.4.4 draws on both the organisational learning and technology approaches reviewed to explore the issue of contextual and technological heterogeneity in hospital innovation, and develops the third and final research question of the thesis.

2.4.1 Learning in clinical practice

Based on Crossan et al.'s (1999:529) definition of organisational learning, hospital innovation is defined as: "the formalisation (or institutionalisation) of what is learned (at the individual and group levels) into procedures, rules and routines". Institutionalisation is the process by which an organisation exploits the knowledge that has been accumulated within it in order to achieve its goals. This process can take a long time (and, once it has occurred, may no longer suit the organisational context). Institutionalisation is seen as an outcome of interactions between learning processes at different levels in the organisation, defined below:

Intuiting (individual level)

Intuiting is defined as a subconscious process at the individual level determined by past pattern recognition (Crossan et al. 1999). It relies upon the knowledge that the individual has accumulated over their lifetime. It is tacitly learned and communicable to others through imagery and metaphors.

Interpreting (individual and group level)

Interpreting is defined as a conscious process of comprehension and connection with an individual's cognitive map (Crossan et al. 1999). A cognitive map is composed of existing knowledge and language connections that partially exist in the outside environment. Interpretation, as it occurs via a common language, can take place in dialogue and through communication with others until an understanding is reached.

Integrating (group level)

Integration is defined as coherent and collective action (Crossan et al. 1999). Integration involves the mutual adjustment of collective behaviour and the creation and reinforcement of a collective understanding. It is characterised by a shared language, common tasks and a collective engagement in similar organisational processes and goals.

2.4.2 Knowledge aspects of technology evolution and learning in clinical practice

Supported by Nelson and Winter (1982), Dosi (1988), and Freeman and Perez (1988), organisational learning is affected by knowledge factors of technology evolution such as changes in technological regimes and interactions with aspects of the organisation-internal practice-based knowledge regime such as the technical knowledge stored in routines.

Technical knowledge evolution is path dependent, and builds on elements of the technology 'bundle' such as skills, structures, processes, artefacts, routines and capabilities that were accumulated in the past, shaped by 'technological trajectories' that are enabled and limited by what has been learned in the past, both inside and outside the organisation (Dosi 1988). Knowledge evolution is incremental, partially unpredictable, and accumulated through painstaking processes and individual commitments to problem-solving (Rosenberg 1976). Via processes such as learning-by-doing and –using, organisations accumulate and create knowledge (Rosenberg 1982) and expand their 'bodies of practice' (Nelson 1998).

The process of technical knowledge evolution is characterised by changes in its complexity and diversity (Rosenberg 1976; Dosi 1988). For example, organisations are affected by changes over time in the technical knowledge in external products (Patel and Pavitt 1997). Changes such as the multitude of technologies embodied in products affect their knowledge requirements in the organisation and differ in their suitability for organisational practices (Granstrand and Sjolander 1990). Product properties such as the degree of their emergent nature, systems, sub-systems, sub-components, and network attributes affect organisational processes of customisation and routinisation (Hobday 1998). Technologies may compete in organisations for similar organisational functions (Arthur 1989).

External to the organisation, technical change can bring about changes to the external practice paradigm (Nelson et al. 2011). Organisations are not closed but open, and knowledge (for example, in the form of information, technologies, and people) flows across their boundaries (Schumpeter 1939). Organisations are part of wider innovation systems and knowledge is accumulated through feedback and interactions within and across these systems (Lundvall 1992).

External technical knowledge changes at different rates (Dosi 1982). Thus, knowledge requirements of technologies change over time. Organisations differ in their absorptive capacity, which affects the extent and degree to which they can keep up with changing technological environments (Cohen and Levinthal 1990; Zahra and George 2002). Where one aspect or functional demand may be met in the organisation, other aspects may not (Wang and von Tunzelmann 2000).

Based on these theoretical considerations, I expect hospital innovation to be affected by knowledge aspects of technology, which leads to the first research questions and sub-questions:

RQ1: How do technical change processes in diagnostic imaging technologies (CT, MRI and PACS) affect learning in clinical practice?

- *What is the role of technical accumulation processes internal and external to the hospital with respect to learning in clinical practice?*
- *In what ways do cognitive features at the individual, group, organisational and sectoral levels support or constrain learning?*

2.4.3 Sociological aspects of technology evolution and hospital innovation

According to Pinch and Bijker (1984), technology evolves via social processes of negotiation between different social groups whose perceptions of the technological artefact differ and change over time. In any social system, such as an organisation, the configuration of social groups shapes which perceptions dominate the negotiation process and which perceptions get rejected or accepted (Blume 1992). The structure of the social system both affects and is affected by the negotiation process, which may give rise to different social configurations over time (Bijker et al. 1987). In addition to structure, social systems have social norms which shape the behaviour of social groups and their interactions, and which affect the process of technological evolution, and the stabilisation of the artefact and the finding of its role in the social system (Barley 1986).

Based on this theoretical reasoning, I expect hospital innovation to be affected by social aspects of technology, which leads to the second research question:

> ***RQ2: How do social processes of technical change in diagnostic imaging technologies affect learning in clinical practice?***
>
> - *What is the role of social features of technological systems and communities internal and external to the hospital with respect to learning in clinical practice?*
> - *In what ways do social features at the individual, group, organisational and sectoral levels support or constrain learning in these technology areas?*

2.4.4 Differences between technology areas and clinical practice contexts

The theoretical perspectives reviewed in sections 2.2 and 2.3 suggest that there are similarities and differences between organisational contexts, technology areas and social systems in their innovation processes and outcomes, which cannot be known a priori. Organisations differ in the extent and degree of individual intuiting, interpreting, integrating, institutionalising and their interactions between these processes (Crossan et al. 1999). Based on Rosenberg (1982:143), contextual specificities are assumed to determine technological change processes in an organisation or sector. Organisations differ in their technology 'elements' and 'bundles', such as skills, artefacts, tacit knowledge, routines, procedures and product specifications (Bell and Albu 1999). Social systems differ in their social groups, perceptions, and norms affecting the process of technology evolution in the organisation (Pinch and Bijker 1984; Barley 1986; Blume 1992).

From this I infer that technology areas and clinical practice contexts will differ in the variety and extent of influence of knowledge and social factors underpinning organisational innovation processes, leading to the last research question guiding the study:

RQ3: Why do some technologies in clinical practice develop more easily than other technologies?

- *For what reasons are CT, MRI and PACS more easily routinised in some clinical practice settings than in others?*

Chapter 3

Research Design and Methods

This chapter first describes the exploratory case study design, and justifies the choice of producing contextualised theory with novel qualitative empirical data. Section 3.2 discusses the selection of clinical practice as the unit of analysis, and CT, MRI and PACS as cases. Section 3.3 describes the use of interviews for the collection of data, the choice of hospital sites, and the use of qualitative techniques for ordering, finding patterns, and for interpretation. It also describes the use of observations and archival searches for triangulation and improvement of validity. Section 3.4 summarises the methods used in the study.

3.1 Research design

Medical innovation is often seen as processes occurring in a 'black box'[24] (Greenhalgh et al. 2004; Djellal and Gallouj 2007; Yaqub 2008). While existing empirical studies of innovation in hospitals provide important insights, this thesis argues that a close and detailed examination of technological routinisation processes in CT, MRI and PACS will contribute further knowledge on the topic because some of these aspects may have been hidden in the past.

Looking into the details of technology underpinning innovation, such as learning conditions and constraints, problem-solving procedures, changes in individual tasks, emergence of social groups, and patterns of interaction can reveal information about the accumulation of

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[24] The 'black box' metaphor has been used in many different research areas to explain the need for a focus on process rather than inputs and outputs, for example in investigations of technical change (Rosenberg 1982), in studies of hospital innovation (Greenhalgh et al. 2004; Djellal and Gallouj 2007), and in the exploration of change in organisational routines (Feldman 2000; 2003).

technological knowledge (Morlacchi and Nelson 2011)[25]. It can also uncover differences between hospital organisations and practice contexts that may otherwise remain unexplained (Greenhalgh et al. 2004).

A deep understanding of technology requires contextual analysis (Hughes 1983). This is because technological change processes are complex, idiosyncratic and impossible to separate from where they are taking place (Rosenberg 1982). The complexity and richness of process data tends to get lost upon aggregation, as in quantitative studies. The aim of this thesis is not to produce results that are generalisable to the population, but to generalise to analytic concepts in the field of innovation and technological learning, and to produce 'contextualised theory' (Hughes 1983).

In process studies of technology it is difficult to draw boundaries between the exploratory, descriptive and causal components and characteristics. This is in part because the focus is on obtaining a multi-dimensional view of understanding relationships and interactions between processes, how they affect one another, the conditions under which they occur (Bell and Albu 1999), and the varying degrees of determinism of interactions over time and across contexts. Processes are not separable from their contexts, and it is impossible to list a set of causal factors and separate the effects of everything else. A case study approach allows for flexibility in this sense, by giving opportunity to uncover phenomena that cannot be isolated from their context, such as social processes which do not have clear boundaries from other events (Yin 2009).

This thesis contributes to existing theory via the analytical abstraction process of 'appreciative theorising' (Nelson and Winter 1982). The analysis is guided by constructs and conceptual relationships of the theoretical framework, and aims to contribute to the theories that have guided the justification and formulation of the research questions. The use of existing theory meant that I did not use a research design based on the grounded theory approach (Glaser and Strauss 2010).

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[25] Greenhalgh et al. (2004:620) in their literature review identify process studies of routinisation as "the most serious gap" in the healthcare literature.

Understanding technology and change requires an uncovering of the processes by which problems are solved, learning takes place, and knowledge is applied, all of which differ across technology areas and contexts (Rosenberg 1982). Learning processes are very difficult to detect and examine (Hobday 1995). Case studies allow for discovering surprises and unplanned interactions, and for obtaining a lot of different information on previously unknown processes and implications for theory and policy (Yin 2009).

Qualitative methods of data collection are better suited for exploratory studies in novel empirical areas for which quantitative indicators do not exist (Yin 2009). My use of qualitative data on processes, procedures, tasks, individual and group knowledge exchange and conditions for interaction and problem-solving builds on existing studies of learning and change in hospitals and firms (Van de Ven 1991; Crossan and Berdrow 2003).

Guided by the theoretical framework for organisational learning and technological evolution, this study is inductive rather than deductive (Moser and Kalton 1971). Inductive studies of organisational learning (Pentland and Feldman 2005) and technological change (Rosenberg 1982; Bijker et al. 1989) proceed with a conceptual framework rather than a theory, and hope to contribute to theory in an iterative process. The focus is on finding relationships and processes of technological and social mechanisms, rather than their quantitative determinants, and thereby obtaining a "holistic" and integrated view of the research context, its logic, arrangements, explicit and implicit rules, guided by a theoretical framework and finding implications for theory[26] (Miles and Huberman 1994:6).

This thesis follows in the tradition of studies of technology that have approached the topic using "thick descriptions" of large amounts of detailed and deep information structured using a number of "middle-range" concepts (Bijker et al. 1989:3-5) which are open and flexible enough for the discovery of contextual complexity. Such studies place a "heavy interpretative load" (Bijker et al. 1989:3-5) on the researcher, and sometimes the load can

[26] Inductive research finds implications for theory from the data, while deductive approaches do it by hypothesis testing (Glaser and Strauss 2010).

only be lessened by a lot of tacit experience in researching and writing about the subject (Glaser and Strauss 2010). I tried to remedy the effects of my own limited experience by not making any unsubstantiated claims and keeping my analysis as close to the empirical observations and theoretical framework as possible given my existing skills. Where this was not possible, I modified the framework (Yin 2009).

To obtain detailed information that may be generalisable to theory without pre-conceived causal relationships between constructs, this study poses ‘how’ and ‘why’ questions (Yin 2010). ‘How’ and ‘why’ questions are answerable using rich contextualised data obtained from a variety of data collection techniques (such as semi-structured interviews, observations, and archival searches), which enable triangulation (Glaser and Strauss 2010). This is in contrast to surveys which aim to establish causality (Moser and Kalton 1971).

The case study method accommodated the demands of ‘how’ and ‘why’ research questions that have a wide variety of variables, with different kinds of outcomes and not just one result (Yin 2009:18). A further advantage of the case study method is flexibility and openness in data collection for exploratory studies. Although I aimed to use the same method for all cases, the different degrees of change in the cases selected, and differing contexts meant that I had to remain flexible in the type and amount of data that I was able to obtain, placing more emphasis on procedures and changes that I was able to get a lot of information on. The downside of openness and flexibility is that it can lead to a method of studying innovation that is “messy, stop-start, and difficult-to-research” (Greenhalgh et al. 2004:614), as periodically encountered during the fieldwork. I tried to avoid this by revisiting plans, writing and analysing, and addressing problems as they arose (Glaser and Strauss 2010).

This study is guided by historians, economists and sociologists who view technology as a dynamic process (Rosenberg 1976; Hughes 1983) and tries to take a longitudinal rather than cross-sectional perspective on technological change in hospitals. A problem with basing my investigation of past and present events on interview data was that people may not always remember what happened in the past or remember it accurately (Moser and

Kalton 1971). I tried to remedy this by collecting data from archival documents as well as interviews and observations. A further problem was that as I focused on the not-so-distant past (three to seven years) it was not possible to say whether events and features were indeed as important as they were claimed to be by others or interpreted to be so by myself, as longer historical periods might allow. This is a relatively common problem with studying present and recent events as we do not have the benefit of hindsight. I aimed to remain reflexive and critical about what I interpreted as relevant and less relevant information.

3.2. Unit of analysis and selection of cases

The unit of analysis chosen was the “clinical practice” because it was broad enough to accommodate processes, procedures, tasks, rules, interpretations and routines for the exploration of technological learning in hospital organisations (Greenhalgh et al. 2004; Nelson et al. 2011; Morlacchi and Nelson 2011). For example, knowledge in organisations evolves through the application of what has been learned in practice in one area, to similar practical problems in another area, changing learning conditions in both areas (Rosenberg 1976).

Practices reveal how organisational processes are carried out, and, for example, what the role of individual, group and contextual features is in their execution and evolution (Feldman and Pentland 2003). Organisational practices uncover performance aspects, problems that are solved, and practice components that are changed (Feldman and Rafaeli 2002). At the organisational level, features of technology converge towards and evolve with organisational practices (Rosenberg 1976; Tidd et al. 2005).

Clinical practices can be operationalised and identified by interviewees because people are usually able to express the role of individual tasks, procedures, routines, and problems and changes with them, and for what reasons they occurred (Feldman 2000). For example, routines are often associated with ‘practical’ examples in the literature (Nelson and Winter 1982; Feldman 2000; 2003). Routines are also a useful concept with which to view both the knowledge-based (Grant 1996a; 1996b), social aspects of organisational processes (Feldman 2000; 2003) and also to analyse organisational change (Adler et al. 2003).

The variety of components and aspects that can be contained in organisational practices can help uncover differences between technology systems, and how they layer one over the other, between contexts, and over time (Hughes 1989). Practices are also useful for exploring the role of individuals and groups in the ‘construction’ of a technological regime in an organisation, their perceptions, and ‘closure’ of an artefact in a social context (Bijker 1995).

I selected the cases of CT, MRI and PACS because they fit the assumptions of my framework. In part, they all featured in the same technological paradigm (ICTs), their technological systems all overlapped with and deviated from the X-ray practice paradigm in hospitals, and they all relied upon technological capabilities and advancements largely outside the field of medicine (Gelijns and Rosenberg 1999). These aspects meant that they could be analysed using a neo-Schumpeterian view of organisational change.

I also chose these technology areas as cases because of their differences (Yin 2009). The fundamental technical and scientific principles on which they all rely differed, and they emerged at different times in hospitals (CT and MRI in the 1980s, PACS in the 2000s). CT was heralded as a success from its beginnings in medical practice (Gelijns and Rosenberg 1999). MRI had been successful in the 1980s, and then its applications petered out, and were picking up again in the 2000s. PACS was a major focus of more recent large-scale government investments, and had mainly been described as a challenge to clinical practice (Hendy et al. 2005).

Case selection was motivated by analytical rather than statistical reasons, because the objective was not statistical but analytic generalisation (Yin 2009). Multiple cases are more suitable for drawing analytic conclusions than single cases. I replicated the same method for all three cases to compare and contrast results, to come to more valid and reliable conclusions, and to clarify the reasons why similar or conflicting results had been produced (Yin 2009).

Coherence and overview in the cases was helped by adhering to a case-study protocol (Yin 2009:82). The protocol was a ‘rolling’ one, as doing fieldwork in the NHS was very difficult and presented many surprises, so I needed to maintain an additional margin of flexibility. The protocol was kept to maintain a ‘mental line of enquiry’, which helped me not stray too far from the overall research focus.

3.3 Data collection and analysis

I selected five NHS hospital sites in East Sussex mainly because they embodied the characteristics alluded to in the framework. For example, the hospital sites offered diagnostic imaging services in one or more of the technology areas chosen as cases. I also chose the hospitals because they were in the process of investing resources in these areas both autonomously and through government expansion programmes (NHS Plan and NPfIT) (for example, BSUH 2004), which indicated ‘technological momentum’ (Hughes 1983). I assumed studying these sites would produce findings with relevance for technology policy.

The hospital sites were also chosen for reasons of geographical proximity and ease of access. East Sussex was my place of work and where I lived, and where my University was located. Some of the hospitals were part of the Brighton and Sussex Medical School, which I could access during my studies, carry out guided conversations with doctors and researchers, and obtain contacts for the definitive interview survey.

NHS hospitals are publicly financed and researching them could provide complementary evidence to the existing literature on medical innovation which is largely US- and private hospital-focused. A primary aim of the case studies was to collect new data. Carrying out the study solely in the UK could result in a geographical bias. However, many important aspects of the cases had their roots in the UK. The advantages of focusing on a geographical region with a rich history in these areas were thought to outweigh the negative influence of a bias that would skew them.

Doing fieldwork in the NHS has a high administrative burden. I sought and obtained NHS Research Ethics Approval from the South East NHS Ethics Approval Office to gain admittance to local hospital sites. During the preparation of the documents, I held several meetings with hospital administrators, medical school research and administrative staff, doctors, and both face-to-face and telephone conversations with regional NHS offices in preparation of the human subject protection documents and the research plan. Collecting data in hospitals outside East Sussex would have required fulfilment of additional formal administrative procedures[27].

The hospital sites are varied and mixed. There are urban and rural hospitals, a specialised neurological hospital, a general hospital, and a large university teaching hospital. The diversity in practice contexts is largely a feature of how NHS hospital services are organised in a region. Clinical services are highly specialised and many of them are available locally so that patients do not need to travel large distances to take advantage of them. For example, one historical aspect of the NHS is to meet local health service needs (Webster 2006).

I carried out a pilot study to gain familiarity with the cases in preparation for the interview survey. I conducted about seven pilot interviews in hospitals in London and Peterborough, and with radiology researchers at the Brighton and Sussex Medical School, placing emphasis on understanding the clinical practices, their contexts, features of the cases and perceptions of doctors and technicians. I wrote up and presented the results in a DRUID Doctoral Conference in the form of a conference paper (Sinozic 2006). The pilot study, conference presentation and feedback helped me improve the research design and interview schedule.

[27] Seeking and obtaining NHS Research Ethics Approval took almost one year.

The definitive survey involved 42 in-depth semi-structured interviews with radiologists, radiographers, neurologists, neurosurgeons, breast radiologists, breast surgeons, medical physicists, nurses, radiology managers, and hospital managers. To improve internal validity, I interviewed people who were engaged in different hospital departments, performed different functions, had different roles and were engaged in different operational routines. I also interviewed people at different levels of seniority in the hospital, such as nurses, doctors, departmental managers, hospital managers and members of the Trust advisory board.

Availability of hospital staff was often unpredictable so I remained flexible in scheduling and re-scheduling interviews, and moving between sites. I kept detailed transcripts, logs, and descriptions of each case to keep them separate and fresh in my mind as I arranged my enquiries in different practices. I recorded all interviews after obtaining written consent from my interviewees, and following the ‘24-hour rule’ (Yin 2009) I transcribed them all within one day of finishing them.

I used a combination of the ‘snowball method’ (Moser and Kalton 1971) and searches of hospital databases to contact interviewees. The snowball method was particularly useful as individuals were familiar with others involved in their practices and would introduce me directly to them, which almost always resulted in the scheduling of a further interview. This allowed for an on-going inclusion of individuals and groups (Glaser and Strauss 2010) associated with the practice.

During each interview I took extensive notes, which I added to once the interview was completed. Whenever possible, I took small breaks between interviews that occurred in the same day to make more notes and record my observations, both descriptive and analytical, while I could remember them well.

In addition to interviews which formed the central component of the data collection, I collected data using a combination of other methods. I observed all activities in the practices to which I was permitted access. I attended a ‘multi-disciplinary team meeting’

(MDTMs) and one technical conference, which allowed me to obtain more information on the cases. Combining different methods of data collection allowed me to check for internal validity and reliability of information, and to triangulate (for example, questioning respondents based on my observations) (Glaser and Strauss 2010).

Archival searches were also an important component of data collection. For example, the NHS Hospital Activity Statistics, the CIPFA public records service, the Trust and hospital databases, hospital annual reports, white papers and reports on the evaluation of radiology services in UK hospitals, hospital websites, and articles in the local and national press. The hospitals provided valuable access to the NHS database and the NHS Brighton and Hove Trust library.

During the data collection and some case redesign process, I remained open to new leads and possible revisions to interpretations in order to avoid bias. I did this by periodically talking to colleagues and fellow students about my results as I was collecting and analysing them. It was particularly useful to be surrounded by critical and helpful colleagues who offered alternative explanations and suggestions to improve the data collection and thus make the overall study more robust. It was advantageous to be doing my data collection locally, enabling me to go back to the office on a weekly basis to talk about how my fieldwork was progressing.

The data was analysed in two main steps. I first ordered the data, and secondly then coded and interpreted it. Once I had collected all the interview data and transcripts, observations, field notes, and archival material, I started experimenting with ordering, using techniques for analysing qualitative data (Miles and Huberman 1994). I created matrices in which I displayed the data, organised it, and found categories and relationships. This involved a lot of trial-and-error experimentation, which kept the data in the forefront of my mind until I became more confident in interpreting it and in making analytic generalisations.

The choice of research design and methods introduced potential researcher bias and subjective bias to the study. Researcher bias, for example in the form of enquiring and interpreting to confirm my own assumptions, was reduced by reflecting upon my own intentions and analysis, and being open to novel analytical suggestions from the literature. Qualitative data is sometimes more prone to subjective bias than perhaps objectively quantifiable data. I tried to minimise this by using multiple sources of data and cross-checking my observations and conclusions with my interviewees and colleagues.

3.4 Summary

A case study approach was chosen to explore learning processes in clinical practice, to make analytic generalisations guided by a theoretical framework. Clinical practice was chosen as a unit of analysis because the interesting and relevant procedures, rules, tasks, routines, social groups, interactions and problems were assumed to converge on them, and the concept was broad and operationalisable enough to uncover the detailed new empirical data I aimed to find. I selected CT, MRI and PACS technology areas as cases because of their importance and change in hospitals. I did a pilot study in hospitals in London and Peterborough to gain a practical understanding of the cases. Definitive interviews were held in five hospital sites in East Sussex. The hospitals possessed the characteristics underlined in the framework, as well as variety, and they were relatively easy to access. I triangulated the interview data with observations and archival searches. The data was analysed using qualitative techniques of ordering, coding, finding patterns and creating matrices to aid interpretation and the making of analytic generalisations. Researcher bias was reduced by remaining open to other analytic interpretations based on the literature and maintaining a broad framework. I tried to reduce bias by using multiple data sources, and cross-checking my results with different interviewees to improve validity.

Chapter 4

Contextual Background: History, technology, and policy of CT, MRI and PACS

This chapter presents a background context to the empirical chapters. Section 4.1 shows the beginnings of diagnostic imaging in medicine and the historical evolution of X-ray technology. In Sections 4.2, 4.3 and 4.4 aspects of the developmental histories, scientific discovery, and technical details of CT, MRI and PACS in the healthcare sector are described. The objective of these sections is to chronicle some of the important events and features that have shaped parts of organisational and technological contexts for learning in clinical practice. Section 4.5 describes the policy setting of diagnostic imaging in the UK healthcare sector. The purpose of this section is to help understand procurement, regulation and management of these technologies in the UK and to highlight policy aspects which the empirical chapters aim to inform.

4.1 X-rays: Historical foundations of medical diagnostic imaging

Ever since W. Roentgen's discovery of X-rays in 1895 diagnostic imaging has been an important technological area in medicine. During that time, physicists were concerned with elementary relationships between electricity, magnetism and light (Bleich 1960; Schuster 1962; Harder 1986; Mould 1995). Roentgen discovered X-rays by experimenting with the sending of electric currents through small glass tubes[28], and examining the associations between different voltages, the anode (at one end of the tube), the cathode (at the other end) and the movement of particles between them. The anode and cathode were placed in a glass tube, which was then evacuated using a vacuum pump. Applying voltage to the plates moved particles (which would later be identified as electrons) through the tube and made it glow. Roentgen came upon a type of ray that not only made the tube, but also the screen surface opposite, luminous (Bleich 1960). By holding his hand in front of the 'invisible

[28]Roentgen used a tube developed by P. Lenard, a variation of the Crookes tube (developed by the English chemist W. Crookes in 1876) (Kevles 1998:17; Blume 1992:21).

light' Roentgen found that some rays passed through and left black dots on the screen. Some rays were absorbed by the bone and could not pass through[29].

Roentgen discovered that the rays had three important properties that would later change medicine: (1) they could pass through opaque objects; (2) the extent to which they passed through objects differed according to different material densities; and (3) when they hit a photographic plate, they did not produce a photographic image of the object, but the image of its 'shadow' (Kevles 1998). The peculiar deflection and refraction properties of the rays were identified by Roentgen as new and unknown, and he named them "X" – rays[30] (Roentgen 1898). By discovering rays which could pass through matter, hit photographic film, and produce an image, Roentgen discovered the basis of radiography (Bleich 1960). The discovery of X-rays was revolutionary in science and society and the focus of much subsequent technological effort and change in medicine (Burrows 1986; Blume 1992).

The evolution of X-ray technology in medicine can be described as having occurred in two main stages: (1) changes up to the inter-war period, and (2) changes post-WWI (Kevles 1997). The potential of X-rays as a medical device were apparent soon after their initial detection, and spurred major improvements to it. Much like its discovery, important early changes were mainly technical and occurred outside the field of medicine (in engineering and in physics where the technicalities of the device were familiar) (Burrows 1986). These very early X-ray devices were quite complex and different from one another, characteristics which made them challenging to develop and use. Major technical problems were the electric current, and characteristics of its central components such as the instability of the gas tube and blurring of the image (Barclay 1949). Moreover, the devices at the time were not safe, occasionally caused burns and electrocution, and more serious after-effects of radiation which were felt many years after exposure but whose dangers were less well-documented at the time (Kevles 1997).

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[29] Other rays were scattered and left random grey shadows on the film, known as 'noise'.

[30] Over the next twenty years, physics research found that X-rays were electromagnetic waves with a very short wavelength in comparison to visible light. Like visible light, X-rays were understood as a stream of particles, called photons. X-rays photons were found to have more energy than visible light photons (Gardiner, 1964).

The Coolidge tube, credited to W. D. Coolidge, was a major improvement to the early device. At the time, the gas tubes that were used were highly unreliable (Gardiner 1964). Problems with measuring the voltage, its stability in the tube, and maintaining a vacuum to balance out the X-rays were technical aspects that needed to be solved to produce an accurate image (Gardiner 1964). This occurred with the invention of the Coolidge tube. Despite its superiority, the Coolidge tube did not replace gas tubes in widespread hospital use before 1920, almost two decades after it was developed (Kevles 1998).

The further problem of early X-ray apparatus was blurring of the images. Blurring was caused by two main processes: first, when entering the body X-rays ionize molecules causing them to emit more rays. The lack of focus provided for these rays causes them to hit the film in a random manner, causing blurring. Second, X-rays scatter on their own, and this causes blurring as well. The invention that is acclaimed to have solved this problem is the Bucky-Potter grid, which helped focus and channel the rays, producing a better image. Although involving quite a simple step of positioning two metal grids between the patient and the tube, and the patient and the photographic plate, it was a tremendous improvement of the device (Burrows 1986).

Commercial X-ray devices were introduced to the market one year after Roentgen's discovery (Mitchell, 1988). The firms that entered the X-ray market were the same firms that dominate the diagnostic imaging device market even today[31]. The German firm Siemens, specialised in electromechanics, was one of the pioneers in commercialisation of X-ray devices. In the US, the firm General Electric, was another forerunner, and it started by designing a better tube, including a high-frequency coil to power it. Improvements in cathode tubes, as well as advancements in physics knowledge of voltage, wavelengths and their relationship to X-rays allowed for higher precision, depth and accuracy in the administration of X-rays and their usefulness in diagnosis (Kevles 1998:107). In each of the efforts of improvement, such as tubes, their stability, the speed of taking a picture, photographic plates, and so on, there was competition between patents (Kevles 1997:108).

[31] For detailed accounts of the evolution of the diagnostic imaging industry, see Mitchell (1988) and Gelijns and Rosenberg (1999).

Improvements sometimes required more complicated production methods of the apparatus, most of which the manufacturers were unprepared for, and as a result, innovation was incremental and slow (ibid.).

X-rays radically altered the medical profession, and public perceptions of medicine, as well as culture and art (Henderson 1988; Adler and Pointon 1993). Uses of X-rays in medicine for examining bones were immediately apparent[32]. However, in the earlier years the technology had a heterogeneous customer base: X-rays were not strictly medical devices nor were they strictly part of a medical specialty, but could be manufactured and tested on people in an unregulated way (largely because its dangers were either unknown or ignored) (Kevles 1997; Gelijns and Rosenberg 1999). X-rays were particularly useful in WWI for the identification of bullets and broken bones. Dentists and coroners also found them very useful in their practices, as did criminologists (Kevles 1997:43-45). Although the most common application was, as it is still today, for the examination of bones and the chest, increasingly doctors were discovering its uses for imaging the gastrointestinal tract, neck and brain.

X-ray technology transformed medicine in several important ways. The approach to medicine at the time was that it was more an art than a science[33], and X-rays (with their scientific basis and relative accuracy in visualisation) played an important role in making medicine more scientific (Howell 1989). They introduced a new science-based role for diagnosis, making the hospital more like a laboratory with machines (ibid.). The medical approach at the time was that disease was unique to each patient, and X-rays provided an opportunity to generalise diseases across patients, with similarities across cases.

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[32] X-rays are useful in examining bones which absorb a lot of the rays. They are also useful in examining veins and other soft tissue when a contrast agent is used (Wolbarst 1999:12). Tumours and cancerous tissue is difficult to detect on X-rays because their density is similar to surrounding tissue and can be undetectable because of limited radiographic contrast (Wolbarst 1999:12). Even today, X-rays are amongst the most common and least costly method of imaging diagnosis (NHS 1999).

[33] In the 19th century, disease was considered unique to each patient and inseparable from them. X-rays contributed to an overall shift in thinking about disease as attributable to specific causes that were generalisable across patients (Kevles 1998:39).

The diffusion of X-rays in medicine led to major improvements, both directly and indirectly, in the equipment and the medical sector. Doctors, in particular the early users who experimented with the device on patients, played a major role in their innovation and institutionalisation in medicine (Pasveer 1989). For example, through the process of “retrospectography” doctors in the US circulated X-rays without a diagnosis. The person who took the picture would attend the operation or autopsy, where X-rays of the affected organs would be made. Then a ‘correct’ diagnosis would be made and compared to the original X-ray images, determining what the diagnosis should have been (Kevles 1997).

Doctors’ involvement and experimentation led to improvements in understanding how to ‘read’ images and make diagnosis of health conditions, the main skills in what would later become the medical specialty of radiology (Pasveer 1989). Through their interaction with sales representatives, doctors fed their complaints about the device back to manufacturers who improved the product (Burrows, 1986). Doctors increased their specialisation and demands on the equipment, leading to further product improvements via user-driven incremental innovation (Rothwell 1977; 1986).

During WWI the professional use of X-rays was interrupted (Pasveer 1989). Increased demand for X-ray services, and no regulation of their provision, helped create conditions in which any person owning an apparatus could perform scans. Radiologists and other medical professionals asked for a continuation of the professionalisation of the service in the form of practical and theoretical education, to help counteract the decline in its status (*Archives of Radiology and Electrotherapy*, 1918:205 cited in Pasveer 1989:366).

The two medical specialties that at the time profited most directly from their use of X-rays were surgery and dentistry (Kevles 1997). Surgeons improved their operations dramatically after seeing bullets and shrapnel on X-ray film. Improvements enabled by X-rays, and developments in antiseptics and anaesthetics, helped surgery become the most prestigious medical specialty (ibid.). Dentistry was the second medical specialty to integrate X-rays into clinical practices. The use of X-rays by dentists also improved the identification ability of people working on forensic applications. Many advances in finding new roles for X-rays in medicine were made by surgeons (especially conditions of the brain) (Jennett 1986).

Despite the widespread diffusion of X-ray devices and enthusiasm that surrounded their use, the medical sector was a difficult market. Important aspects of their institutionalisation in medicine took a long time (over thirty years), and the technology did not stabilise until the 1950s (Pasveer 1989). Purchasing the device and installing it in hospitals was not difficult and occurred quite swiftly[34], but the multiple processes involved in institutionalising the product in hospitals was very slow (Howell 1995). X-rays required new skills – those of technicians – who were not doctors (Pasveer 1989). It gradually became apparent that these technicians, as they accumulated experience, became better at ‘reading’ and interpreting the information on the images, and this experience made them important members of the medical profession (Blume 1992:27). Doctors, however, were unwilling to cede power to another group of professionals.

The process of stabilisation of the technology in medical practice occurred through several power struggles. First, there was a power struggle in terms of which group – engineers, photographers, or doctors – would be allowed to publish in radiological journals (Howell 1989). Over time, doctors assumed control over the technology. This period marked a transition from X-rays as a technology with a wide range of uses (for example, photography and entertainment) to its use as a piece of medical equipment (Chamberlain 1929).

Second, there was the power struggle between doctors and technicians; doctors worked hard to keep technicians below them in the professional hierarchy, and they eventually won (Blume 1992; Kevles 1997:59). Radiologists were determined that technicians would have an inferior role in the department, despite being able to operate the equipment and interpret scans (Kevles 1997:84). Moreover, technicians had played a very important role in X-ray research. This changed as doctors assumed control of the practice, excluding technicians from scientific journals that some of them had previously founded (Kevles 1997:59).

[34] By 1910 approximately 67% of US hospitals had the equipment (Kevles 1998:57).

Third, doctors competed in using X-rays for diagnosis or therapy, and eventually stabilised upon diagnosis as the principal, and therapy as the marginal, application (Kevles 1998:58). Using X-rays as a diagnostic tool had several benefits. It allowed doctors to compare organs before and after treatment. It also changed the doctor-patient relationship in important ways: for example, it allowed patients to see the diseased parts of their body for the first time, and to participate in the treatment process (Kevles 1997:58).

4.1.1 Post-WWI and the inter-war period: Institutionalisation, standards and technical change

In the period between the World Wars, over thirty years after the discovery of X-rays and the production of the first X-ray device, radiologists created their position as X-ray specialists in medicine, and established radiology officially as a core medical field[35] (Blume 1992; Kevles 1997:77). Important aspects were the establishment of formal training (such as the creation of the Cambridge Diploma in 1920) (Pasveer 1989). During this period the number of firms in the X-ray industry grew quickly. The emergence of the radiology specialty, the main user group for X-ray devices in hospitals, was an important factor in expanding the X-ray market (Tunnicliffe 1974).

Since the early days radiation exposure through X-ray devices was unregulated, which had the effect that many patients and people who worked with the equipment had been burned or exposed to high levels of radiation later causing diseases such as dermatitis or leukaemia (Mould 1993; Kevles 1997). This began to change in the inter-war period, when the international radiology community started to unify recommended dosages and guidelines for radiation exposure. The US-European communities at the time decided upon the

[35] Between the 1910s and 1930s, medical practice was gradually transformed by increased specialisation (Kevles 1998). Medical boards in the US and Royal Colleges in the UK were formed to oversee the certification of specialists. This began with ophthalmology in 1917, otolaryngology in 1924 and obstetrics and gynaecology in 1932 (Kevles 1998:83). The radiology speciality had its own medical board in 1934 (Kevles 1998). These developments marked the separation of the body in different parts for the purpose of medical treatment (Kevles 1998).

roentgen and the *curie* as measures of the strength of radiation emitted from the radiation source[36].

An important next step was formalising standards for exposure, which was a lot more difficult than quantification, and often exposure levels were quite arbitrary (Kevles 1989). Acceptable levels of exposure needed to be set for different kinds of persons, those working with the machines, clinicians, different kinds of patients, and different areas of the body (ibid.). It was often the case that researchers did not agree on what dosage was acceptable. Standards were revised many times in the decades following.

While radiology was professionalising and stabilising, the technology was not (Gelijns and Rosenberg 1999). Technical changes were the development of tracers and contrast agents, which enabled visualisations of processes as they occurred in the body (Kevles 1997:70). The most famous tracers, polonium and radium, had been discovered in 1898 by Marie and Pierre Curie, but it was not until after 1934 that they would be injected into the body and tracked by detectors (Kevles 1997:71)[37]. Further technical improvements were provided by new contrast agents (for example oil and iodine, whose usefulness as contrast agents was discovered as doctors made images of the brain and spinal cord) (Mould 1993; Kevles 1997).

4.1.2 WWII and post-WWII: the development of the transistor, and further consolidation of policy via public welfare systems

Wartime research stimulated advances in microwaves, radar, ultrasound and new materials, and had an important impact on medical devices advances as well. Military procurement of the electronics industries led to the creation of new electronics capabilities which benefited

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[36] The *roentgen* measures the amount of radiation that produces one electrostatic unit of charge in one cubic centimetre of air at zero degrees centigrade and 760mm pressure; the *curie* is a measure for the unit of radiation emitted from a gram of radium (Kevles 1998:88). Both X-rays and radium emit ionizing radiation, but radium has a shorter wavelength than X-rays, and is fundamental in the development of radiotherapy (also developed by Marie Curie, in the 1920s).

[37] Advances in the area of radioactivity and radioactive substances followed rapidly and even though they were not applied to X-ray imaging directly, they laid the scientific and technical foundations for nuclear imaging, which would become important much later on (for example for MRI, described in section 4.3).

the devices industries (Mould 1993; Gelijns and Rosenberg 1999). The development of the transistor, the integrated circuit and the microprocessor were important technical developments in the post-WWII era which, through their convergence with X-rays, led to a much improved device (Kevles 1997; Gelijns and Rosenberg 1999)[38]. The establishment of public welfare systems following WWII, together with the growth in demand in the healthcare sector, growth in the number of skilled radiologists, and the emergence of health insurance coverage, transformed the market for and the diffusion of X-ray devices (Gelijns and Rosenberg 1999).

Until the 1950s, X-rays were the only technology for medical imaging purposes. The technology enabled diverse clinical services in neuroradiology, in coronary care (angiography) and in breast screening through mammography (Blume 1992:36; Mould 1993). In the 1940s and 1950s the use of X-rays expanded to many different health conditions, and also gained in popularity in obstetrics. By 1955 one in seven pregnant women was radiographed during her pregnancy (Blume 1992:28). Radiology grew tremendously in scale and became a universal clinical practice (Blume 1992:28).

In summary, important aspects of technology policy surrounding X-rays in medicine in this period were the establishment of its role as a diagnostic device in medicine, the emergence of its control by radiologists and technicians as subordinates, the establishment of international standards for quantification and exposure, and the nationally-specific programs for their distribution (which were implemented in the post-WWII era with the formation of public welfare systems). In the 1950s many industrialised countries, such as the UK, established publicly financed healthcare systems (Barr 1998) and the distribution of X-rays in these countries was centrally organised (Gelijns and Rosenberg 1999). In the 1970s X-ray technology converged with computing, leading to a radically improved imaging device: the computed tomography (CT) scanner.

[38] Briefly, AT&T and Bell Labs developed the transistor in 1947. Later improvements in the transistor led to the development of the integrated circuit in 1960, and the microprocessor in 1972 (Gelijns and Rosenberg 1999). The emergence of image amplifiers and the integration of X-rays with electro-optical technologies reduced radiation and spatial separation (becoming the basis for angiography) (Gelijns and Rosenberg 1999).

4.2 Computed Tomography (CT): History and technology

CT is credited as an important example of how computers and electronics revolutionised medical diagnostic imaging and the healthcare sector (Mitchell 1988). The development of the CT scanner is largely credited to G. Hounsfield, who designed the first device in 1973 at the firm Electrical and Musical Industries (EMI) (Burrows 1986). Its primary technical principles are the computer processing of vast amounts of X-ray signals and their reconstruction in 3-D images (Mitchell 1988). Like X-rays, its history is based on interactions between science, engineering and medicine. Notable preceding developments are computing in the 1930s, ’40s and ’50s, mathematical advancements in the reconstruction of 3-D images in the 1950s, developments in the relationship between X-rays and different object densities and the building of the first model CT (using gamma rays instead of X-rays) in the 1960s, experimentation with principles of rotation, radioactivity, and connections made between imaging and ‘third generation’ computer processing technologies in the 1960s.

One of the first mechanised ways of computing was introduced by the mathematician Blaise Pascal in 1642 with the development of the mechanical calculator. Almost two hundred years later, in 1833, a device that demonstrated the flexibility of a computer was developed by the English mathematician C. Babbage who created the ‘Analytical Engine’ which could be programmed to solve arithmetic problems, with inputs and outputs being performed using punch-hole cards (Randell 1982; Mahoney 1988). Babbage’s ideas were the basic framework of today’s computers; his design, however, was not developed further at the time mainly because of engineering limitations.

The history of digital computers is highly contested, and the activities that led to the realisation of “firsts” are various[39]. In the main, there seems to be consensus that antecedent

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[39] Many different perspectives have been used to explain computer history (for example, Noble 1984 on the relationship between computers and productivity, and reviews of advancements in different components of computing, for example, on hardware see Randell 1972; 1982; Bashe et al. 1986; and on software, Backus, 1977 (credited with inventing FORTRAN). Instead of reviewing these fascinating interpretations, I provide a brief description leaning more towards a (limited) review of (contested) “facts and firsts” (Mahoney 1988:114), mainly because of space limitations.

activities were concentrated in the period leading up to and immediately following WWII, and that they occurred in the UK, Germany and in the US. In the UK, the major inventive successes in the early development of computers took place at Bletchley Park in the late 1930s and the early 1940s, culminating in 1943/44 in the building of the COLOSSUS computer by A. Turing, T. Flowers and their colleagues (Randell 1972; 1980; Agar 2003).

The COLOSSUS computer was a result of a collective effort of a group of scientists and practitioners focused on the UK's (secret) cryptographic work pre-WWII and advances in electronics for that purpose (Agar, 2003). Briefly, the COLOSSUS was a result of activities led by Turing and his team, in collaboration with R.P. Tester, M. H. A. Newman and D. Michie (Randell 1980). A. Turing is credited with the first conceptualisation of "programmable data processing", which is similar to the conceptualisation Babbage had had (Randell 1980:4). Together with Flowers, with background experience in electronics and signalling, and colleagues S. W. Broadhurst and W. W. Chandler, they experimented with the development of early electromechanical devices such as the use of cathode gas discharge tubes instead of relays for commutators, which would later contribute to the electromechanical advancements needed to develop the COLOSSUS (Randell 1980).

At the same time in another "hut" at Bletchley, other people were learning and experimenting with similar activities that led to the creation of the HEATH ROBINSON machine, which was important because of its advances in operating capacity and operating speed (Randell 1980:16). This machine had some limitations (for example, the strain the tape was putting on the sprocket drive) and needed other knowledge to solve this. So, Flowers was brought into the team and contributed by increasing the electronic complexity of the device (he increased the number of valves, and introduced the idea of having the equipment on permanently in order to stabilise it) (Randell 1980).

Together, they built the Mark I COLOSSUS, the first "special-purpose program-controlled electronic digital computer" (Randell 1980:25); electronic design was done mainly by Flowers, Chandler and Broadhurst (Randell 1980:18). The machine was operational in

1943. Its key technological features were the clock pulse, binary hard valve electronic circuitry, shift register, two-state circuits and clock control, and cathode followers (Randell 1980:19). When Dr. A. W. M. Coombs joined the group, he helped in the production of the Mark II machine, which was five times faster than the Mark I prototype (Randell 1980:19).

After the war, major work in the UK continued in Manchester, where F. Williams, T. Kilburn and G. Tootill developed the Small Scale Experimental Machine (SSEM). The SSEM is claimed to be the world's "first stored-program computer" (Lavington 1980). It became operational in 1948, and was first in a series of production versions of computers, the patents for which were later used by IBM (ibid.).

In Germany in the early 1940s similar advancements to those in the UK were made by K. Zuse (Rojas 1996). Zuse's first computer, called the Z3, was built in 1941 but differed from the COLOSSUS in that it was built out of telephone relays. Zuse's research was partly financed by the Nazi government and went largely unnoticed by the UK and US inventors at the time. In the German literature on computer history K. Zuse is widely considered as the inventor of the modern computer (see, for example, Alex 2007).

In the US, in 1937 a more complex device than the COLOSSUS had been built by J. V. Atanasoff and C. Berry, an advancement on the idea of the program-controlled electronic digital computer, with program control using plug-boards and punched-card machines (called the "ABC" computer) (Randell 1973; Burks and Burks 1989). The ABC is credited with introducing electronic binary logic and the capacity to solve 30 simultaneous operations (Gustafson 2002).

Also in the US, the "first electronic general-purpose calculating device" was claimed to have been developed at the University of Pennsylvania, called the Electronic Numerical Integrator and Calculator (ENIAC) (Randell 1973). Similar to the Mark I, the ENIAC was a massive machine, but by being able to compute a thousand times faster than other machines, it was a considerable step forward in increasing the volume and speed of computations compared to other existing electronic computers at the time (ibid.). The

ENIAC was succeeded by the EDVAC, which was another important step towards the modern computer; it had a memory which stored data as well as the program for the data (Campbell-Kelly and Aspray 2004).

Both the COLOSSUS and ENIAC were quite similar in that they were both specialised program-controlled digital computers (Randell 1980). The proximate step to the modern digital computer was made in the ENIAC group, in their production of the EDVAC, which is sometimes claimed to have been the “first practical stored-program computer” credited to Eckert, Mauchly, von Neumann and Goldstine (although this is not uncontested) (Randell 1980; Campbell-Kelly and Aspray 2004). In 1973 a U.S. District Court invalidated the ENIAC patent and concluded that the ENIAC inventors had derived the invention of the electronic digital computer from Atanasoff (Burks 2003).

Further advances in computing involved incremental developments on the COLOSSUS, ABC and ENIAC designs, and the addition of transistors in the 1950s. In the 1960s systems used integrated circuits, single silicon chips that contained many interconnected transistors and other electronic components were developed (Campbell-Kelly and Aspray 2004). In 1971 Intel made a revolutionary silicon chip containing 2,300 transistors, as much computing capacity as the first computers, and with the tiny size of a postage stamp (ibid.). Ten years later, Intel released a further chip which contained sixty times as many transistors and yet was the same size. In the 1990s the Pentium chips contained millions of transistors. Among these previously inconceivable advances, important ones for diagnostic imaging have been advancements in programming languages, software, connectivity, and communications, as well as flexibility in the acquisition and modification of information (ibid.).

Mathematical advances in the reconstruction of 3-D images were made through various scientific efforts, of which perhaps the three most important ones were work on the reconstruction of sun-sports by R. Bracewell in 1955, and mathematical improvements in 1967 on this subject by Bracewell and by researchers in England working on the reconstruction of a 3-D image of viruses through electron microscopes (Kevles 1997:147-

148). Bracewell had first used Fourier transforms for astronomical image reconstruction, and then in 1967 developed a new mathematical solution that would later be used in CT scanners. The virologists in Cambridge, England, although working in another discipline from Bracewell's, were solving similar problems of reconstructing 3-D images from 2-D data on viruses and they developed the technique of 'back projections' which shot thousands of narrow X-ray beams through the body and, using computers to measure inputs and outputs (and calculating the energy absorbed by the body), reconstructed 3-D images from the information (Kevles 1997:148).

A second scientific contribution is credited to the experiments of W. Oldendorf in Pennsylvania in the 1960s, who advanced scientific knowledge on the relationship between X-rays and different object densities. Oldendorf is said to have been one of the first individuals to model a CT device (Kevles 1997). Oldendorf used gamma rays (instead of X-rays) and, by rotating them, sent collimated beams to a photon detector displaying a two-dimensional image (Kevles 1997:151). The additional data that were created by the rotating rays, however, could not be interpreted (without a computer) and Oldendorf soon abandoned his project (Kevles 1997).

Critical connections between imaging, computing and different body densities were made in South Africa in the late 1950s and early 1960s by the nuclear physicist A. Cormack,[40] who advanced these ideas by producing 'maps' of different 'body' densities using a phantom. Working together with the computer programmer D. Hennage, he built an experimental scanner which used a computer to reconstruct images of asymmetrical phantoms (Kevles 1997:152).

Indirectly or directly building on these advances, and largely through his own efforts at EMI, Hounsfield developed the CT scanner (Blume 1992; Kevles 1997). Hounsfield was an electrical engineer who had gained experience in radar research in the Royal Air Force (RAF), and at EMI he worked most intensely on information theory and pattern

[40] Cormack, together with Hounsfield, would in 1979 win the Nobel Prize in Physics for the development of the CT scanner.

recognition. A key aspect was that, at this time, Hounsfield's mathematical problems could be solved with the available computers, and computers at the time could already present pictures in pixel format (Kevles 1997:157). Hounsfield made many of the necessary connections between X-ray technology, algorithms, computing power and visualisation techniques to produce the 3-D image of the human body that distinguished the CT scanner from its predecessor X-ray and other imaging technologies (Hounsfield 1973; 1980). Unlike academia where incremental advancements are published as they arise, EMI, led by profit motives, guarded its discoveries. Therefore little is known of the precise details of Hounsfield's work prior to EMI putting the CT scanner on the market.

The difference between CT and X-ray devices is not the signals that are emitted (these are the same X-ray signals), but how they are produced and processed into image data. The CT scanner is composed of a housing within which a rotating "fan" beam of X-rays and a ring of hundreds or thousands of small radiation detectors are enclosed (Wolbarst 1999). The housing rotates around the patient's body, sending out narrow beams of X-ray radiation. The radiation detectors measure how much radiation emerges from the other side of the patient, and sends this information to the computer for processing. The thin X-ray beams 'slice' the body into transverse slices of anatomy, viewing each one separately from the side and from multiple angles and from between 700 and 1,500 different perspectives. The computer then works 'backward' from the data by mathematically reconstructing the spatial distribution of X-ray attenuation properties within the body to produce what the 3-D image must have looked like to have yielded the transmission data (ibid.). By measuring the absorption of X-rays in the human body (building on the work of Oldendorf on the relationship between X-rays and different densities of matter), taking cross-sectional cuts, and combining this data to produce a 3-D image, the CT scanner is able to eliminate lots of interfering patterns, provide a lot more contrast and differentiate between a much broader ranges of tissue than traditional X-rays (ibid.).

CT scanners, once they hit the market, underwent rapid technological improvements. The diversity of players and the increased complexity of the CT scanner meant that technical advances were various and companies created differentiated devices (Trajtenberg 1990).

Major changes occurred in the area of image construction time and image quality; first-generation scanners produced in the 1970s took five minutes to produce an image, second and third-generation scanners took 15 and 10 seconds respectively, and fourth generation scanners less than 5 seconds (Mitchell, 1988).

CT scanners diffused quickly in industrialised countries. Unlike X-ray technology, CT already had an existing market and medical speciality within which to “fit”: healthcare structures that were previously established with X-rays technology were there for CT (Blume 1992). A few years after EMI commercialised the scanner, large firms such as GE and Siemens that dominated X-ray sales started to take over (Gelijns and Rosenberg 1999). Siemens and GE were familiar with navigating the healthcare market (unlike EMI) and had already built up their reputation with doctors by previously selling them X-ray devices (Gelijns and Rosenberg 1999). In privately financed healthcare systems such as the US, CT scanners diffused even more rapidly because funding was not centralised and hospitals were focused on profiting from the novel service (Gelijns and Rosenberg 1999).

CT expanded the medical focus in conventional radiology from bones to include imaging of soft tissue such as abdominal and pelvic organs, lungs, brain and spinal cord. CT enabled better definition and differentiation, making it possible to delineate abnormal tissues such as infections and tumours. For example, radiologists can, by seeing the tissue, put needles and catheters through the skin and drain infections without having to do surgery. Moreover, through enhanced visualisation provided by CT, doctors can treat tumours very effectively (Kevles 1997). Most hospitals had no previous experience with CT, and the required technical skills were unavailable in hospitals at the time. Similarly to the early days of X-rays in hospitals, medical doctors struggled to maintain their superior role to technicians (Barley, 1986). Because these structures had been established in the past, they largely succeeded in doing so (Barley 1986).

Advancements in computing made many other new technologies, products and systems in diagnostic imaging possible. One of these is MRI technology.

4.3 Magnetic Resonance Imaging (MRI)*:* History and technology

The technical principles underlying MRI are entirely different from those of X-rays and the CT scanner. Unlike CT which is based upon ionizing radiation technology, MRI is based on the principles of magnetic fields and radio-waves (Oldendorf and Oldendorf 1991; Lufkin, 1990). Scientific discoveries underlying MRI development are credited to the period between WWI and WWII, and to the years following WWII.

Between the two world wars, scientists made discoveries about the atom being composed of heterogeneous particles, namely electrons, protons and neutrons. In the 1920s, the Austrian physicist W. Pauli discovered that the inside of an atom's nucleus could be manipulated and, when exposed to magnetism, would move with angular momentum and become magnetic (Lufkin 1990; Blume 1992). The link between these advancements and nuclear magnetic resonance (NMR) are associated with the American physicist I. I. Rabi[41].

Rabi produced measurements of the relaxation time for particles to return to 'normal' after the magnetic field is removed (Oldendorf and Oldendorf 1991). As an alternating magnetic induction is turned on at the particular frequency of the atom (its resonance frequency), the protons in the nuclei resonate with it (ibid.). The nucleus imaged is usually hydrogen (the most common element in the human body). As the magnetic field is altered, the protons emit an alternating magnetic signal that can be transmitted to a receiver. When the signal is turned off, the protons relax. NMR records two main signals, T1 and T2, both of which are relaxation times (the times for the protons or neutrons return to their equilibrium state). These discoveries, and further experimentations with radio signals, such as pulsing, gave rise to the physics sub-discipline of NMR.

MRI is essentially the medical application of NMR. NMR was first used by chemists who used it to understand molecule structures. Its application to organic compounds in the 1940s and 1950s opened up opportunities for understanding its potential applicability in

[41] In 1946 NMR in solids was confirmed by E.M. Purcell at Harvard and by F. Bloch at Stanford in liquids (Gelijns and Rosenberg 1999). Like Rabi, they later received the Nobel Prize for their discoveries.

tracking blood flow and water tissue in mice, and thus its applicability to medicine (Kevles 1997). The application of NMR principles to medical imaging took place after two important technological developments: first, the development of powerful superconducting magnets: and second, the introduction of computer processing technologies (Blume 1992; Gelijns and Rosenberg, 1999). These connections are credited to the work by R. Damadian, P.Lauterbur and P. Mansfield (Oldendorf and Oldendorf 1991).

In his work during the late 1960s and early 1970s, Damadian, one of the first people to make the link between NMR and its medical applications, focused on examining the differences NMR could pick up between tumorous and healthy tissue in rats. In 1977 Damadian manufactured the first whole-body NMR imaging machine. Because of the abundance of hydrogen nuclei in water, and the differences in water content between tumorous and healthy tissue (the spins in healthy cells relax back quicker than cancer cells), the data from the experiments was useful in examining tissue health. At the time, however, Damadian's NMR signals had no spatial dimension (Kevles 1997:181).

At the same time, the chemist Lauterbur, was experimenting with the use of magnetic field gradients to obtain one-dimensional spatial information (Kevles 1997:181). Lauterbur's gradients were very similar to the problems Bracewell and Cormack, and in particular Mansfield[42] in the UK, were trying to solve, but being a chemist he was unaware of the problems physicists were addressing at the time (Kevles 1997:182). Lauterbur's work on gradients and Mansfield's work on k-space trajectories, and later on echoplanar and volumetric 3-D images, were to be the scientific steps required to link NMR principles to imaging on the computer screen (Kevles 1997:183).

The spatial resolution of the image produced by an MRI device is determined by the strength of the superconducting magnet, measured in Tesla units (Wolbarst 1999). The first MRIs with permanent superconducting magnets were half a Tesla, while at the time of

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[42] The Nobel Prize for MRI imaging was awarded in 2003 to Lauterbur and Mansfield.

writing the stronger MRIs had 12 Tesla magnets, which is 240,000 times more than the average magnetic field humans are exposed to on a day-to-day basis[43].

Like X-rays and CT, the development of NMR initially had no connection to medicine, but was the result of discoveries in physics and chemistry (Kevles 1997:176). However, differently from X-rays for which the medical applications were immediately obvious, NMR applications to medicine were realised almost 30 years after their discovery (Kevles 1997:176). In terms of their dependence on computers to reconstruct images from huge amounts of data, MRI and CT are similar. Unlike with X-rays, where differences across densities are visible without computing, in MRI the necessary calculations that need to be performed to produce a proton-density-weighted MRI image cannot be made without computers (Wolbarst 1999). Indeed, MRI was developed a few years after CT, and profited immensely from the advancements in algorithms that had previously been made in CT technology (Kevles 1997:175).

After the first MRI scanner hit the market, R&D improvements were performed by private industry, first EMI and Philips, and in the late 1970s by Siemens (Gelijns and Rosenberg 1999). The developments in MRI in the 1980s and 1990s led to many incremental improvements to the equipment – for example, in the hardware and image processing times, and changes in the devices that arose from feedback with adopters who found that the strong magnets caused many problems with other equipment in hospitals, which led to modifications of buildings, and precautionary measures, as well as improvements in visualisation software which continue to take place (Gelijns and Rosenberg 1999).

In market developments of MRI, CT had played a very important role as a fore-runner to expensive equipment in hospitals (Kevles 1997:187). Doctors were excited about MRI, having seen what CT could do. CT had created a market for very expensive equipment and opened the door to selling expensive MRI machines to hospitals (which were at first three

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[43] The effects on humans of using strong magnets is considered safe, although much still remains to be discovered as the technology develops in practice (Wolbarst 1999).

times as expensive) (Gelijns and Rosenberg 1999). Both pieces of equipment were the single most expensive instruments in hospitals (Gelijns and Rosenberg 1999).

MRI was not immediately conceived as a radiology technology. Damadian’s first applications of MRI were for pathology rather than radiology. But when the first MRI machines were produced, they were demonstrated to radiologists not pathologists, because it was easier to sell to an already established market (Blume 1992:218). Mallard (in Blume 1992:218), in his first addresses to the Royal College of Radiology in 1981, stated that interpreting MRI images would not be as similar as CT was to X-ray, but rather new applications and interpretation methods would need to be found, combining knowledge of biological and chemical properties of different kinds of tissue (which are expressed differently in X-ray and ultrasound, for example) and their measurement in magnetic resonance.

MRI imaging has made the most dramatic improvements in the capacity to see the brain. Because it is so powerful in seeing soft tissue (high water – and thus high hydrogen atom – content), it is able to detect brain damage and conditions that were not visible before, such as consequences of baby shaking in infants, patients suffering from partial paralysis, blurred vision, blind spots or symptoms of multiple sclerosis, dementia, soft tissue cancers, knee injuries, breast lesions, the heart, and many more (Kevles 1997:194). MRI is both superior to CT in terms of visualisation power, and it is also less harmful to the patient because it does not involve radiation. MRI, through the process by which it creates signals, is extremely detailed, and can map out the body atom by atom (Oldendorf and Oldendorf 1991; Mansfield 2013).

MRI in comparison with CT is also mostly fast in scanning (less than 15 minutes) and can be running and used all day, but it is still a more expensive technology than CT (Kevles 1997:189). MRI is in many ways considered superior than CT, but often because of factors such as the considerably lower cost of CT, greater familiarity on the part of clinicians, and more medical guidelines, CT tends to be used more routinely than MRI (Wolbarst 1999).

The strength of the magnets makes MRI a lot more difficult to install in hospitals than CT scanners (Wolbarst 1999). MRIs require shielding, and sometimes separate buildings need to be built to house them and separate them from computer equipment and other instruments vulnerable to distortion via magnetisation (Kevles 1997:191). An MRI machine needs to be on all the time to prevent a ‘quench’ (this can occur when the helium that cools the superconducting magnet boils off, which could cause everyone in the room to suffocate) which can make them more expensive to maintain (Kevles 1997:191).

In comparison to X-rays and CT, MRI is the technology which is undergoing the majority of changes in terms of its medical uses and applications - for example, in brain imaging (Andreasen 1989), in the planning of detailed and sensitive operations, blood imaging, imaging free radicals, and many more applications that are continuously being developed and broadening in scope and from which new tools are being created, such as functional MRI (fMRI), fast MRI cardiology, and electron paramagnetic resonance (EPR) imaging (Wolbarst 1999).

4.4 Picture Archiving and Communications Systems (PACS): History and technology

PACS is a healthcare sector-wide information system for radiology. In CT and MRI, as previously described, computer technology is used for image reconstruction. PACS uses other capabilities of computers such as information communication and storage. In a hospital, PACS has the potential to connect all digital imaging devices such as digital X-ray, CT, MRI, nuclear medicine devices, Positron Emission Tomography (PET), other radiology units, optical film scanners, long-distance communication links (teleradiology) and remote workstations (Wolbarst 1999:88). As the name suggests, PACS is important for the acquisition, storage, display, and communication of digital radiographic data (Duerinckx and Pisa 1982; Huang et al. 1988).

Digital imaging communication systems were already recognised as a possibility in the 1970s with scientific and engineering roots in Europe, and innovative developments are credited to scientists in the US[44]. PACS and digital imaging more broadly arose from a number of key contributions from medical informatics research, mathematics and physics researchers (Wiley 2005). Its history is closely related to three main aspects – the creation of standards for medical informatics in imaging technology, the development of PACS prototypes, and their testing in clinical settings.

Standards for digital diagnostic imaging are associated with DICOM (digital imaging and communication in medicine), which began in 1983 and was developed by scientists from the field of medical informatics (Wiley 2005). DICOM, credited to S. C. Hori of the University of Pennsylvania, involved the creation of standards to enable computer systems in medicine to interface with each other (Huang 2003). The harmonisation of digital imaging standards allowed communication between radiological outputs from different manufacturers, such as a CT scanner, an ultrasound scanner from Siemens, and an MRI scanner from Toshiba so that they were compatible and viewable on the same PACS (Huang 2003). An important consequence of this was the integration of previously digitally quite separate specialties such as dentistry, pathology and cardiology to be linked via the same data and information systems (Wiley 2005).

In the 1980s in the US, several groups of scientists were instrumental in developing PACS prototypes and testing them in the healthcare sector. In 1982 the first PACS conference was organized by Duerinckx, who brought together researchers working to create networks for single technologies such as ultrasound and CT images. The first PACS system was built in the University of Kansas in 1982/83 with support from a private company interested capitalizing on radiology information systems in future. Simultaneously, at UCLA, the pioneer B. Huang was employing his graduate students to digitise X-ray data in paediatric radiology. In the early 1990s DICOM was completed and the harmonisation of standards made it easier for PACS systems to be created and connected (Wiley 2005).

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[44] In Europe in the 1970s Jean-Raoul Scherrer in Switzerland developed the first digital medical information display system for patients (Huang 2003).

PACS has been characterised by rapid technical advancements and new products, systems, software and applications. PACS software and hardware can be used to display images in a large variety of ways, increasing their flexibility (Wolbarst 1999:85). By providing the capacity to view and report on images remotely (wherever there is a networked computer), it has enabled practitioners from different physical locations to access the same information simultaneously (making possible teleradiology and telemedicine) (Wiley 2005).

PACS enables the processing of images such as enlargement, reduction, rotation, inversion, stretching, or transformation (Wolbarst 1999). PACS software can adjust the grey scale and optimise apparent contrast in images; it can be used to draw a sharp edge to increase artificially the sharpness of a border, and help distinguish clinically relevant patterns (Wolbarst 1999:84). Some visual noise can be reduced with digital filters, dramatically improving images (Wolbarst 1999:85). For example, some display programs can combine different kinds of information (for example from MRI and PET) in a single image, and greatly improve its diagnostic value (Wolbarst 1999:86).

A further important aspect of PACS is the ability to archive all available diagnostic images in a computer database (Wolbarst 1999:88). It allows for storage as well as integration of different kinds of medical information (for example, other diagnostic reports, a patient’s historical medical record, lab reports, or previous images) on a patient, which can then be transmitted within the hospital and the healthcare system, or, in theory, anywhere. PACS can also incorporate software for image analysis and interpretation, using computers for pattern recognition and diagnosis (Wolbarst 1999:89).

4.5 Policy aspects of diagnostic imaging technologies in the UK healthcare sector

The UK healthcare sector is a highly regulated and mediated market in which policy plays a uniquely important role for reasons such as risk to patients, cost-efficiency, cost-effectiveness and equity (Barr 1998). This section describes how CT and MRI devices and PACS systems are financed and regulated in the UK healthcare sector.

4.5.1 Financing, distribution, and procurement of medical devices and systems

Often advanced as an important distinguishing feature in medical devices policy in modern healthcare sectors is the way in which national healthcare is financed (Gelijns and Rosenberg 1999). In privately financed healthcare systems such as the US, medical devices and systems diffused very rapidly, the main constraint being their price (Lazaro and Fitch 1995). In other industrialised countries such as the UK and the rest of Europe, which have primarily publicly financed healthcare sectors, procurement has, in relative terms, been largely centralised and diffusion has been slower (and the size of the market remains small compared to the US) (Lazaro and Fitch 1995).

In the UK NHS, national policy concerning the distribution of diagnostic devices and systems has changed over time, beginning with regional- and hospital-level distribution in the 1980s and 1990s (which was narrowly limited to financing) to more centralised and broadly defined national-level programmes such as the NHS Plan and the National Programme for Information Technology (NPfIT) in the 2000s (DoH 2002). In the 1980s and 1990s, regional-level decisions were made by regional Strategic Health Authorities[45] (SHAs) which had a limited budget with which to provide for healthcare in the region (NHS, 2003). SHAs distributed funds to NHS Hospital Trusts, composed of one or more hospitals and healthcare providers. Trust criteria for purchasing CT and MRI scanners were based on the availability of imaging devices in the hospital, the age of the existing scanner, the supply and availability of hospital radiology and technical staff, the population catchment area of the hospital, whether it was a teaching or non-teaching hospital, and its specialisation and specialised services (NHS 2000). Hospitals, if short of funding, also engaged in 'scanner appeals' for charity from the local population to raise funds or entered into 'public-private-partnerships' (PPPs) which gave hospital access to scanners that were partly financed by private industry (NHS 1999).

[45] Since the time of my fieldwork in 2005-2006, changes to the organisation and formal structure of the English NHS have taken place. In 2012 the UK Government published the 'Health and Social Care Act 2012', which deals with the abolition of Primary Care Trusts and of Strategic Health Authorities, and instead delegates commissioning power to clinician groups (DoH/UK Government 2012).

Regional, Trust-level and hospital-level allocation of funds for the procurement of medical devices and IT systems in the 1980s and 1990s led to regional disparities in their distribution across the UK and to patient access to radiological and IT services (NHS Executive 1998). This condition attracted political attention through the Wanless Report (Wanless 2002) which formed the basis of the NHS Plan and the NHS Cancer Plan, centralised, large-scale programmes addressing, broadly, the “technological needs of modern healthcare services” (NHS 2000; 2003) and NPfIT, under which a range of IT systems (PACS being one of them) was to be centrally procured and implemented in hospitals over a ten-year period (NHS 2000).

In the early 2000s the UK Department of Health implemented the NHS Plan and the NHS Cancer Plan, in which the purchasing and procurement of CT and MRI scanners, and the improvement of diagnostic imaging services were central political goals, and which led to dramatically increased diffusion of new CT scanners in urban and rural hospitals (NHS, 2000). The NHS Plan addressed the structural and technological challenge to improve healthcare services by measures such as changing funding structures, devolving decision-making, formulating national standards, adding flexibility to clinician professional boundaries, and introducing new technology programmes focusing on IT development in the NHS. For example, in the period 2000 to 2003, over 200m pounds were spent on supplying CT and MRI scanners to NHS hospitals (NHS 2003). The Cancer Plan focused more specifically on cancer services, to which diagnostic imaging is central, and by 2003 these two programmes provided an additional 21 MRI scanners and 52 CT scanners to NHS Trusts, as well as 1000 extra cancer care consultants, and launched several new initiatives to improve skills and training, information, research and palliative care (NHS 2003).

NPfIT, a second important set of programmes, was implemented in 2002, addressing a broad range of IT systems (NHS 2003). NPfIT was allocated a budget of 12.4 billion pounds (NHS, 2003) and attracted a lot of political and media attention mainly because it has been heralded as a ‘failure’ in IT implementation in healthcare (BMA 2007) and criticised for its ‘top-down’ approach to implementation, in particular because of the difficulty in proving itself successful and its exclusion of end-users in decision-making, systems design and integration in work practices (Clegg and Shepherd 2007; Collins 2007; Cross 2005; Hendy et al. 2000; Kuhn and Giuse 2001).

The NPfIT programme was administered via the UK Department of Health's Agency 'Connecting for Health', in a process that involved private industry healthcare service providers (BT, Cable & Wireless and Atos Origin) (National Audit Office 2006; Clegg and Shepherd 2007:213) who managed projects at the regional level. The Central National Programme Team' was responsible for the procurement and development of NHS IT systems at the national level, in liaison with industry service providers (National Audit Office 2006; Clegg and Shepherd 2007:213). The programme was managed at the regional level (London, Southern Cluster, Eastern Cluster, North West & West Midlands Cluster and North East Cluster), in cooperation with regional Strategic Health Authorities (SHAs). The SHAs cooperate with the local NHS organisations (NHS Trusts, Primary Care Trusts) and local service providers (CSC Alliance, Fujitsu, BT) (Clegg and Shepherd 2007:213).

4.5.2 Policy formulation processes

In the UK healthcare sector, technology regulation in medical devices and information systems is institutionalised in various organisational forms and processes such as formal and informal regulatory authorities, health technology evaluation organisations, healthcare research organisations and professional medical bodies and associations. Regulatory authorities include the National Institute for Health and Clinical Excellence (NICE) which was set up in 1999 to produce information and guidance for healthcare decision-makers and clinicians as aids to resource allocation, processes and treatments in the form of regulatory advice, directives, and medical guidance (NICE 2001; 2002; Birch and Gafni 2002). NICE[46] influences health technology policy by publishing medical guidance[47] and

[46] NICE has a series of programmes for the evaluation of medical devices such as the Medical Technologies Evaluation Programme focusing on cost-efficiency and cost-effectiveness of new technologies (DoH 2011; Campbell, 2012). Despite its international reputation, the centralised aspects of technology policy formulation such as NICE is contested. For example, Birch and Gafni (202:188) state: "In a population as large and diverse as that of England and Wales one might question the validity of centralised decisions about technologies based on information on national averages as a way of maximising health gain".

evaluating medical technologies through a policy process regarded as international best practice in health technology regulation (OPSI 2009; Schlander 2007; Campbell 2011; Birch and Gafni 2002). NICE informs health technology policy through processes of technology appraisals, clinical guidelines, and cost-effectiveness studies through what is considered by some as a democratic and independent process with a broad and diverse range of actors such as clinical experts, patient groups, manufacturers, and national collaborating centres specialised in the epidemiology of specific disease conditions, over diverse formulation and consultation periods (Schlander 2007).

Medical guidance for diagnostic imaging is also issued by the professional medical body, the Royal College of Radiologists, who formulate and implement education and training standards, and continuing professional development (CPD) standards for clinical professionals in radiology and oncology (RCR, 2011). The Royal College of Radiologists is also engaged in a series of other activities, such as public involvement and informing patients about imaging service quality in the NHS, patient and public engagement in radiology services, and informing patients about local services (RCR 2011). The Royal College of Radiologists process of standard-setting is informed by a variety of interactions with other organisations and thematic priorities such as the National Radiotherapy Awareness Initiative (NRAI), the Society and College of Radiographers (SCoR), Cancer Research UK (CRUK), the Institute of Physics and Engineering and Medicine (IPEM), the NHS and others (RCR 2011).

Technology evaluation authorities such as the Medicines and Healthcare Products Regulatory Authority (MHRA) are separate from regulators such as NICE, but they also rely upon similar data once technologies are in use, specifically regarding the safety and workability of devices, making sure they are safe and meet the radiation standards

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[47] For example, in 2003 NICE issued a clinical guideline for the treatment of people who suffered a head injury, specifying medical indications requiring a CT scan (NICE 2003). NICE guideline formulation is managed by the National Collaborating Centre (NCC) for Acute Care: “a group of health professionals and patient/carer organisations who manage the development of clinical guidelines for NICE. The NCC follow international standards of guideline development. They establish the guideline development group consisting of service users and carers, health professional and academics who reviewed the worldwide data alongside current clinical practice and the experience of service users; and the feedback they receive from two rounds of widespread consultation” (NICE 2003:2).

(Campbell, 2012). For medical devices, the MHRA implements EU Medical Devices Directives in the UK (OPSI 2009).

Health technology assessment (HTA) more generally has gained in importance in the UK since the 1980s and 1990s. HTA addressed factors such as the increasing complexity of new technologies, increasing healthcare costs, and advancements in evaluation in the social and medical sciences (Wennberg and Gittelsohn 1973; Anderson and Steinberg 1984; Davis et al. 1990; Menon and Marshall 1996). The UK Department of Health has implemented programmes and commissioned organisations to examine the technical, economic and social consequences of technological applications (Luce and Brown 1994). Technology assessments differ for drugs and medical devices. Technology assessment for drugs includes more peer-reviewed clinical trial data, whereas purchasers of medical devices often have to rely on information that has not been as critically reviewed (Luce and Brown 1994).

Considered the most important organisation commissioning research in healthcare technology in the UK is the National Institute for Health Research (NIHR), a funding organisation of the Department of Health, which commissions studies through a number of programmes such as the UK Government's 'Best Research for Best Health' strategy[48] (DoH 2006). These programmes include areas such as evaluation of efficacy and health service and delivery research, and 'response mode' research programmes, for universities and research institutes, and through formal research networks, clinical research facilities and centres for applied research (NIHR 2012). The NIHR has a budget of approximately 200 million pounds per year and has a specialist liaison team working with companies manufacturing medical devices, diagnostics, and pharmaceuticals (NIHR 2012).

[48] This is also part of the UK Government's 10-year 'Science and Innovation Investment Framework 2004-2014' (DTI and HM Treasury 2004).

4.6 Summary and reflections

Diagnostic imaging technologies emerged from interactions between science (for example the discovery of X-rays, the principles of NMR and advances in mathematics) and technology (for example progress in electronics and in medical diagnosis). Social and political aspects such as the setting of standards, the professionalisation of the medical uses of X-rays, formalisation of training, and regulation to reduce the dangers of radioactivity and magnetism on people, shaped the role of these technologies in medical care. The evolution of diagnostic imaging technologies shaped medical practice through the establishment of the radiology specialty, and the rise in importance of other specialties such as surgery and influenced neurological capabilities (e.g. MRI and psychiatry, Andreasen 1989). Nobel Prizes were awarded to individuals credited for the inventions, in recognition of their significance in science and in society.

UK policies shaping the conditions under which these devices and systems are supplied, distributed, financed and regulated in medical care are complex and diverse. Much has been invested in improving access and quality of diagnostic services in the UK NHS. This thesis argues that further important insights into the evolution of these technologies in the UK healthcare sector can be revealed by investigating technological accumulation processes of CT, MRI and PACS at the practice level.

Chapter 5

Learning and Innovation in Clinical CT Practices

This chapter analyses changes in learning conditions and operational routines involving CT technology in two cases of hospital work practices.

Section 5.1 describes changes in learning conditions in two procedures part of a cancer diagnosis and treatment routine in a large urban teaching hospital. Section 5.1.1 explains how conditions for knowledge co-ordination and exchange shifted to enable the solution of diagnostic problems. It describes how changes in medical guidance, diagnostic information and disease complexity affected the process by which clinicians solved complex cancer cases. Section 5.1.2 describes changes in individual learning and collective action in the planning of radiotherapy treatment. It explains how planning capabilities were created through tacit knowledge accumulation and changes in knowledge breadth, depth and flexibility of a community of practice.

Section 5.2 describes the development of departmental capabilities in CT scanning in a rural general hospital. Section 5.2.1 describes how historical social norms for changes in departmental roles, mentoring, and participation in a CT department created learning conditions which supported the creation of capabilities and increase productivity to meet higher demand for CT scans and accommodate a hospital shortage in radiology skills. Section 5.2.2 describes how the acquired departmental knowledge provided a basis for national medical guidance in CT scanning, and processes that affected the integration of the protocol in another hospital.

Section 5.3 summarises the main findings of the chapter.

5.1 Changes in innovation conditions for diagnosis and treatment planning of pelvic cancer in a large urban teaching hospital

Cancer diagnosis and treatment are amongst the most important clinical services of modern healthcare (NHS 2000). They involve a wide range of procedures such as diagnosis with imaging and pathological testing, cancer treatment with radiotherapy and medications, and monitoring and after care[49]. The interviews for this case were carried out in a hospital whose cancer services are the main services for a region with over two million people. During the time of fieldwork the hospital was partially restructured and the catchment area of its cancer services expanded from 500,000 to 2 million people, encompassing large parts of the South East region of the UK (BSUH 2004).

This section explores changes in learning conditions in two procedures forming part of the same operational routine in the hospital. The change in learning conditions for the diagnosis procedure involved integration of national medical guidance for "multi-disciplinary team meetings" (MDTMs), which were meetings between diverse clinicians for the diagnosis of cancer in specific areas of the body[50]. Since approximately 2005, medical regulation for the implementation of multi-disciplinary team meetings was integrated in NHS hospitals which provide cancer services (NHS 2000; CfH 2005). This routine involved the diagnosis and treatment of pelvic cancer, and therefore I focused on learning and change aspects of MDTMs on this topic.

Radiotherapy planning, the second procedure in the routine, involved 'mapping' the region of the patient's body with a CT scanner, to mark the parts that need to be treated with radiotherapy. The change in the radiotherapy planning routine involved the creation of capabilities within which changes in learning conditions originated at the individual and

[49] Cancer is an extremely difficult disease to diagnose and treat. There are more than 200 different types of cancers which can develop in any of the 60 organs of the body (cancerresearchuk.org, accessed 19 July 2012).
[50] For example, MDTMs were held for lung cancer, dementia, colon cancer, and so on.

group levels[51]. The following sections explore regime features and learning conditions in the case examined.

5.1.1 Changes in learning conditions for diagnosis

Complex cases of pelvic cancer were previously diagnosed by radiologists looking at plain X-ray film and sending the diagnostic report to the oncologist for treatment planning. This case focuses on elements underlying the transition from such an X-ray procedure to a procedure part of a digital diagnostic regime in which the radiologist no longer uses X-ray film, no longer communicates one-way to the oncologist, but instead uploads the digital image with an initial diagnosis to a central database, and makes the final diagnostic decision in a multi-disciplinary team meeting in which radiologists, oncologists and other clinicians decide upon a diagnosis collectively.

Interpreting

Interpreting is a conscious learning process involving the creation of a cognitive map of a knowledge space at the individual or the group levels (Crossan et al. 1999). Learning processes entail, for example, making connections between what is known and what is being found and communicated, the augmentation of individual and group language capacities, and interaction and communication with other individuals and groups (Crossan et al. 1999).

The search for more information is driven by the risk of a wrong diagnosis for the clinician. The legal costs of making a wrong diagnostic decision changed as it became more likely for clinicians to be exposed to higher degrees of accountability and the threat of being sued were a mistake to be made. According to a surgeon interviewed: *"At the back of everyone's*

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[51] I interviewed clinical and technical staff in the radiology and oncology departments, as well as nurses, and departmental and hospital managers. The interview focused on changes in learning conditions that happened in the last five to ten years in the departmental unit for two main reasons. First, this time span was chosen partly because respondents kept emphasising this period as the one in which most innovation occurred, in particular the move to digitalisation of diagnostic images and learning requirements that were affected by this. Second, I focused on this period because this is how long the CT scanner had been located within the cancer unit (prior to that period oncologists had used simple X-ray film for planning radiotherapy treatment, the acquisition of the CT scanner was essential for CT innovation in the hospitals (as explained in Chapter 4).

minds is always the legal. Will I be sued for missing out on something? Will I lose my license for this? This influences the search for more and more information. Whether it is more accurate information, I don't know."

Interpretation by radiologists and oncologists was influenced by increased disease complexity, knowledge requirements and changes in behaviour by raising the imperative for inter-disciplinarity and specialised tacit knowledge. Over time, the complexity of diagnosing pelvic cancer, and making a decision about its type, severity, localisation, and treatment options increased. This made knowledge exchange of *"knowledge from different clinicians working on the same area"* (according to one radiologist interviewed) more important on the one hand, and decision-making based on specialised competencies (*"the radiologist has to make the final diagnosis because to me everything looks like cancer"* (according to one oncologist interviewed), on the other.

Integrating

Integration is a learning process occurring at the group level and visible in behavioural processes such as coherent action based on a shared language, common tasks and a collective goal (Crossan et al. 1999).

Medical guidance transmits social values of technology. Participation in the meetings was voluntary but clinicians attended them because they considered the information they would receive as valuable and attending the meetings was perceived as closely linked to improving patient treatment. One interviewee stated: *"It's all about having as much information as possible, so that you can provide the best service to the patient."* If not attending, clinicians were concerned about the affect this would have on their work: *"I attend all the meetings for my specialty area with different specialists even though I don't have to. I could not go but then I would be a bad oncologist."*

Technical and functional diversity of CT had increased and changed the importance of different skills. Tacit skills of visual comprehension had increased in importance as did the level of specialisation in acquiring them. Instead of being an expert on a 'diagnostic procedure', the importance of understanding visual representations of a small group of diseases in a much more localised area of the body (an organ or a group of organs) within a specific technique area became much more important. Specialists collaborated on making sense of large volumes of different types of information independently of their original training and departmental boundaries. Knowledge was much more dispersed across specialists and it became difficult to detect which types of knowledge would be useful and from where a solution to a problem might come.

The systemic features of CT technology made information available to a broader range of specialists, supporting the creation of interpretation capacities in different parts of the hospital. An oncologist interviewed had accumulated knowledge of diagnosis using CT on her specialised area due to access to the information, its large and increasing volume, and the repeated practice and experience she had in using it. She recalled an occasion in which her knowledge influenced the radiologists' report in a multidisciplinary meeting: *"I now look at a lot of scans, I'm thinking of a meeting we had last week when we discussed a rectum I was looking at, and I didn't agree – I thought the radiologist was underreporting it. The radiologist who was there said "Yeah, well in the context of the clinical information, that changes the report slightly", so we changed the report. We [oncologists] do influence the reporting."*

Some social norms hinder the internal evolution of the technical system. To a certain degree the systemic features of the technology were developed in the hospital, and improved learning conditions for non-radiologists. On the other hand, many aspects were not permitted to develop because decision-making processes had not changed. Decision-making structures (for example, who made the decision on technical aspects of CT such as the size of images to be transported, who could access them and how often) was a legacy of other technologies which did not have the same systemic features (e.g. X-rays). The 'old' structure was maintained by limiting information flow to non-radiologists: *"The images we get to see as oncologists are a different resolution from what a radiologist gets to see.*

Ideally, because we are looking at scans all the time, we would see the same image and have access to the requesting information that the radiologist has."

To sum up, changes in learning conditions for CT were supported by the hospital's implementation of the medical guidance, the voluntary adherence to it by clinicians and the 'meaning' given to the adherence of that guidance by individual clinicians involved in the routine change, changes in knowledge requirements of diagnosing pelvic cancer because of increased disease complexity, changes in the cognitive and functional diversity of CT technology and increase in uncertainty that arose therefrom, and the systemic features of the technology that developed through tacit knowledge accumulation by non-radiologists. The development of the technology in the hospital was hindered by the remaining social hierarchy in the hospital stemming from the previous stand-alone technology. The 'feedback' effect (Crossan et al. 1999) occurred from the sectoral to the group and individual levels, not from the organisational level, supported by the transmission of values through the change in external social norm of the technical system (Hughes 1987).

5.1.2 Changes in learning conditions for planning radiotherapy treatment

Radiotherapy treatment planning in this hospital was in the process of change from planning with X-ray images to planning with CT scanners. This changed the oncologist's tasks from marking areas to treat with radiotherapy on plain X-ray film, to using computer technology and enhanced visualisation techniques to map out the area of the pelvis affected by cancer. The case explores factors affecting learning conditions for CT radiotherapy planning for a small group of radiation oncologists, radiotherapy physicists, medical physicists, and radiographers in the period 1998 to 2005. An oncologist interviewed stated: *"Before the radiology department gave us the CT scanner about seven years ago, planning was done using X-rays. Now, more than 50% of what we plan is planned using CT"*.

Interpreting

Unsupported by hospital managers and radiologists, the oncology team built its CT capabilities by gradually adding individuals with different knowledge bases to the team.

The cognitive explanation for this is traceable back to the knowledge requirements of IT-based systems technologies (Hobday 1998) such as knowledge about the technical engineering aspects of the equipment, knowledge about radiation and radiation exposure, and software skills.

A rapidly evolving technology element, software skills had the shortest life-cycle in the department. Moreover, changes in CT radiation doses and radiation regulation over time made CT planning more dependent on knowledge of physics, which was changing because of external changes in regulation on radiation exposure. This created problems for the oncology unit because it had very few links with other parts of the hospital and with other organisations, from which it could obtain information and knowledge, and generally remained relatively isolated in its learning structures from other parts of the hospital. At the same time, its learning requirements grew because of its replacement of X-ray by CT devices for planning. In comparison, the radiology department had linkages to external manufacturers and software specialists, and made frequent use of them. The oncology department had tried to solve this knowledge gap by including IT specialists and medical physicists in their department.

Even though more people with diverse skills were added to the department, this did not change the condition that CT created novel and unknown problems in its use. This point is illustrated by a statement from a radiation therapist I interviewed: *"It's not that we don't know; it's that we don't know what the problem is. Something stops and then we don't know where to start to look for a solution, because we don't know what went wrong."* At the same time, the requirements of skill types became more difficult to predict. Problems were unexpected as were learning outcomes, the impossibility of 'knowing' in which individual the requisite capabilities resided grew. Over time, this uncertainty was reduced with repetition of parts of practices, only to grow again when new sub-systems were installed and new problems arose (Rosenberg 1982; Hobday 1998; Pavitt 1998).

The process of building up its interpretative abilities by adding more people to the department instead of building connections with other hospital departments was due to the hospital's adherence to existing structures which maintained divisions between departments, as well as the connection between oncology and external firms. For example, this was reflected in the way in which the CT scanner had been acquired in the oncology department, namely without manufacturer involvement (the oncology department 'inherited' the old scanner from the radiology department).

Integrating

The separation of decision-making on technology elements from the locus of learning is a barrier to the development of capabilities of an emergent systems technologies such as CT and MRI. Over the time period explored, changes had occurred in CT devices, their systems, sub-systems, and connectedness to other parts of the hospital, as well as in expectations of radiotherapy planning service performance. The development of CT in the hospital was affected by decisions on product and systems design features which were made separately from where the learning of CT planning of radiotherapy treatment took place. The choice of MRI scanner, for example, did not allow for a linking up with the oncology radiotherapy planning system because it was considered too costly. Decisions such as these were made by managers (concerned with budgeting), less informed by clinical considerations: *"The radiologists said what they wanted but the final decision was made by the managers."* The technologies were being treated as stand-alone artefacts instead of systems technologies and the existing structure had not created conditions under which systems aspects could be developed.

Integration of oncology procedures with other parts of the hospital was difficult because structural changes to support learning interdependencies between oncology and radiology had not fully taken place. The oncologists extended their skills repertoire in CT planning by trying out different techniques, software programmes, and experimenting with the images and planning software. The formal procedure was that they would be supported in their learning by radiologists who would supervise and transfer their tacit skills to them, but this never happened. This was a retention of the 'old' division of labour where the two groups of clinical specialists performed their tasks separately. A radiotherapy physicist interviewed stated: *"The division of tasks - diagnostics done by radiologists and planning for radiotherapy done by oncologists – made a lot more sense with traditional X-ray; now we would benefit a lot more if they (the radiologists) would teach us about (CT) scans"*.

Integration of new CT tasks caused problems at the individual level because CT diagnostic and planning capabilities are highly dependent upon individual-level capabilities. Using CT for radiotherapy planning in the oncology department made the acquisition of a broader range of specialised skills, such as software skills, imperative. The more time passed, the more complex the planning process became, the more problems arose, and different skills were required in their solution. Treatment of areas of the body could be located and marked on a 'phantom', whereas previously the patient would have had to lie still for hours. This was considered to be a highly positive outcome for patients. Paradoxically however, planning the treatment now took much longer than previously, because of the large increase in information that was not previously available: *"Whereas before I had one image to look at, now I have tens of images, from different angles, different planes, and in 3D, which means a complete dependence on good imaging and accurate immobilisation, all of which is increasing every year. It all takes much much longer and I spend much more time on one patient, whereas previously I could get through many more patients in a day."*

Institutionalising

Institutionalising was helped by the flexibility of oncologists working in different hospitals at the same time, and the harmonisation of PACS systems across hospitals. The abolition of images on X-ray film meant that if the communication system was not working, clinicians could not access the required information and deliver the service. To circumvent these problems, oncologists developed their own solutions: *"When I cannot access the data here (in this hospital), I go to the other site where I have access to better screens"*.

Institutionalisation of CT within the oncology department was helped by the creation of a community of practice. It was created gradually through practices emerging from social interactions between diverse localized specialists focusing on highly contextualized problems of CT planning in the cancer unit. At the same time the group became increasingly specialised with a community identity being formed. At first the oncologists focused on learning the tasks themselves, but gradually exceeded their capacities so they called for additional specialists to be located in the department. Medical physicists who had previously been located in the medical physics department, specialist nurses, therapy radiographers, and others joined the group and built an allegiance to it.

The learning processes described demonstrate some aspects of Wenger's (1998) 'communities of practice' concept focusing on a multi-dimensional social interpretation of collective learning through practice, generating a sense of belonging, formation of group identity, and the creation of collective meaning of specific practices and a collective goal. Wenger (1998) considers practice processes to have dual implications, first through the 'inclusion of newcomers' and secondly through the transformation of their individual identities through their inclusion in the same practices. Both of these I found as occurring processes as new specialists were added when problems arose, new skills were required, and stability was achieved as it became more obvious what the usefulness of individual skills was for individual processes. An additional consideration was that these processes were conditioned by the community's narrow focus on CT planning and radiotherapy: *"Here in this (oncology) department we work as a team. In the other hospitals I work at this does not happen; they (the hospitals) are much smaller and they do not have the specialists so people work in different departments at the same time."*

A collective identity was formed through making decisions and rules on how to use the CT artefact or a group of artefacts by working together. The emergent quality of the CT artefact, its associated systems, and the novelty of its applications to the oncology environment, were all suitable conditions for a community of practice to emerge. The scope for experimentation and creativity was large as the rules were relatively unwritten, the cancer centre was in the process of formation, and there was no rigid structural legacy to constrain relational processes. I would thus add to Wenger's (1998) observations that such conditions support the creation of communities of practice (ibid.).

The unpredictability of problems and uncertainty of applying ‘solutions’ made access to other peoples’ experiences of similar problems much more important. For example, a medical physicist interviewed stated: *“If I have a problem I cannot solve, I ask other medical physicists in the UK or globally. There is a sort of gentleman’s agreement that we all share what we know. We communicate a lot more now than we did in the past; there are many more problems, questions people have, and more fora to share solutions”*. Moreover, external links to specialized system-wide communities of practice became more important over time also because of quick-changing product and systems designs, with more inputs required for radiation regulation, and more changes in regulation.

Features important for the creation of CT radiotherapy planning capabilities in the cancer unit demonstrate a ‘feed-forward’ learning process from individual to the group level (Crossan et al. 1999). In summary, important factors were the acquisition of a broader range of specialised skills and the inclusion of individuals with different capabilities within the cancer unit, the creation of a community of practice, and the links between the individuals in the community with other specialists outside the hospital.

Institutionalisation of team-working across the oncology-radiology boundary was not uniform across the diagnosis and planning procedures part of the routine. In the planning part of the routine, unlike the diagnosis part, top-down institutionalisation did not change practices. A possible explanation for the different degree of oncology-radiology collaboration in the two parts of the routine may be that the first part of the routine involved changes in conditions for knowledge coordination and exchange, whereas the second involved changes in conditions for the transfer of tacit knowledge, a much more time-consuming and difficult process (Nonaka 1994; Nelson 1998). The findings also suggest that a more finely-grained inspection of routines is required for a deeper understanding of processes and to understand which parts of the routine are transformed, and which parts remain the same (Feldman 2000), and the social and cognitive factors that affect learning conditions underpinning procedural and routine change.

5.2 Changes in learning conditions in CT scanning in a medium-sized general town hospital

In this section I present my results on the creation of capabilities in CT scanning in a medium-sized general town hospital. During the time of the fieldwork, improving hospital efficiency in CT scanning was a national government priority (NHS 2000; DoH 2002). At the same time, the pressure on hospitals to save costs had also increased (Department of Health 2002; BSUH 2004). Recently the UK government had issued formal support for 'role extensions' of hospital technical staff to perform new 'higher-order' functions in radiology departments in hospitals (DoH 2001; DoH 2002). The following case focuses on a hospital where role extensions of technical and nursing staff have been the norm since the 1990s. The department had contributed to national medical guidance for role extensions during the time of fieldwork.

Section 5.2.1 describes how through historical social norms for changes in departmental roles, mentoring, and participation, a CT department created learning conditions for CT capabilities and helped to meet higher demand for CT scans and hospital shortage in radiology skills. Section 5.2.2 describes how the acquired departmental knowledge provided a basis for national medical guidance in CT scanning.

5.2.1 Creation of departmental capability in CT scanning

Hospital learning in CT occurred by coaching and mentoring technical and nursing staff to perform parts of an operational routine, and helped transform roles and individual functions in the procedure. The procedure that was learned was the preparation of patients for CT scans. In this hospital, the main conditions affecting CT capabilities creation were: (1) social norms for mentoring and participation, (2) the small hospital size and uncertainty in availability of radiology staff on the one hand, and immobility of technical and nursing staff, on the other, and (3) the tacit nature and high resource intensity of knowledge accumulation for the task, making role reversal back to radiologists inefficient.

Interpreting

Interpreting was helped by departmental social norms for mentoring. The radiology manager explained that supporting individual members in the department to learn tasks that were a ‘level up’ in their professional grade had been standard practice in the department for over 20 years. One way in which this reflected itself in individual behaviour was through mentoring of junior staff by senior staff. As senior staff was performing cannulations, junior staff were permitted to observe. After some time junior staff were performing these tasks and senior staff remained to support them until they were able to do it themselves. Mentoring, copying and imitation were important elements in the advancement of human capabilities in the department. These technological processes support Barley’s (1986) analysis of social norms as ‘scripted’ in individual learning behaviour resulting in role changes in routines. It also supports the idea of ‘retention’ of social norms and path dependencies in learning behaviours in the organisation (Nelson 1998).

Over time, horizontal processes for learning through practice (mentoring, teaching) changed the types of specialists that prepared patients for CT scanning from radiologists to technicians, trainees, aides and nurses. Preparing patients for CT scanning involved tasks such as injecting contrasts, performing cannulations and barium enemas. In a gradual but active and persistent process, technicians, trainees, aides and nurses learned to carry out different tasks and procedures in these processes and replaced radiologists in performing these functions. As a result, their roles in the routine changed. Over time, they too mentored other staff in the department.

Interpreting by staff in ‘lower’ grades was, in addition to support by technical, nursing staff and the departmental manager, also strongly supported by radiologists in the department. Radiologists had encouraged and supported the delegation of their tasks to technicians for over two decades, each ‘generation’ of staff continuing to support the next generation in its skills accumulation. This confirms Wenger’s (1998; 2000) positive relationship between community social norms, the history of the community and its future.

The social norms of supporting functional shifts based on skills empowered members in the unit, improving motivation to learn, which was emphasised strongly by the members interviewed. Empowerment in combination with commitment from the staff to engage with one another was considered to be an important underlying factor in improving departmental performance in meeting CT scan requests and bringing waiting lists down.

Integrating

Integration was supported by continuous repetition of specific tasks. Performing cannulations on patients was a highly tacit skill in a sensitive context. It was performed by single individuals and needed to be performed well for the patient not to be harmed. Once learned, individuals needed to carry it out frequently in order to remain proficient at it. If it is done occasionally, the skill is lost, and the individual must re-learn it. These characteristics hold for most of the tasks that the staff in the radiology unit had learned and were now doing routinely instead of radiologists and other staff in higher grades than them. This created a situation in which a shift 'backwards' to old roles was very difficult to achieve. After some time of not performing these tasks, the radiologists did not perform them at all: *"I have been doing this every day, and now if I can't get a cannulation in, the radiologist won't even come and try because they know I am doing it all day every day and they are not doing it"* (radiographer interviewed).

The skills being learned were in themselves not novel – the novelty was in the individuals learning them. Observation and imitation was also facilitated by the low mobility of technical staff and the localised nature of this part of the routine. As stated by Zollo (1997), tacit knowledge accumulation is partially dependent upon the relevant tacit knowledge being physically proximate to the individual trying to learn it, so they are able to observe and imitate.

The delicate nature of the task (it involves inserting a cannula into the body) meant that experimentation was impossible and trial-and-error not permissible. Instead of experimenting, individuals spent a long time observing other members of staff perform the tasks. A positive perception of the senior staff of a learner's ability to carry out the task was fundamental in role change. Staff members who were mentoring junior staff were very slow in giving the responsibility to junior staff because of the high cost of making a mistake. To reduce uncertainty, staff spent a long time mentoring juniors. The sensitivity of the context made learning difficult. Moreover, incremental learning was complicated because tasks needed to be performed swiftly and confidently, and could not be partitioned into incremental steps, as other tasks (which did not involve patients) could be.

The hospital was situated in a small town, where *"people do not move around as they do in big cities, people come here to have a family and settle down, so we have time to get to know each other and build trust"* and *"there is a group here who have been here for over 20 years"* (radiology manager interviewed). Continuity in professional relationships, in particular with engagement in processes where people ask and give help to one another, was an important factor for the staff to maintain a sense of community[52], which helped in task integration.

Institutionalising

A further important norm in the department was the formal recognition of having learned new tasks and gained new experience. The manager of the department had started as a trainee in the hospital and over time was promoted from trainee, radiographer, and reporting radiographer, to departmental manager. Formal internal recognition by progression to different roles was an important factor in her motivation, commitment, and confidence in taking on new responsibilities. The knowledge and experience she had acquired during this process also reflected itself in the external recognition she was receiving from other departments in the hospital, as she was giving lectures in other departments to teach them about CT scans.

[52] The difference in social norms supporting role changes was also found by Barley (1986), who compared social 'scripts' in an urban with a suburban hospital, the suburban hospital being more flexible in changing roles with the new demands of the CT scanner than the radiologists in the urban hospital.

Flexibility in role changes of technicians carrying out radiologists' tasks was both influenced by and supported by the small size of the department. A department with a small number of staff, tasks and procedures were carried out by the individuals who were there and were available. Staff shortage was a problem that was solved by making sure that individuals knew how to do different things, so they *"would not have to wait for a radiologist to do them"* (radiology technician interviewed). Participation in different processes was an important prerequisite for individual learning, and for maintaining departmental self-sufficiency when radiologists were not there.

The hospital had recently merged with another hospital which also had a radiology department and radiologists were shared amongst the departments. This change made their local availability unpredictable, and as a consequence their availability in performing the tasks in the department uncertain. The uncertainty was ameliorated by participatory learning and role changes of technicians who were able to perform the tasks instead of the radiologists, ensuring a smooth workflow.

Radiologists' delegation of tasks to technicians also helped the department in coping with increased demand for CT scans. Staff flexibility in carrying out different tasks was a favourable condition for maintaining efficiency in changing external circumstances: *"we have to get the scans through, and keep waiting lists down; this involves training people to do different tasks"* (radiology manager interviewed).

Capabilities creation was supported by the contractual agreement with the manufacturing firm and previous experience with the same CT device. The department had quick, reliable, direct and proximate access to the information and the support of the manufacturing firm, which had over time impacted positively on departmental learning practices, and enabled the creation of directly applicable knowledge (Gibbons et al. 1994). CT technologies and their knowledge components progress at different rates, reflecting higher rates of external technical change relative to internal (Cohen and Levinthal 1990; Nelson 2003). Because the firm had contractual permission to intensify and diversify its interactions, it was able to shorten the mediation process with the hospital on aspects such as problem-solving with maintenance, usage, and impact on patients (and gain feedback on these aspects). The radiology manager stated: *“our scanner is PPI, which means it is funded by public-private initiative, part funded by a private firm, who in return for providing us with the scanner wants to know all the problems with it, how we are using it.”* On the other hand, the contract had restricted the department’s technical choices such as for components and systems specificities to technical choices made by the firm: *“whenever we have a problem with the scanner, we have to go through them first. That is not always the best option for us but we have a contract with them so we have to do it that way.”*

In summary, the capabilities creation in CT scanning was supported by social norms for mentoring, participation which enabled tacit knowledge accumulation by different members of staff in the department. Different types of specialists learned similar technical skills which improved departmental flexibility in meeting higher demands for scans, and managing workflow if other members of staff were not there. Collective learning empowered members in the department, as did formal recognition and moving up the career ladder, as supported by radiology and managerial staff. The small size of the department and low mobility of nursing and technical staff helped people to build trust.

The procedures in the routine were highly tacit and occurred in sensitive contexts, which made experimentation and trial-and-error learning impossible, so learning primarily involved long periods of observation. The tacit components of the routine were later acquired through repeated practice, and the skills were soon lost if not practiced. In this case, under conditions where routine components are highly tacit and making mistakes can carry a huge cost, learning may be much slower and routines may change slowly, even when social norms supporting change are present. Thus, it is not only institutions that may cause ‘inertia’ with regard to change (Hannan and Freeman 1984), but characteristics of the context of application that are impossible to change (interactions with patients will never be low-risk).

5.2.2 Creation and implementation of a hospital guideline

This section explores aspects of the process of codification of CT practices in the same CT department as in section 5.2.1, and problems with its integration into another hospital department. It looks at changes in learning conditions and factors affecting them.

Making explicit the tasks, processes, radiation doses, and reporting procedures in the form of medical guidance and protocols is important in departmental innovation in CT and in the regulation of operational routines and services in healthcare services more generally (North 1990; Edquist and Johnson 1997). Theoretical approaches to institutionalisation suggest that codification is an important organisational learning outcome (Rosenberg 1976). Standards and laws regulate behaviour, lower uncertainty, and equalise processes across organisational contexts. In healthcare systems, institutions in the form of medical guidance and protocols are considered to have the potential to harmonise routines across departments, hospitals and Trusts (Wenger 1998). In the NHS, organisations such as NICE and the Royal Colleges are important for formulating and issuing guidance. Medical guidance and protocols are also formulated (codified) at the local level, at the level of the region, the Trust, hospital or, as examined in this case, at the departmental level.

Integrating

The main contextual factors that changed and affected the codification and integration processes were changing demand conditions and the merger of the hospital with another hospital. The main cognitive and social factors that affected the integration of the protocol into the other hospital site were, in the codification process, the increased interdisciplinarity in the codification process over time, and in the integration process, the differences in social norms between the two departments, the tacit components of the routine that were impossible to transfer, and the differences in the technical properties of the CT device between the two hospitals, making integration of the same protocol difficult.

Demand for CT scans at the hospital departmental level was strongly influenced by changing individual radiologist preferences and by the increased pressure from the local community for CT services and improved access to high-end imaging techniques. Radiologists in the hospital had changed their preference towards CT scans over other types of imaging, which directly influenced the workload of the CT department, prompting reorganisation to increase productivity. Demand for CT scans is in part funnelled through radiologists' requests shaped by a variety of factors such as changing research evidence, medical guidance, and individual perceptions of technical superiority over other technologies such as X-rays and ultrasound: *"I've actually been asked to do a trendchart showing the increase, and we've actually had a 10% increase every year in scans. So the workload is going up a lot more. Whereas years ago respiratory patients would have a chest X-ray, we now have a consultant whose first line of investigation is a CT scan. So things change as technology changes; the baseline examinations become more complex so you have more pressure on the workload. Workloads go up constantly"* (radiology manager interviewed).

The integration process of the protocol in the second CT department was restricted by differences in contextual specificities which affected learning and change. Codification, however, did not ensure integration and the two departments remained highly differentiated. A radiologist interviewed summarised some of the main departmental differences which made integration difficult: *"The two departments are run very differently; they cannot be compared, or expected to do things similarly. It is down to the tiniest details that are different that makes it impossible to change. The individual consultants running the department do it very differently. Here we are supported in doing role extension, there they are not. Here we have a 1-slice CT scanner, there they have a 64-slice CT scanner. Here when a radiologist is on leave, we do not have lists booked, whereas there they just carry on; the structure of their day is completely different to the way ours works. So they have shorter lists, more of them covering the day. A lot of our radiologists like to follow up certain scans, whereas they don't follow up in [the other hospital]."* (radiologist interviewed)

Processes were difficult to learn and integrate through protocols because of the tacit component of the CT scanning routine. The tacitness of CT technology increased over time as the products and its systems became more complex and intertwined with behavioural processes that were difficult to express and make understandable to others not involved in the routine. This suggests that investments in knowledge bases and changes in social norms reflecting technology demands may be a more suitable option for policy than integration through protocols.

The different technical characteristics of CT scanners made it difficult to learn procedures by imitating the other hospital. The two hospitals had very different CT scanners. This was not a problem with previous X-ray devices which were relatively similar in their diagnostic power, calibration, and so on. Some differences in the two CT scanners became obvious once integration of the protocol was in the process of taking place, and it was ‘too late’ to change the protocol (radiographer interviewed). More generally, this illustrates the unpredictability of technology (Granstrand and Sjolander 1990; Granstrand 1998) in hospital contexts. One way in which unpredictability was reduced was with previous experience with the exact same device, as in the hospital that published the protocol.

Little previous experience using the existing scanner made integration of the scanning protocol slow. The other department had an older scanner and had gained a lot of experience with it, and was more flexible in changing its processes to adapt to a changing technology environment. The integration of the protocol from the other department was also made more difficult by changes in the technological capabilities of the CT device during the integration process. CT scanners are technological artefacts that are conditioned by technological capabilities in manufacturing firms. Part of the interactions between CT artefacts and the radiology department examined were modes of mediation and directionality of information flows between the department and the firm. In the second department, this process was slow and did not involve long-standing contacts and corresponding familiarity which had been built up over time.

Hospital end-users in the department integrating the protocol had restricted technical choices and opportunities to get involved at various decision-points, which made learning more difficult. As the technology was complex with rapidly changing (electronics and IT) capabilities, it was very difficult to ‘unpack’ and understand those capabilities (Lawton and Parker 1999). A further mediation was through technology assessment processes, which the radiology manager had engaged in but not for ‘this’ scanner, as the scanners changed very quickly and processes for similar outcomes needed to be re-learned. The process of product acquisition was important because it had implications for what happened when problems arose. The acquisition of equipment was mediated by the Trust in the second department and hospital users had very little choice.

The difficulty of integration and a low degree of contact with the manufacturing firm was exemplified by the condition that CT manufacturing firms more generally have relatively little structured contact with hospital users, making translation of capabilities more difficult than with other medical technologies such as drugs, for example. Devices firms rarely have direct contact with patients in the development of their work; their devices are usually rolled out and have first contact with users after they have been produced, and after the technical problems with their functioning (which are determined and conceptualized from the point of view of an electrical engineer or a technician, and not so much a clinician or via patients). Medical devices, in comparison to drugs, reach the user interfaces later in the product life cycle, whereas for drugs the translational hurdle is skipped earlier, first of all with the nature of the problem which is biological, and tested and evaluated within a similar scientific and disciplinary framework (the intellectual/cognitive space between biology and the application of the drug to a patient’s biological condition is not as large as from an electrical engineer’s to a patient’s condition and experience of the device) (radiologist interviewed).

Institutionalising

The hospital had recently undergone a merger with another hospital, which affected its learning strategy. Prior to the merger, the two hospital departments had been managed separately. Following the merger, they were managed as one department, with the requirement of making operational routines similar in their execution and performance.

This requirement initiated the codification of CT organisational processes in one department, and its integration into the second department.

The codification process involved the creation of a CT scanning protocol, which the department had experience in, and was able to report on changes in. Over time, the diversity of knowledge requirements for codification changed. The technicalities of the process became more complex and involved a broader variety of people and organisations. In the formulation of certain protocols in the department, the type of specialists involved changed to include a broader diversity of knowledge bases (in addition to radiologists and radiographers) including individuals inside and outside the hospital such as oncology specialists, patient representatives, medical physicists (for radiation doses, for example), and the PACS manager. Whereas previously the protocol was focused on a limited specification of tasks, now it involved a much broader range of tasks, more knowledge inputs, and consultations, for specifications. A consequence was an increase in the process of organising codification, the number of people involved, and the time it took to design the protocol. This increased the importance of contacts in different departments and the wider community of practice (Griffiths 1983; Kelleher et al. 1994). Individuals outside the department were involved in the formulation, partially reflecting the complexity of knowledge and the procedural demands of the multi-technology product (Hunter 1994).

The departmental social norm with regard to role extension described in section 5.2.1 was one aspect that created different learning conditions between the two departments. It had implications for which individuals could carry out which tasks, the technical choices of the department, and its capabilities in adapting to changing staff availability. Thus, CT technology was highly interdependent on departmental social norms that could not be transferred across hospital sites.

To sum up, the codification process was triggered by changing demand conditions and the merger of the hospital with another hospital, ‘merging’ the two radiology departments. The main cognitive and social factor that affected the codification process was increased interdisciplinarity over time. The integration process in the second radiology department was affected by social norms for experimentation and vertical role changes in the department, the tacit elements of the routine which were impossible to transfer, and the technical differences in the device between the two hospitals making integration of the same procedure via a common protocol difficult. Technology elements of CT continue to evolve despite codification and creation of protocols, an important aspect which is under-emphasised in the literature on institutionalisation, as well as the importance of continuous contact with manufacturing firms.

5.3 Summary

This chapter explored changes in learning conditions in two cases of learning in CT clinical practices. In the case of the first procedure, section 5.1.1, which focused on learning in CT diagnosis, described changes in the conditions for knowledge correspondence and coordination. In this procedure, the factors affecting changes in learning conditions were the technical and functional changes in the CT device and its systems over time, and changes in its systemic features. Social factors supporting learning were social values transmitted by and reinforced by medical guidance, and learning was hindered by social norms restricting the systemic expansion of the CT system across the hospital. Other factors affecting CT technology learning in the hospital were increases in the complexity of the cancer disease, and increases in the risks and perceived costs of making a wrong diagnosis for doctors.

With regard to the second procedure in the routine, section 5.1.2 focused on learning in planning radiotherapy treatment in CT, and explained changes in arrangements for accumulating highly specialised skills for collective action. Technological accumulation in this procedure was affected by changes in the knowledge requirements of CT devices and systems from outside the hospital, and by the lack of any obvious cognitive or social boundaries to the technology, and was supported by interactions with individuals in other parts of the hospital and the wider community of practice. Structural factors that hindered learning were the separation of decision-making on technology elements from the locus of learning, and by the lack of structures to support learning interdependencies across the hospital, while learning was supported by the creation of a community of practice in the hospital which was supported by the inclusion of newcomers, and the transformation of individual functions, professional identities and roles in the practice.

This chapter also examined changes in learning conditions with respect to CT in a second hospital, this time focusing on the creation of CT capabilities, and processes of codification and integration of a medical protocol. The first part of the routine, described in section 5.2.1, involved the creation of capabilities in CT scanning. Capability creation was supported by the observation of other individuals performing the tasks, physical proximity for tacit knowledge transfer, practice, interaction with manufacturing firm, and long-standing experience with the specific CT device. Social factors supporting the creation of capabilities were social norms for mentoring, participation and delegation, empowerment of individuals in performing the tasks, formal recognition, and time to build trust and familiarity.

The second procedure in the routine involved codification of the CT scanning procedure in one hospital site, and the beginnings of the process of integration of the same protocol in another hospital site. The codification process was supported by change in individual preferences, changes in learning strategy, experience with the practice, diversity of knowledge requirements which were met in the codifying department, and experience with the CT device. Social norms for role extension supported codification. Integration was hindered by differences in social norms, different departmental structures, fragmentation of decision-points and learning loci during the process, and a low degree of structured communication within the department. These aspects are summarised in Table 5.1 below.

Table 6: Summary of learning processes and changes in learning conditions in the CT clinical practices examined

CT operational routines and procedures	*Organisational learning processes*	*Knowledge factors*	*Social factors*	*Other factors*
CT diagnosis and planning				
Brief description of case: This case describes a change in a diagnosis procedure in a hospital	Interpreting	Change in artefact complexity; increase in ambiguity in interpretation of diagnostic information; change in artefact 'systemness' properties changing interpretive requirements in different parts of the hospital.	Extra-hospital changes in values and expectations.	Change in the complexity of pelvic cancer.
	Integrating	Change in technical and functional aspects of CT devices over time affecting skills requirements and their accumulation; CT had no obvious cognitive or social boundaries so difficult to locate know-how and to predict future knowledge requirements.	Change in medical guidance and their interaction and reinforcement with existing social values in the hospital; changes in social groups involved in the procedure; learning obstructed by static elements of regime, specifically decision-making structure and rules on access to other devices part of the system (for example, high-resolution monitor screens).	Increase in the risk and perceived costs of making a wrong diagnosis.
Brief description of case: This case describes a change in a CT planning procedure in an oncology department (in the same hospital as the CT diagnosis procedure)	Interpreting	Oncology department interpretation processes influenced by gradual additions of individuals with diverse skills (software, medical physics) to the department.	Learning conditions were affected by hospital adherence to social norm of departmental divisions and division between oncology department and CT manufacturing firm.	

	Integrating	Separation of decision-makers (e.g. radiology department) from locus of learning (e.g. oncology department) is a barrier to integration in emergent systems technologies such as CT; departmental CT capabilities are highly dependent upon individual-level CT capabilities, which need a long time to be accumulated (i.e. clinicians have many other tasks to accomplish in a day and CT had the effect of increasing their workload).	Integration was helped by reducing the burden on patients (before patients needed to lie on a table for hours while treatment is being planned, now treatment can be carried out on a phantom without the patient having to be there).	
	Institutionalising	Institutionalisation was helped by the accumulation of skills and collective learning over time; it was hindered by structural norms such as departmental divisions.	Institutionalising was helped by the flexibility of oncologists to work at different sites to access CT images, and the harmonised PACS systems across these sites; institutionalisation was helped by the creation of a community of practice in the oncology department; a common goal in the department, and no existing relational norms within the department from the X-ray regime which might have constrained the creation of feed-forward learning processes underpinning the creation of the new routine.	

Creation and implementation of a CT diagnosis protocol				
Brief description of case: This case describes aspects of a CT regime in a small town hospital	Interpreting	Tacit knowledge accumulation by staff in ‘lower grades’ through copying, mentoring and imitation.	Social norms for mentoring, empowering staff in lower grades through skills acquisition, active support by the departmental manager, and by the radiologists in the department, incentives to interpret and acquire new skills through empowerment.	
	Integrating	Continuous repetition of highly tacit aspect of procedure; observation (over long periods of time), imitation.	Small hospital in small town so long time to build trust and familiarity between individuals, and to build a collective identity and a community.	
	Institutionalising	Interaction with manufacturing firm and manager’s long-standing experience with the specific CT device; small departmental size (shortage of skills) so need to train others to lower uncertainty of skills unavailability (radiologists move around hospitals and are not always available, but waiting lists continuously need to be kept low).	Recognition of learning through promotions; small departmental size so flexibility in roles required to meet performance goals.	
Brief description of case: This case explores codification aspects of a CT regime in the same small town hospital, and its	Integrating	Increase in demand for CT scans; integration of externally formulated protocol difficult because	Change in individual radiologists’ preferences in favour of CT scanning.	

attempted transfer to a hospital it recently merged with.		of contextual differences such as: high tacit component of routine impossible to transfer, differences in CT scanner devices; differences in the ways in which the processes are organised in the two hospitals.		
	Institutionalising	Feedback processes of institutionalisation difficult because of contextual differences (as described previously); limited technical choices of end-users.	Institutionalisation difficult because of differences in social norms of hospital having to introduce the protocol and the hospital which had produced it (specifically skills accumulation associated with norms for teaching lower grade staff to perform higher grade tasks).	Change in learning strategy prompted by the merger with another hospital.
		Change in individual technology preferences; change in learning strategy; experience with the practice; diversity of knowledge requirements met in the department; experience with the device.	Social norm in role extension (codification context); restriction of technical choices of end-users through fragmentation of decision-points in the process; low degree of structured communication in the integration process.	

Source: Author's own analysis.

Chapter 6

Learning and Innovation in Clinical MRI Practices

This chapter analyses changes in learning conditions and institutionalisation processes involving MRI technology in two cases. Section 6.1 describes aspects of the creation of a learning environment through the institutionalisation of an MRI procedure for the diagnosis of dementia in a large urban teaching hospital. This section explains how organisational learning processes enabled change in an MRI medical practice regime. Section 6.2 explores change in learning conditions in one case of institutionalisation of medical guidance for MRI for the diagnosis of breast cancer. This section describes how external medical guidance, differences between MRI devices, changing research evidence, processes of user configuration, changes in patient preferences, and non-uniformity in patients and their medical conditions, built hospital routinisation processes of MRI. Section 6.3 summarises the main findings of the chapter.

6.1 Changes in learning conditions for an MRI procedure for dementia patients in a large urban teaching hospital

This case traces the formulation and implementation of a medical protocol[53] for the diagnosis of dementia patients in a large urban teaching hospital. A medical protocol is an example of a codified institution that specifies aspects of a medical procedure by which patients with certain health conditions are to be treated (Lawton and Parker 1999). In the English NHS, protocols are said to enable control over clinician activities (Griffiths 1983; Kelleher et al. 1994). They can also standardise healthcare practices and raise healthcare quality (Hunter, 1994). Medical protocols can be formulated by specific individuals and professional groups in single hospitals (Lawton and Parker 1999). In the UK, NHS medical protocols can be formulated by a variety of clinical specialists in hospitals as well as in specific organisations such as NICE and the Royal Colleges (NICE 2003).

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[53] The protocol involved a change in image sequencing for dementia patients, the specification of higher resolution images and different scan parameters (neurologist interviewed).

In the case explored, the formulation and implementation of a protocol was led by an individual neurologist scientist and occurred at the hospital level. The following section identifies some of the learning processes and factors that shaped aspects of MRI evolution in this procedure and hospital context.

Intuiting

Individual intuition is impossible to observe, so in order to understand aspects of this process in the MRI learning in the hospital, I focused on the origin of intuitive insights and the ways in which they were shared between individuals (Crossan et al. 1999). Learning through intuition was based upon knowledge accumulated in the past which guided research questions in the present. At the beginning stage of the process of protocol formulation, the intuition of the neurologist was based upon the knowledge he had accumulated throughout his scientific career and clinical practice, and his vision and intention to investigate different MRI sequences and resolutions in their application for imaging different conditions and types of dementia. Both at the formulation and implementation stages, his scientific intuition broadened the search space of the technology in this particular hospital context by opening up the process to different areas of discovery (in addition to providing a service to patients and informing and standardising hospital practices). The narrow restriction to dementia patients and the combination with the individual neurologist's knowledge base increased the depth of his investigations, by increasing the knowledge of the applicability and usability of MRI for dementia, and by adding to the scientific understanding of dementia.

Intuition was prominent as a learning process because of the early stage of evolution (i.e. the low level of stabilisation) of MRI technology in the hospital and the healthcare sector. Guidelines for MRI for dementia imaging were not numerous or well-known in the hospital, and their creation required intuition about what would work in the specific practice context, on the one hand, and what would produce the research results that would be useful for the scientific enquiry, on the other. In contrast to the CT case explored in the previous chapter, the protocol for CT (an older technology in the UK healthcare sector for which some national guidelines existed at the national level at the time) the protocol for CT could not be innovative (it had to follow national guidelines). MRI, in contrast, was still in the process of finding its role in dementia imaging in the hospital and the wider healthcare sector, and innovativeness at the hospital level, and the need for intuition, was more important than for some more stabilised aspects of CT.

Interpreting

Experience in one specific technology area made communication between differently skilled professionals easier. Communication was helped by a collective language to do with the one technology area, which crossed organisational departmental and professional boundaries. The individual experiences of the neurologist, and the experience in different ‘bits’ of the MRI technology bundle of the other professionals he interacted with during the codification process were aided by their focus on a device in which their experiences as well as their previous medical, technical and scientific knowledge converged.

Interpretation was aided by their individual past experience with *different* aspects of the technology (for example, PACS and medical physics), and it was their combination through mutual exchange that helped the innovation process because different information was required throughout the process, and sometimes they were unknown so the neurologist needed to go back and forth between differently skilled individuals to proceed with codification. The neurologist, guided by his research interest and requirement for access to patients to answer his research questions, needed to create a medical protocol that could answer his research questions and be followed in the hospital. To formulate a feasible protocol, he needed to combine his intuition and interpretative abilities with others who were familiar with the hospital organisational processes and capacities in MRI imaging and neurological imaging. Interaction with medical physicists, neuroradiologists and radiologists at the hospital was helped by incremental problem-solving at the formulation stage. Medical physicists possessed the intuition and knowledge on physics aspects of MRI imaging, neuroradiologists were familiar with MRI sequencing and diagnosis of dementia through MRI, and radiologists were important because the MRI scanner was located in their department and they needed to specify how and when it could be used for this specific purpose. Through interaction with these individuals, the neurologist slowly and incrementally collected the information and different knowledge aspects of the technology in the hospital that he required for his codification process of the new guideline.

Interpretation had to focus on specific technical characteristics of the device and individual and group familiarity with them. MRI devices were highly heterogeneous in their technical capacities and the device that was used in the hospital had to be researched for its specific technical capacities. Interpretation therefore was not, as the literature suggests, only an interaction between individuals and groups, but also with the technical artefact which was being learned. It was unsure if the scan parameters in the protocol could be repeated elsewhere with a different device (which also reduced the possibility of transferring existing dementia protocols to the hospital), and whether it would yield the uniform results, so the process of knowledge accumulation with regards to technical aspects was site-specific. More generally, the neurologist stated that non-uniformity in devices made it increasingly difficult to institutionalise clinical practices in MRI across hospitals.

Interpretation was aided by leadership. The neurologist was in a position of power because of the role of MRI research in the hospital, the importance of the neurological centre for the strategic orientation of the hospital in the region, and his accumulated knowledge and acquired capabilities for codification. His position of power shaped the inclusion and exclusion of social groups in the process. Inclusion in the process of interpretation was important for subsequent feasibility in carrying out the protocol at a later stage. If individuals were included during formulation and interpretation, they had an easier time in understanding the requirements of the protocol later on and helping its routinisation.

The interdependence and interaction with the (local) scientific community benefited interpretation processes because it made a wider variety of interpretative abilities available to the individuals and groups in the hospital. The reorientation of the hospital from a general to a teaching hospital changed the individuals included in the interpretation process of MRI technology. The neurologist who led the protocol formulation process was a researcher from the nearby medical school, and he was newly involved in the development of MRI at the hospital. By bringing into the hospital additional language and skills of MRI research, he changed how people in the hospital thought about the technology and initiated new ways of thinking (for example, using MRI for investigative purposes as well as for patient services). The strategic reorientation of the hospital brought with it new resources (researchers, doctors, students, equipment) which influenced interpretation by combining different search spaces (clinical, scientific, and operational) to the overall knowledge base of the hospital. It also played a crucial role in the implementation process because the research-minded doctors in the hospital and the students were familiar with using MRI for research and could follow the protocol's instructions.

The strategic change of the hospital to a teaching hospital changed individual attitudes in the hospital towards experimentation. In the protocol formulation and implementation stage, dialogue and communication between individuals involved questioning and testing because of the protocol's investigative nature. This is different from the CT case explored in Chapter 5, where the protocol specified an operational procedure that was not experimental.

Involvement of individuals in the interpretation process and formulation stage of the protocol reduced technological uncertainty. Learning through interpretation which occurred at the protocol formulation stage allowed individuals such as the neurologist leading the process, and other neurologists and radiologists involved, to participate in the definition of tasks in the protocol, and to shape the routinisation of the technology. Language and skills that were involved in this process at the formulation stage made it easier to steer the evolution of the technology at a later stage, and increased the probability that certain problems would be reduced later on.

Commitment benefited interpretation. The individual neurologist scientist was highly motivated and committed to producing a feasible protocol that would also answer his research questions and enhance his scientific standing. He needed to have access to patients for this and the hospital was a requisite for that. His commitment to furthering his research motivated him to overcome any obstacles to interpretation and collective understanding of the individuals who would carry out the protocol. He was familiar with making connections between different types of knowledge and had a broader view of MRI technology than some other personnel in the hospital. His research interests inspired other neurologists and radiologists in the hospital to participate in the formulation of the protocol and its integration into clinical practice. Science had a high status in the hospital and people enjoyed being part of scientific discovery. This increased their commitment to it.

The availability of new and different technological resources influenced capability development in the hospital positively. By asking new (scientific) questions, the hospital was solving different problems from those that it encountered in its operations and, in turn, made different knowledge resources available to the hospital and the science system. Interpretation was helped by the hospital's connectedness, through the medical school, to the wider scientific and technological system of MRI. The protocol was guided by the research questions shaped by the wider scientific community (a knowledge aspect of the wider system which, by bringing with it additional resources to the hospital, influenced learning positively), which helped in individual learning in the hospital (the neurologists and radiologists involved in the new routine learned through interpretation and interaction the wider meaning of the protocol), and improved MRI capabilities in the hospital. Connectedness and interaction with the scientific community changed problems and solutions.

Specialisation of the protocol on dementia focused the language in the interpretive process, the specification of tasks, and provided a common topic of convergence for the individuals and groups involved. MRI became more complex and to understand its processes and capacities in the narrow field of dementia imaging the neurologist had to become more and more specialised, narrowing the breadth of language involved in interpretation. At the same time, the hospital was a complex organisation and many different people were involved in carrying out individual tasks, and this had increased with MRI usage over time. Both scientific enquiries and technological change in MRI became deeper and broader. The neurologist summed these aspects up in the following observation: *"the times when you could be good at many different techniques are over. Nowadays you have to be really good at one thing, an expert in one small technique of one small area, and do everything else in a team of professionals who know how to do the other things."*

During the interviews with the neurologist scientist, and neurologists, neurosurgeons and neuroradiologists in the neurosciences centre, it was evident that the neurologist scientist did not view the hospital as an organised form of separate departments as did the other interviewees, but instead he saw the hospital as a variety of people who knew different things and whose tasks needed coordination regardless of their professional boundaries. Interpretation benefited from the more open and flexible map of the hospital of the neurologist scientist, in contrast with the more hierarchical organisational structure of the hospital which was how some of the other interviewees saw things. This benefited the search process of interpretation, by broadening the scope of knowledge that was exchanged and used. For example, learning in the new MRI technique was unpredictable and it was unknown at the outset which inputs of information would be important in the process of protocol formulation and implementation. The openness of perception of the neurologist scientist and his familiarity with uncertainty of the research processes helped him in consulting a diversity of specialists in the hospital, thereby benefiting the final protocol by adding to its knowledge value and increasing certainty in its execution.

The integration of research questions about dementia in the protocol reflected the need for experimentation and discovery in MRI. MRI had over time increased its technical capacities in neurological imaging of changes in brain volume, which opened up a new avenue of investigative enquiry into the relationship between dementia and the brain. The interpretation process thereby overlapped with the discovery process, and the possibilities for the creation of new language, instruments, and techniques for the disease. Interpretation was characterised by the need for translation of technical capacities of the specific MRI device to the complex knowledge requirements of sophisticated clinical enquiries. In the implementation phase of the protocol, interpretation benefited from interactions between the clinical and scientific understanding of the neurologist scientist, and the data obtainable from the MRI artefact.

Creating associations between scan parameters, patient diagnostic requirements, and scientific requirements involved a complex process of interaction between the two bodies of knowledge (bodies of understanding and bodies of practice), which was helped by the capabilities of the individual neurologist scientist, and his boundary-spanning role between the hospital and scientific context of knowledge production. In a direct way, the formulation and implementation of the scientific MRI protocol created an overlap between the locus of scientific, technological and organisational learning processes and search spaces.

Integrating

Integration involves the development of a shared understanding and the undertaking of coherent and collective action (Crossan et al. 1999). I found the following factors important in changing learning conditions for MRI integration in the hospital: at the protocol formulation stage, the changes in technical capacities and knowledge requirements of MRI neurological imaging influenced by technical change outside the hospital system, change in requirements of scientific discovery, and organisational changes in the hospital which changed the types of patients treated in the neurological centre and changed the role of the hospital as the main provider of neurological services in the region.

At the stage of protocol formulation, integration involved the coordination and exchange of knowledge between various medical specialists (neurologists, neuroradiologists, medical physicists) at different points in time in a non-linear, experimental way as shaped by the knowledge requirements of the MRI procedure being formalised, interaction with scientists for the inclusion of scientific research questions, changes in patient requirements, and the organisational changes of the hospital context. At the implementation stage of the protocol, as learning conditions had been influenced by explicit formulation and sequencing of new tasks and procedures in dementia imaging, learning through integration was more organised.

A collective goal of protocol formulation helped in organising individuals to provide their collective inputs. Communication and interaction between individuals was shaped by the knowledge requirements for the protocol, which was affected by changes in technology and changes in research on dementia, and changes in neurological services in the hospital. The neurologist scientist who was driving the protocol formulation process invested much effort in gaining support for the protocol from the other members in the hospital and the medical school. Collective contributions to the protocol were helped by the organisation of neurological meetings in the neurosciences centre.

Conditions for learning through collective action for specialised MRI diagnosis were changed by the transformation of the market (the type and volume of patients) for diagnostic services for the hospital. A recent national healthcare reform had changed the types of patients for neurological services at the hospital. After the reform, the hospital received a higher proportion of acute neurological patients, relative to chronic neurological patients. Chronic patients were diverted to community and general practitioners. A neurologist interviewed summed up the implications of the reform[54] for himself and the hospital's neurological services: *"Prior to the reform the ratio of new patients to old patients (patients I had a diagnosis on), would be 1:3. For old patients I knew they had Parkinsons or myasthenia and was monitoring their care and therapy, I wasn't making a diagnosis. Now it's more than 60% new patients, so more scans are being requested and being made, more new diagnoses being made, so more need for neuroradiological services"*. Thus, the intensified focus on diagnosis (relative to monitoring) provided more patients for the new dementia protocol in the hospital.

[54] The reform is part of a government policy to treat chronic patients closer to home, so they do not have to travel to the neurosciences centre for check-ups, and the hospital gets more funds for treating new patients than for treating old patients (neurologist interviewed).

Integration was helped by the use of a hospital-wide research project for MRI imaging for neurological conditions. This formalised the interaction between different specialists at the hospital, advances in the science base, and all the information that the hospital has on the patient (which would in a different condition remain confidential). The research project enabled researcher access to patient information, and collective problem-solving on specific complex cases, supporting inter-disciplinary knowledge exchange. It also provided funds to send students to different hospitals in the country to learn new MRI skills and software techniques and come back to the neurosciences centre in the hospital and teach everyone else. Integration benefited from the openness of the hospital to resources external to the organisation. In contrast to what is suggested in some studies on organisational learning (e.g. Grimshaw, Thomas et al. 2004) the organisation is not a closed but an open system, and learning processes are influenced by interactions with other organisations and systems.

Institutionalising

Processes of institutionalisation involve learning through rules, procedures and standardised and repeated organisational practices (Hobday 1998). Learning through institutionalisation in this case benefited from capabilities that individuals had accumulated in the past, their familiarity with other staff in the task sequence, and the structural legacy of the neurology specialty which encompassed radiological services within the department itself.

Learning through existing neurology routines helped in the MRI innovation process. It took a long time of repeated practice of reading different types of scans for individual neurologists to build up expertise in their specific medical area. The techniques with which knowledge had been accumulated changed over time, but the narrow specialised focus on one specific medical area did not change, making interpretation of new techniques and their integration in clinical practice easier. As one neurologist stated: *"I see a lot of people with back pain. I look at discs compressing nerves. At first I saw images of discs in the back and I was not sure whether the discs were actually pressing on the nerve producing the pain. To learn this, I had to see a lot of people who were 'normal' who had no back pain, so to see* *what was normal I had to compare it with what was abnormal. What I learned then is useful for me now, no matter which imaging technique I use".*

To have confidence in learning through routinised processes, it was important to know the people who were doing the reporting: *"because there are radiologists who over-report and radiologists who under-report and until you know which person is reporting, you can't rely on the report"*. MRI images could be transmitted and reported remotely, but because diagnosis depended so much upon capabilities that were embodied in individual radiologists, people had to know each other to be able to rely on each other's' inputs.

The MRI routine benefited from the historical integration of radiology within internal processes of neurology. Neurology, a surgical specialty, had integrated and routinised radiological practices within its core functions for a very long time. For other non-surgical medical specialties, radiology was a remote service, making learning in MRI through routinisation less common.

Learning benefited from the integration of neurological research practices with the already practiced network structure (a relatively stable institution) of neurological services. A separate clinic had been set up for imaging dementia patients and other patients specifically for research purposes. The competencies used were spread out over different sites for research projects (a multi-centre study). The clinic that was set up ensured that specific dementia patients were sent to the clinic and underwent the specified tests. The network-type practices of multi-centre research work overlapped with the network structure of neurology services: *"we (at the neurosciences centre) work in a network, which is very different from other medical specialties who work in a team. This makes working with different people and people from imaging very common. In other specialties the relationship to other specialties is very different…more remote…"*.

Feed-forward and feedback

Crossan et al. (1999) state that learning processes are not distinct from one another but there are feed-forward and feedback processes between them. Feed-forward, as described in

Chapter 2, is a concept used to denote the process of learning from the individual and group levels (intuition, interpretation, integration) to the organisational level (institutionalisation). Feedback, in contrast, represents the changes in learning conditions for the individual and group levels that are brought about through institutionalisation (from the organisational to the group and individual levels).

In this case, the feed-forward process of MRI innovation (the protocol formulation stage) was led by the neurologist scientist, who shared his interpretation by communicating with individuals with whom there was a convergence on MRI knowledge, helped by his commitment and leadership, and collective clinician interests in research activities and improving services to patients. Feedback during protocol formulation was governed by the strategic orientation of the hospital towards research and teaching which, in turn, supported feed-forward by the neurologist by institutionalising the process of investigative patient treatments. During protocol implementation, feed-forward benefited from individuals having been previously involved in protocol formulation now having to carry out the procedure. External factors such as changes in the patient population of the hospital to more acute patients, increased the repetition of the procedure and its institutionalisation supported feedback learning processes.

Section Summary

In summary, both knowledge and social factors relating to MRI technology influenced learning processes in the hospital. Intuition in protocol formulation was helped by past experience in related technology areas (imaging, neurology). Scientific knowledge embodied in key individuals broadened the search space in the hospital to scientific problem-posing and –solving in addition to operational problem-solving, and helped in intuiting during the protocol formulation and implementation stage. The early stage of role-finding and evolution in MRI technology area (in comparison with CT) in the hospital placed importance on intuition (in particular on guesswork and experimentation).

Interpretation processes were aided by individual experiences in the same broad technology area (MRI imaging, diagnosis, protocol formulation, implementation of routines in the hospital) through convergence on similar language and familiarity with dementia imaging, making communication easier. On the other hand, interpretation was helped by differences in knowledge bases and experience in the hospital because of the differentiated knowledge requirements of the protocol and the boundary-spanning role of the neurologist. Interpretation was site-specific because of the technical idiosyncrasies of MRI devices, and their connectedness to other social processes in the hospital (patient treatments, information exchange, imaging sharing and distribution, meetings, and so on). Interaction between the interpretation process was characterised by these other systems aspects of MRI, some of which were unknown at the outset. Interpretation was aided by leadership and commitment, supported by the neurologist's power in the hospital and his research interests. Change in the hospital strategic reorientation towards scientific research improved interpretation by changing attitudes in favour of experimentation. Involvement of different social groups in interpretation reduced technological uncertainty. Increased specialisation on a narrow technique in a particular medical area focused interpretation and simplified the problem. The open and horizontal cognitive map of the organisation of the neurologist leading the innovation process helped facilitate inter-departmental communication.

Integration was helped by the availability of skills and a collective research goal provided by the creation of and integration with the medical school. Integration was helped by the change in market, which channelled to the hospital the patients that were required for the protocol. The research project, aided integration by creating organisation-wide institutions in favour of dementia research.

Learning through practice of neurologists in the past had benefited MRI institutionalisation, as did familiarity with other specialists in the routine (for example, whether they leaned towards over- or under-reporting). The historical role of radiology within neurology benefited the institutionalisation process of new radiological routines. The institution of a networked way of working helped in the innovation process (operational routines and structures overlapped with innovation structures).

At the protocol formulation stage, feed-forward processes occurred between the individual neurologist scientist, and other members of the hospital through communication of aspects of imaging that they converged upon. It also benefited from including different bits of information supplied by the individuals in the process into the protocol. Feedback during protocol formulation was helped by the strategic reorientation of the hospital towards research and teaching. During implementation, feed-forward was helped by previous involvement in the formulation stage, and external factors such as changes in patient population which influenced the extent and degree to which the protocol was repeated in clinical practice (more repetitions aided routinisation).

6.2 Changes in learning conditions for an MRI procedure for breast scanning in a group of hospitals in a region

This case traces the creation of a breast imaging routine using MRI in the South East region of the UK. It explores aspects of the formulation and implementation of an MRI protocol[55] for breast cancer diagnosis in a regional cancer network organisation and group of three hospitals providing cancer diagnosis services to the regional population. The formulation and implementation of an MRI protocol was chosen to explore aspects of learning processes framed by codified forms of institutions, a relatively common policy to influence hospital organisational behaviour and technical change in the healthcare sector (Crossan et al. 1999). The MRI protocol was formulated by a the regional cancer network, an organisation that had been set up two years before I conducted my fieldwork, to monitor, audit, and steer the standardisation of cancer services in the region. Their main staffs in the organisation were clinicians such as breast radiologists and breast surgeons (who were also consultants in the local hospitals) and administrators. I carried out interviews with medical and administrative staff in the regional cancer network organisation, and with breast radiologists, breast surgeons and a hospital manager in the local hospitals. This section describes learning processes of intuition, interpretation, integration and institutionalisation

[55] The protocol specifies, amongst other things, that women who fulfil the criteria that they have BRCA1 and BRCA2 genes qualify for an MRI examination of their breasts.

in the formulation and implementation stages of the new MRI breast imaging protocol, and highlights the technological barriers and supports to learning.

Intuiting

Intuition was supported by previous experience with MRI in breast imaging. Patients differed in terms of factors such as disease heterogeneity and change in health conditions over time, which made experience in pattern recognition through MRI an important personal resource. The use of MRI scans for breast imaging was, prior to the formulation of the protocol, a relatively rare procedure in the region (the majority of diagnostic services in breast diagnosis were performed using different imaging techniques, such as mammography) and long-standing experience (as much as over twenty years) was required to build a solid understanding of the role of MRI in breast diagnosis (for example, MRI for breast diagnosis was mainly used for special cases such as silicone implants, ruptured implants and scarred tissue, which are not very frequent occurrences). Moreover, breast radiologists worked in different hospitals in the region and their experience within different organisational settings was important for intuiting in which hospital which aspects of the protocol may or may not work, and narrowing down the protocol specifications so they could be implemented in the small but diverse hospital population.

Intuitive insights were provided by knowledge inflows from outside the hospital system. The discovery of the relationship between higher rates of breast cancer and certain genes was a scientific discovery that had been increasingly gaining in recognition as a basis for a change in clinical practice. This information had been shared amongst the clinical staff in the regional cancer network through their institutionalised interactions for protocol formulation of cancer services, and between them and the local medical school.

Interpreting

Interpretation was helped by individuals making connections with their practices in the distant past because experience with techniques was not uniform but changed continuously over time. The formulation of the MRI guideline was in part an accumulation of previous experience of local breast radiologists in the use of MRI: *"The equipment was bought in about fifteen years ago and we tried it out, I did a lot of MRIs back then. Then I didn't anymore because I didn't see the benefit. Now again I am using more MRI as new research results come up."*

Collective action in changing MRI clinical practices was made more difficult by structural changes in decision-making in the hospitals in the region. In the last decade or two the hospitals had a narrower range of decision-makers (mainly clinicians) on protocol formulation and implementation. Over time this diversity increased to include managers, finance staff, patient representatives, and local charities. A further feature of the structural change was the increase in the power of managers and finance staff, and a decrease in the power of clinicians and patients. This had the consequence that discussions were (narrowly) focused on price, and as the clinical value of MRI protocols was difficult to measure (it was measured by the financial and managerial social groups who made the decisions), clinicians had to invest a lot more resources in interpretation of the value of the routine MRI screening in the region.

Interpretation at the protocol formulation stage was made more difficult by the uncertainty of the implications of the protocol in the different hospitals in the region (hospitals differed in their MRI devices, availability of radiology staff, patient population, and many other aspects which were involved in implementing the protocol but which were not all known to the staff in the regional cancer network). Moreover, MRI devices were characterised by rapid technical advances which increased the differences between the hospitals as time went by (for example, differences in software, image size, and connectedness to the hospital and regional PACS system).

Integrating

Integration in protocol formulation was helped by the creation of new organisational forms (such as the regional cancer network) which institutionalised communication processes, monitoring and auditing of cancer services in the region, and the formulation and implementation of new techniques. A formal imperative for collecting information for the protocol eased communication between the staff in the regional cancer network and the staff in the hospitals who would later implement the protocol.

Integration in the protocol formulation stage was difficult because many times the information that the regional cancer network required for the formulation of the guidance was unknown to the hospital with the MRI scanner. A breast radiologist in a hospital summed up this problem: *"Each time a new MRI machine was introduced to the hospital, it was treated as an improvement on the old one, usually limited to phrases such as 'higher resolution'"*. Often the staff in the hospital would declare that they knew how to solve certain issues that were predicted to come up were the protocol implemented, but later the 'solution' to the problem would not work, and the staff from the regional cancer network had to go to the site to suggest a solution. Inter-organisational interactions for learning showed that hospitals were highly open organisations whose interdependencies for the creation of new institutions with other organisations and parts of the regional healthcare system were comparatively high.

Some aspects of the medical institution for MRI were easier to implement than others, and this differed across hospitals. One aspect of the new MRI protocol defined which patients to treat and which not to treat using MRI. In one hospital, this was used as a reason for rationing services and an explanation to patients (for clinicians to defend the choices they made in their clinical practice), at the hospital level. One breast radiologist interviewed stated: "*all the time patients are coming and they are saying we want this (MRI) treatment, so we try to meet those demands, although it is difficult because it is not cost-effective to treat everyone with MRI. So now when we have a protocol, so then we can say we have no choice – this patient does not meet these criteria so this is what we have to do"*. In a second hospital in the region the protocol required the acquisition of an MRI scanner, and started a process of a local scanner appeal. This showed that it was relatively unpredictable what feedback processes (from the regional to the departmental level) new institutions would have on the regional hospital population.

Increased pressure for performance (as one breast surgeon called it: *"the push for 100% accuracy"*) was in conflict with what patients would tolerate. Accuracy in diagnosis was highest with biopsies, but patient tolerance for such invasive diagnostic techniques had reduced over time, in favour of non-invasive techniques such as MRI. Moreover, other non-invasive techniques such as mammography, which had been the norm for a long time, were increasingly considered as intolerable because of the pain inflicted on the patient from compressing the breast during the process. Together these factors increased pressure on clinicians to use MRI and to provide an accurate diagnosis with the technique. The same breast surgeon summarised this point: *"In the past we would do an operation just to look inside. If we suspected breast cancer, we would do many more biopsies, a lot of which were negative; now this is no longer acceptable. You have to be almost certain that there is something there to get at (to perform a biopsy), and at the same time to not miss any breast cancer, and one way is to improve your imaging. But biopsies still remain the 100% (accuracy)."*

Learning was challenged by pressures for performance before stabilisation of the technology in the hospital. Moreover, trial-and-error and experimentation processes, requirements for learning, were not tolerated. The pressure to ensure and secure a highly accurate diagnosis, with the least possible invasiveness, made MRI imaging a highly attractive option for patients. However, the low level of stabilisation of the artefact in the hospital was reflected in statements such as: *"[…] we do not know how applicable it [MRI] is, how reliable it is, it was not developed for medical applications so we do not know whether it is really better (than other imaging techniques)"*. At the same time, expectations that patients placed on accuracy in diagnosis had increased over time, at a much faster pace than the techniques were learned: "*In making diagnoses in the past for ten thousand women, it was considered acceptable to miss four or five cases of cancer; now even missing one or two is considered unacceptable" (both statements made by breast surgeon interviewed).*

Integration at the regional level was hindered by the technical dynamism of MRI devices, and their heterogeneity across hospitals in the region. The intended outcome of the medical protocol was to harmonise practices in the region. This had been easier with relatively 'simple' artefacts such as X-rays, but not for MRI. It was said by a consultant breast radiologist that: "*each MRI is different, each machine is completely different from the other. If you calibrate one and get a scan, in another hospital it will be a different scan because you can't calibrate that machine the same way, it's a different machine. Every machine is completely different from the other, and they get more different as more software is added to them".*

The process of institutionalisation via learning feedback processes (from the regional to the hospital level) worked better for the drugs paradigm than for the devices paradigm for two main reasons. First, medical guidance for implementation in different hospital organisations was a way in which the regional cancer centre aimed to change clinicians' behaviour in local hospitals. Processes of institutionalisation that were initiated in this way were the same for a variety of medical technologies such as drugs and devices, even though drugs and devices were very different technologies. A consultant radiologist interviewed summed up this point: *"with drugs you know what you've got; you can manufacture 10,000 pills of the same kind, and you can be pretty sure that they are all identical. With MRIs that's not the case. Every MRI is different."* MRIs, which had features of complex products (Crossan et al. 1999), were much more difficult to institutionalise for reasons such as heterogeneity of devices in the hospital, making it difficult to implement norms to guide clinicians' behaviour.

Second, medical devices were not exposed to the same processes of clinical trials as other medical technologies such as pharmaceuticals, and this often had the consequence (unless hospitals had learned to use the technologies for a long time) that a medical device was introduced to the hospital without a substantial knowledge gap or role gap of the device in the organisation. For drugs, guidelines had more knowledge to draw on as knowledge was accumulated during the clinical trials and spread through publications, the process of ethical commissioning, and so on, all of which preceded guidelines. Drugs also largely had predefined roles in hospitals. Medical devices, in contrast, were not subject to the same rigour as clinical trials and the knowledge surrounding them was not made available to clinicians to the same degree as for drugs.

Learning through integration was hindered by the complexity and diversity of other processes in hospitals, which had to be carried out before and after the MRI diagnostic procedure was carried out. The protocol over-simplified the extent and degree to which other aspects of the MRI process had to be changed to accommodate the changed protocol. For example, MRI scanning of the breast was only part of the process; there were still many other decisions that had to be taken in the process that could not be codified, predicted or pre-defined. There was a strong element of uncertainty and unpredictability in clinical practice; every patient was different, and every condition was considered as different, making routinisation difficult. For example, a surgeon needed to decide how to proceed with the information that was obtained from a scan: *"If the scan shows microcalcifications (early stage cancer) which cannot be felt but show up on the scan and if the microcalcifications are extensive and there is a lump somewhere else, do I just remove the lump or the microcalcifications as well? And what if the microcalcifications are in both* *breasts, do I remove both breasts? These decisions I have to make all the time, use my own judgment all the time."* Moreover, MRI provided more information that was previously non-detectable, but now the clinician was faced with a more extended set of decisions to make, which increased even more as the machines became more powerful.

Learning through integration was made more difficult by some clinicians' ambivalence towards following medical guidelines. On the one hand, clinicians' had trained for many years to be able to make relatively autonomous decisions about which patient treatments to provide, and guidelines restricted those choices. On the other hand, following the guidelines reduced the possibility of being sued. A surgeon interviewed summarised these points: *"There is a big debate about guidelines – are they making us (clinicians) like robots? We have a lot of training [so] why can't we decide for ourselves if a woman needs MRI? But if we do not follow the guidelines and something goes wrong, it becomes difficult to justify. If the patient fell outside the guidelines and developed breast cancer, then it is defensible (not to have used MRI), but if not, then I can get sued".* Learning in hospitals was thus a complex interaction between individual capabilities, choice restrictions, and legal threats shaping behaviour (the latter two mediated from outside the hospital and relatively unpredictable to the clinician).

Collective action in MRI at the hospital level was made more difficult by changes in, and level of importance of, the science system external to the hospital organisation. Part of the process for informing MRI use for breast diagnosis was several years of *'medical evidence of effectiveness'* or *'solid evidence'* for support (oncologist interviewed). Evidence was an important driver of guidance formulation. Over time the importance of scientific evidence in guiding protocol formulation has increased. In the case of breast cancer in particular, public fear had grown, focusing pressure on hospital medical innovation in the area of high-end diagnostics. However, the translation of 'evidence of effectiveness' to clinical practice involved individual and organisational operational capabilities which were difficult to accumulate. For example, individual clinicians needed to build up their knowledge of MRI, creating a group within the hospital who would support them in carrying out the process, all of which had to happen before the process had a chance of being effective in the hospital.

A further aspect governing clinical practice are clinical audits, which are national level assessments that *"make sure that people are keeping up with the standard"* (breast radiologist interviewed). Once the MRI guideline had been introduced at the regional level, a few years later the cancer network would review regional cancer services using an audit. A further important dimension in the formulation of the MRI breast regional guidelines is that cancer is a priority of the strategic health authority (regional health authority) and the national NHS Cancer Plan (Crossan et al. 1999; Feldman 2000). Both institutional and political supports at the regional and national levels were important co-evolutionary mechanisms of the change process for MRI innovation.

In the process of implementation of the new regional MRI guidelines, hospitals were treated like organisations with organisational capabilities but instead they depended much more on individual capabilities. A breast surgeon interviewed summarised this point: *"no matter what they (the regional cancer network) say in the guidelines, if there is not a radiologist in the hospital that knows how to use MRI, it will not get implemented; we will send the patient somewhere else, or not do it."*

Integration was made more difficult by MRI competition with other technology areas. Different technologies were used in the regional hospitals for cancer screening, such as mammography, ultrasound, scintimammography, and image-guided biopsy. As new technologies such as MRI were assessed for their applicability for breast cancer screening, this changed the process of consideration of the other technologies in imaging services. For example, mammography had previously been the first line of inquiry for all clinicians in the main regional hospital for breast screening, but over time more clinicians first screened with MRI. In some cases, they were added on to the screening process and used in progression after the other tests had been made, in others they replaced existing technology areas for those applications, and the application was moved to a different technological realm such as MRI. This required a lot of adjustment and learning which was made more difficult because of the individual level of action, and in some cases the areas moved back and forth and back again, as new information was gained and opinions shifted, making routinisation very difficult. Such shifts had consequences for other members of the breast screening team, who had to adjust their behaviour to accommodate it but could not predict when another change would be required.

Institutionalising

Institutionalising involves the organisational-level exploitation of what had been learned at the individual and group levels. To understand the factors that were important for the institutionalisation of the MRI practice at the hospitals in the region, I explored the goals of the individuals and groups in the hospitals regarding the technique, the conditions required to routinise it, and the factors supporting and hindering the stability of the new MRI routine.

In every hospital in the region the MRI protocol provided the impetus for a creation of an organisational routine for MRI breast diagnosis of women with certain genes. In every hospital this had been interpreted in different ways, had different interactions with hospital processes and resources, and required different adjustments. In all hospitals, it can be said, that the external impetus (scientific evidence mediated through the regional cancer network), was more challenging to existing hospital structures than feed-forward learning processes, which started from the individual and group levels and ended with their institutionalisation at the organisational level.

A further aspect of MRI technology which came from a different social group (patients) to those involved in its translation (clinicians) is demand for MRI services. Patients (customers) had power to demand services, which unlike in the private sector, whose direct cost consequences they did not have to bear (the price mechanism did not work in this case) created a condition in which production needed to be increased without an increase in resources, often at the expense of learning. Patients demanded equality, but the complexity of service provision in hospitals made it difficult to provide that (also patients were different, and health conditions were different).

The MRI breast process was helped by its conceptual connection to the improvement of diagnostic accuracy and care: *"in spite of cost and the trouble it will take, we look for better methods for not missing out on a diagnosis and that is where MRI may help. It's not because we have learned how to do MRI or because we know it's better but because we want more accuracy and to improve the care we give" (breast radiologist interviewed).*

Institutionalisation was more difficult because of differences in the power of individuals in the routine, and significant parts of the routine were at the discretion of the individual clinician. Some considerations were implicit in the MRI guideline for breast imaging and in the selection of patient-users that were not included in the guideline itself. One example of this was the age of persons to be treated. Formally, the guideline did not specify the age range of patients to be scanned with MRI, and in that way promoted inclusivity. Informally, a surgeon stated, this was not the case: *"You see a forty-year old woman comes with a breast lump and you can't really make the diagnosis with a mammogram, and she qualifies for the MRI, then you do an MRI, but if a ninety-year-old comes with a similar lesion and she qualifies, I would probably not do that. Everyone will tell you there is no ageism in the NHS, but there is."*

Skills supported institutionalisation, especially experience with MRI for breast imaging as this knowledge is cumulative and highly tacit. Even if the data may have been accessible to everyone as an image, the interpretive knowledge was acquired through experience (*"a thousand mammograms a year, six years training, three sessions a week dedicated to breast imaging, that is what you need to be a breast radiologist"*) (breast radiologist interviewed). Difficulty in interpretation did not necessarily increase with artefact complexity – in some cases ultrasound (a relatively simply easy-to-buy machine) may be more difficult to interpret: *"the physical skill you can learn very quickly, but the mental skill, and the experience of understanding what you are seeing, understanding the physics and the experience of seeing thousands and thousands of patients so you know what you are seeing and subsequently correlating it with pathological findings takes years" (breast radiologist interviewed).*

Routinisation was helped when clinicians saw MRI testing as part of wider diagnostic processes and integrated MRI testing with other diagnostic processes they understood and were experienced in. Breast scans were normally carried out as a process of elimination and it was the integration of the tests from different diagnostic techniques, and the information accumulated from the combination of these tests that provided the basis for a diagnosis. Even under conditions where the data could be obtained in different departments, the interpretative knowledge and coordination of tests were important factors and it was important to have the tests integrated and not have partial bits of information dispersed in different departments and hospitals. Routinisation was helped when the tests were used in progression, one incrementally building on the other *"like a better magnifying glass"* (breast radiologist interviewed). The transition to new technologies in this case was easier when they had not replaced one another but rather complemented each other in providing more information to the clinician.

Routinisation was helped by the length of time MRI had been used for breast cancer diagnosis in the hospitals. MRI breast imaging procedures took a long time (approximately twenty years) between the time when it was first used heavily in the local hospitals in the early 1990s until hospital routines were in place and until medical guidance in the area were produced. Individual clinicians in the regions were very enthusiastic about using MRI, but these were the early stages of evaluation of its efficacy in detecting cancers. This period slowly tapered off and users reverted back to already established processes for breast screening, and increased selectiveness as to which patients were to be treated with MRI. In the last five years the research evidence of associations between genetics and cancer incidence had increased, raising the interest in improving diagnostic services for higher risk patients.

Routinisation was helped by research evidence on MRI, and the high importance of scientific research in guiding behaviour in the sector. The increased evidence for MRI efficacy in breast cancer diagnosis aided the hospital organisation to change internal structures to exploit existing MRI resources in the hospital. This was also influenced by an intensification of cancer as a research and national service priority, a socio-political choice.

Discoveries that connected cancer incidence with new ‘objectively’ quantifiable ways to characterise patients, such as the existence of specific genes, increases the patient population and thereby the demand for the service.

Different types of guidance made more information available and MRI routinisation easier. The extent and degree to which MRI services were assessed, such as through audits and standards for quality of cancer services at the regional hospitals, had increased over time. Moreover, new organisations such as the regional cancer network and specialised community cancer services had been set up, which created bigger technical systems for MRI. The increase in assessments and guidance had made more information on MRI procedures available, helping its integration. Moreover, doctors in the region worked at different hospitals at the same time, which helped them understand the barriers and supports to routinisation in different hospital contexts, and obtain more information to draw on as problems arose.

The national priority for the improvement and expansion of cancer services (NHS 2003) had focused clinicians’ attention on specialisation in diagnostic techniques. Factors such as increased pressure to meet clinical standards in diagnosis (of which there were more over time) had changed hospital organisational ‘species’ towards more focus on specialisation on diagnostic services. This had supported the routinisation of MRI by giving it a broader institutional imperative. External factors such as the reorganisation of regional and local healthcare provision priorities, acquiring new types of clinicians, and changes in the definition of the patient population had affected these changes. Moreover, the creation of a local university teaching hospital, and the medical school, brought more and different resources to the local hospitals, helping specialisation and routinisation in diagnostic techniques.

Feed-forward and feedback

Through feed-forward learning processes new ideas and actions flow from the individual to the group to the organisational level, and through feedback processes what has already been learned moves from the organisational to the individual level (Sutton 1998). This case explored aspects of formulation of a new institution for MRI clinical practice at the regional level, for implementation at the hospital level.

Feed-forward learning processes in the MRI procedure were helped by individual previous experience with MRI for the same technique, and individual and hospital organisational experience with using MRI in integration with other diagnostic tests. Feed-forward was also helped by individual specialisation in breast cancer diagnosis, which influenced hospital specialisation in the same area. Feedback learning processes were initiated by the formulation and implementation of the MRI breast screening protocol from outside the hospital organisations (from the regional cancer network organisation), information provided by scientific evidence and changes in patient conditions and preferences.

Section Summary

This case study explored changes in learning conditions in the process of institutionalisation of a new MRI routine for diagnosis of breast cancer in a regional hospital system. This section summarises some of the main technological and contextual factors that changed and affected learning processes of intuition, integration, interpretation, and institutionalisation of the MRI routine in the regional hospitals.

Learning through intuiting was helped by previous experience in MRI for breast imaging and by scientific insights from outside the hospital organisations on the connection between MRI and breast cancer diagnosis. Interpreting was aided by past knowledge accumulation in MRI at the individual level. Collective action through processes of interpretation were hindered by structural changes in the regional hospitals such as changes in the actors involved in decision-making who imposed different organisational goals (for example, financial and managerial instead of clinical goals). The implementation of the protocol formulated by the regional cancer network organisation differed across hospitals because each hospital had a different MRI device which had developed differently within the hospital structures, and had different, sometimes unpredictable, interactions with other hospital processes. Interpretation was supported by the increased availability of information about MRI techniques in the national and regional healthcare sector, changes in pressure for diagnostic accuracy, and a change in patient preferences for non-invasive diagnostic techniques. Interpretation was made more difficult by the technical dynamics of MRI in the different regional hospitals, which were rapid and relatively unstandardised across the region. MRI techniques rely heavily on individual capabilities and numerous factors and incremental decisions in the process (for example, the interpretation of the patient's condition, and fuzzy boundaries in decision-making in cancer treatment). The integration of a new MRI routine via medical guidance was made more complex when the clinicians' relationship to medical guidance was ambivalent (for example, "are guidelines making us like robots?"). Integration was supported in hospitals where MRI techniques were used in integration with other diagnostic techniques which were already routinised (for example, when MRI scanning was used as a complement to other technologies in breast cancer diagnosis and not as a substitute).

Institutionalisation processes differed across hospitals and were helped by the clinicians' belief that they improved accuracy in diagnosis. Institutionalisation was led from outside the hospital system (initiated by the regional cancer network) and in some cases was more difficult to manage than if it had developed from within the hospital organisations themselves in accordance with existing individual and hospital organisational capabilities. Institutionalisation was helped by an increase in the availability and importance of scientific evidence on MRI for the sector more generally, the opening of the new medical school in the region, the creation of a regional teaching hospital, and the increase in individual hospital resources that came with these changes. More guidance on MRI procedures increased the availability of information on the technology and influenced individual clinicians' beliefs in the technique as superior to previous techniques, which, given the high degree of clinicians' power in individual hospitals, helped the institutionalisation process. Changes emphasising the importance of cancer services as a national healthcare priority brought more resources to individual hospitals in the region, and positively affected MRI routinisation by influencing the areas of specialisation within which MRI techniques were routinely integrated (such as breast cancer diagnosis).

6.3 Summary

Section 6.1 described processes of codification and routinisation of a medical protocol for MRI for the diagnosis of dementia patients in a large urban teaching hospital. Briefly, intuition in protocol formulation was helped (as all learning processes) by past experience in related technology areas (imaging, neurology), scientific knowledge embodied in key individuals, and the early stage of role-finding and evolution in MRI technology area. Interpretation was aided by knowledge accumulated in the past by different individuals in the hospital, by leadership and commitment to problem-solving, by hospital strategic change towards research (which made more resources available to the hospital), by the involvement of diverse social groups in the protocol formulation process which reduced uncertainty in routinisation, and by increased specialisation on a narrow technique and the communication structures that emerged therefrom which helped interpretation, as did an open and horizontal cognitive map of the hospital organisation leading the innovation process. Integration was helped by skills availability and a collective research goal, changes in patients, and the creation of parallel supporting institutions for dementia research. Institutionalisation was supported by the learning through practice of neurologists in the past, as well as by familiarity with other specialists in the routine (for example, whether they leaned towards over- or under-reporting). The historical role of radiology within neurology benefited the institutionalisation process of new radiological routines. The institution of a networked way of working helped in the innovation process (operational routines and structures overlapped with innovation structures). Feed-forward learning processes were initiated by the individual neurologist scientist, and by group communication in the hospital on aspects of MRI their know-how converged upon. Feed-forward learning was aided by search for and inclusion of different know-how in the hospital by the individual neurologist scientist. Feedback learning processes were helped by the change in hospital strategy towards research and teaching, involvement of key individuals in the process of codification for the protocol, and also involvement of the same individuals in the routinisation of the specified processes. External factors changing and supporting learning (MRI) within the hospital were changes in patient population channelled to the hospital's neurology centre.

Section 6.2 traced aspects of the process of learning in MRI and the formulation and implementation of an MRI protocol for breast cancer diagnosis in a regional cancer network and hospitals in a region. In summary, learning was aided by previous experience in MRI for breast imaging and by scientific insights from outside the hospital organisation. Interpreting was aided by individual MRI capabilities. Learning was made more difficult by structural change in the regional hospital regarding decision-making, creating a dichotomy between organisational goals and goals of the MRI protocol. Institutionalisation of MRI processes was hindered by differences in MRI devices and their evolution across hospitals, and by unpredictable interactions with other organisational processes. Interpretation was helped by increased availability of information about MRI techniques, changes in public and patient pressure for diagnostic accuracy, and preferences for non-invasive diagnostic techniques. Interpretation was more difficult in conditions of rapid technical change in MRI devices (from outside and inside the hospital). Learning in MRI was helped by capabilities at the individual level, and made more difficult if the clinician had an ambivalent attitude towards medical guidance. Integration was supported in hospitals where MRI techniques were used in combination with other diagnostic techniques that were already routinised (for example, when MRI scanning was used as a complement to other technologies in breast cancer diagnosis and not as a substitute).

Institutionalisation in this case was initiated from outside the hospital, and was supported by individual clinicians' belief in MRI for diagnostic accuracy, by the availability of information, and by existing individual and hospital organisational capabilities. Institutionalisation was helped by increased availability of scientific information and skills, and by the increased resources supplied to the region following the creation of the local teaching hospital and medical school. Increased resources to individual hospitals were also influenced by changes in the importance of cancer services as a national healthcare priority. Learning processes characterised by feed-forward aspects were helped by individual previous experience and specialisation in MRI for the same technique, and its integration with other diagnostic tests. Feedback learning processes were initiated, and to a certain degree supported by, the formulation of the MRI breast screening protocol from outside the hospital organisation, and by information provided by scientific evidence and changes in patient conditions and preferences towards less invasive diagnostic techniques.

The table below summarises the main learning processes and factors affecting learning conditions in hospitals in the two cases of MRI innovation examined in the chapter.

Table 7: Summary of changes in learning conditions MRI clinical practices examined

MRI clinical practice	***Organisational learning processes***	***Knowledge factors***	***Social factors***	***Other factors***
Diagnostic technique for MRI scanning of dementia patients				
Brief description of case: the case describes how a medical protocol for scanning dementia patients using MRI was created and implemented in a large urban teaching hospital.	Intuiting	Past experience and skills accumulated in MRI technology areas such as diagnostic imaging and neurology; knowledge accumulated through scientific experience (broadening the search space of discovery in the hospital).	Early stage of role-finding of MRI in the hospital allowed for flexibility in the creation of structures and norms; creation of norms for experimentation and guesswork in the newly formed teaching role of the hospital.	
	Interpreting	Past experience and skills in related technology areas in medical care; diversity in knowledge bases within the hospital which met the differentiated knowledge requirements of the protocol (for example, medical physics); knowledge of site-specific resources and structures which helped in codification and routinisation at the hospital level; increased specialisation of the hospital towards diagnostic services; open and flexible cognitive map of the neurologist scientist in leading inter-departmental communication in the protocol formulation process.	Individual leadership and commitment to problem-solving; distribution of organisational power in favour of scientific experimentation; creation of social norms supporting scientific experimentation and discovery.	Hospital strategic reorientation towards teaching and research.

	Integrating	Hospital organisational availability of individual capabilities and skills;	Structural change in the types of patients who were channelled to the hospital neurological services (i.e. more acute and less chronic patients, a change that required more imaging services).	
	Institutionalising	Familiarity between individuals and groups in how they performed their individual practice elements;	Historical central function of radiology within neurology; historical networked way of working of neurology which overlapped with requirements of networked MRI routinisation.	
	Feed-forward and feedback between the learning processes	Feed-forward: Individual neurologist scientist communication with different individuals in the codification process; creation of an MRI routine in the hospital with scientific enquiry at its core; changes in patient population (repetition of the practice aided its routinisation).	Feed-forward: inclusion of individuals who were involved in carrying out the routine in the process of codification.	Feedback: strategic reorientation of the hospital towards research and teaching; changes in patient population.
Diagnostic technique for MRI diagnosis of breast cancer	***Organisational learning processes***	***Knowledge factors***	***Social factors***	***Other factors***
Brief description of case: the case describes aspects of the process of formulation of a medical guidance for diagnosis of breast cancer using MRI for a group of three hospitals in the same region by a regional cancer network organisation.	Intuiting	Previous experience in MRI for breast imaging; scientific insights from outside the hospital organisations.		
	Interpreting	Past knowledge accumulation in MRI for	Structural change in social groups involved in	

		breast diagnosis; more information and guidance on MRI techniques made available through communication channels, some steps in the interpretation process from scientific evidence towards applicability to the hospital contexts; more difficult because of technical dynamics of MRI for which language did not yet fully exist in the hospital; rapid technical change in MRI devices.	organisational-level decision-making; change in public and patient pressure towards accuracy in diagnosis (for example, lower tolerance of mistakes, increase in perceived threat and cost of being sued for making a mistake); change in patient preferences for non-invasive diagnostic techniques.	
	Integrating	MRI devices highly heterogeneous from one another making integration difficult; technical dynamics of MRI devices (for example, through the addition of software components); high reliance upon individual capabilities; supported by integration with processes of other diagnostic techniques.	Clinicians' ambivalent attitude towards medical guidance (for example, "*are they (medical guidance) making us like robots?*"	
	Institutionalising	Differences in hospital resources in the region (e.g. MRI devices, availability of radiology skills for MRI); initiated from outside the hospital organisations (not the organisational level); availability of skills and capabilities at the individual and group	Structural mismatch between organisational performance goals defined at the hospital level (for example, cost-saving) and requirements of the protocol defined at the regional level (for example, learning, experimentation, and adjustment of other organisational processes)	Creation of a medical school in the region; creation of a regional teaching hospital; change in clinicians' power for institutionalising MRI influenced by protocol; increase in resources for cancer services influenced by change in national priority and creation of

		levels; increase in technical and organisational resources that came to the regional system of hospitals with the creation of the medical school and the teaching hospital; changes in information availability on MRI for breast cancer diagnosis.	(hospitals are open organisations).	large-scale government programmes for the improvement of cancer services.
	Feed-forward and feedback between the learning processes	Feed-forward: helped by individual experience with MRI for the same technique; individual and group experience with the integration of MRI with other existing diagnostic processes in the hospital; helped by individual-level experience and specialisation in breast cancer diagnosis. Feedback: the formulation and implementation of the MRI breast screening protocol from outside the hospital organisation (the regional cancer network); information provided by scientific evidence; changes in patient conditions, perceptions, and preferences.	Clinicians’ belief that MRI improved accuracy in diagnosis.	

Source: Author’s own analysis.

With regard to the relevance of the findings for the understanding of organisational learning, several points stand out. First, hospitals are not closed organisations, as some organisational learning scholars seem to suggest (e.g. Crossan et al. 1999). Rather, learning processes and conditions are shaped by technological changes both internal and external to the organisation, and interactions between them. Instead of being localised within the hospital organisation, hospital resources (for example, skills, information, patients) flow freely across hospital organisational boundaries. Second, the importance of different learning processes differs according to the organisational and sectoral interpretation of the technology for clinical purposes (for example, dementia or breast cancer diagnosis, as described in this chapter), over time (for example, interpretation was more important during codification and institutionalisation dominated by feed-forward learning processes, as in the case described in section 6.1, whereas integration was more important in feedback learning processes where institutionalisation was initiated from external impulses as described in section 6.2). Third, changes in hospital organisational routines are not strictly driven by one performance goal, as Feldman (Crossan et al. 1999) suggests; rather, they can be driven by a variety of factors such as external standards (for example, as in the breast cancer imaging case) or by individual research motivations (for example, as in the case of dementia imaging using MRI). Fourth, while the end-service may be comparable across hospitals (e.g. a diagnostic service using MRI), the process of routine change in every hospital differs strongly according to the knowledge accumulated, the social agency processes they interact with, and the market structure (Crossan et al. 1999). Fifth, in clinical practice contexts, capabilities are highly embedded in humans, which means that the ‘organisational memory’ of routines existing when a person leaves the organisation may be limited to simple tasks rather than complex operational routines. Sixth, medical technologies have multiple points of mediation, which makes organisational learning processes difficult to predict. Finally, complexity and heterogeneity of MRI devices makes institutionalisation of processes across different hospital sites uncertain, and user involvement in codification reduces uncertainty in the routinisation process.

Chapter 7

Learning and Innovation in Clinical PACS Practices

This chapter explores changes in learning conditions and processes involving PACS technology in two hospital cases.

Section 7.1 traces innovation in PACS in a medium-sized general hospital located in a town in the South East region of England. It explains how institutionalisation aspects of a technological regime involving hospital-wide PACS medical information systems were enabled by managerial organisation of gradual step-wise restrictions of technology choice and knowledge exchange conditions for unlearning. Changes occurred in organised repetitive problem-solving focused on the inclusion of clinical specialists with diversified skills, incremental feedback and feed-forward processes with managed directionality towards system change (for example, involving rule changes, changes in specifications of actor inclusion and exclusion, and changes in access to patient information). Organisation of individual and group interactions for changing features of the internal X-ray regime were informed by goals of the healthcare regulatory authority and contracted firm.

Section 7.2 presents the second case of PACS integration in a large urban teaching hospital. It shows different learning conditions and outcomes from the previous case and reflects two learning phases. The first phase shows unmanaged and unplanned processes of knowledge accumulation and the gradual emergence of learning and service production structures with group and hospital-wide integration. The second phase shows an external imposition of managerial and structural norms in conflict with internal learning, subsequent resistance, emergence of parallel structures, and signs of beginning gradual convergence between internal and external norms.

Section 7.3 summarises the main findings of the chapter and provides some reflections on their implications for learning theory.

7.1 Changes in learning conditions for PACS in a general hospital in a town

This case describes processes of PACS institutionalisation in a medium-sized general hospital in a town in East Sussex. As described in Chapter 4, PACS is an information system for radiological imaging partially enacted in the form of a large-scale UK government programme involving contracts, timelines, and rules of operation and product and systems specifications (NPfIT, 2004). This case describes PACS innovation and organisational technological processes following NPfIT execution in a hospital, and some of the factors enabling and obstructing the hospital's transition from an X-ray imaging regime to a digital imaging regime.

As discussed in Chapter 4, PACS is a broad term for a radiological information system that includes software for the storage, manipulation and sharing of radiological images and data, monitor screens, computer hardware, MRI, CT and digital X-ray scanners, to replace elements of analogue and paper-based diagnostic imaging in hospitals. In my investigation I focused on aspects of PACS that were newly learned in the hospital, where my interview partners had been directly involved at the individual, group and organisational levels, and for which key events and processes were recent enough so they could be recalled in the interviews. At the time of the fieldwork PACS had been in the hospital for approximately one year. Three main changes in learning conditions in the building up of PACS capabilities in this hospital in the period since PACS installation were identified: the first was creating conditions for routinisation by restricting choices for operational behavioural processes and providing support for problem-solving and unlearning of previous habitual actions and interactions in hospital operations; the second was incrementally adjusting rules and procedures to reinforce, expand, and maintain PACS routines as they gradually included different individuals and groups in the hospital; and third, maintaining connections with and absorbing changes in external technical systems as they evolved. As in the other cases examined, some learning phases overlapped, and within them some learning processes occurred simultaneously. In the following sections I present the main findings on learning processes at the individual, group and organisational levels.

Intuiting

Intuiting involves comprehension, gaining insights and new ideas and an unconscious recognition of patterns via previously acquired tacit knowledge (Crossan et al. 1999). These processes are impossible to observe, and to identify their existence and understand their relevance for hospital PACS learning I focused on the source of ideas and the ways in which they were communicated, shared and used between individuals in the hospital (Crossan et al. 1999). The main individuals directly and actively involved in the phase of specification and formulation of changes in behavioural rules in the hospital (for example, seizing the production of paper-based images) were the hospital PACS manager, nurses, and radiologists who had experience in using PACS in other hospitals.

The PACS manager had seven years of experience in the transition to PACS imaging in another hospital, during which time he had accumulated knowledge that helped in presenting the system to this hospital. He needed to 'feel' how to present the PACS integration process in a way that would provoke least personal resistance by radiologists, ideas which were built upon his previous experience, and at the same time keep his intuition open for pre-empting, identifying and finding solutions for problems that arose in the hospital context of application. Part of the difficulty in PACS integration in hospital organisational processes was that it required a regime shift involving, for example, radically different work practices for radiologists and all other staff in the hospital (for example, in the information radiologists and others obtained, how radiologists and others obtained it, and how radiologists and clinicians in the hospital interacted with other staff and patients while carrying out individual tasks during the delivery of the diagnostic service).

Sharing of preliminary insights by the PACS manager occurred most frequently with nurses. The hospital nurses were *"sympathetic to my questions and problems with getting radiologists to use PACS"* (PACS manager interviewed). Nurses, a group of staff whose experience was broad rather than specialised, were a group in the hospital who had earlier experience in the radical transition to IT for all their main work tasks (for example, for activity logs and recording patient data). This had helped in understanding certain learning difficulties and incompatibilities that might arise in the hospital transition to PACS. Nurses were also a group of staff whose main location for work was the hospital (they did not move around between hospitals, as clinicians did), making their availability more predictable and easier for the PACS manager to build up familiarity and trust with them. Experience with other staff and in the hospital context meant that nurses could rely on their intuition to understand aspects that might work and those that would come up against resistance from radiologists in the hospital.

The second organisational learning phase involved the adjustment of radiologists' work tasks to obtaining imaging information digitally, reading and analysing it in this changed form, and reporting it. Intuition for recording and recognising disease patterns on digital representations of radiological images drew on radiologists' previous experience in analogue pattern recognition. Some insights came from what had been learned by using ubiquitous IT systems in clinical practice such as email and booking systems, as certain solutions were applicable to PACS. Insights on, for example, the uploading of radiological images (MRI images, for instance, are of a large size and could not be uploaded onto the hospital PACS) were communicated and managed by technical staff who had more practice in the process.

Intuition was important for understanding changes in the wider technical system, via products, systems and regulation. Connectedness to other hospital and healthcare organisations, and understanding guidance for PACS that came from outside the hospital organisation were important. Familiarity with decision-making processes within the NHS, and between the hospital and private firms (such as the main IT firm administering PACS implementation in the South East region) helped in learning. The PACS manager, for example, made decisions on system specifications within the hospital, aided by interaction with the local firm to understand changes in technical requirements and diagnostic imaging industry developments. Moreover, PACS implementation in the hospital was part of a wider government program (NPfIT) which continuously influenced hospital goals and requirements. PACS was a systems technology highly interconnected and interdependent with the national healthcare sector, so it was important to be able to detect sector-specific institutional changes.

Interpreting

Unlike intuiting which is largely an unconscious process, interpreting is the conscious creation of a cognitive map of a knowledge space, and the making of connections between understandings using language capacities either individually or through communication with others (Crossan et al. 1999). In order to capture these processes, I explored aspects of communication with regard to problem-solving in the use of PACS for pre-specified tasks, the interpretive processes involved in the replacement of diagnostic functions of the X-ray regime with the digital imaging regime, and the creation of a collective meaning of PACS in the various social groups in the hospital.

Interpreting, or the making of connections between different cognitive maps of user individuals (nurses, radiologists and technicians), was helped by physical proximity between problems and their communication (i.e. Mode 2 knowledge production). PACS know-how is highly tacit and individuals were proficient in its software techniques to varying degrees. The localisation of PACS users to an area in the hospital with monitor screens of the highest resolution, concentrated learning activities and diverse users in the same physical space. This helped communication between individuals and the showing of solutions to one another. Individuals participated in joint problem-solving in one physical space in the hospital, and then left the area to work on PACS in their respective departments, and to share what they had learned in other parts of the hospital. This helped make radiology a systems technology by ensuring its functions, techniques and language were relatively spread out or more ubiquitous throughout the hospital.

The transition of certain radiological processes to PACS was largely a managed process and certain aspects of learning were forced by choice restrictions and changes in the rules of operation. For example, the radiology manager imposed the rule that images were no longer to be available on paper, but only in digital form: *"I'm not paying for film for* *anyone (any clinician) anymore; either you use the [PACS] system or you don't get to see the image"* (radiology manager interviewed). This method of controlling clinicians' behaviour was considered effective in this hospital because the formation of a community of practice was supported by the manager as well. For example, the largest monitor screens were located in the PACS department, in close proximity to nurses with experience in hospital information systems and PACS. As radiologists clustered around the monitor screens throughout the day to see their images in the highest resolution, they interacted with nurses and other radiologists when there was something they did not understand. Over time, the PACS department became a main location for communication and learning.

PACS know-how was highly tacit, learning processes relatively unstandardised and the novelty of PACS made it difficult to identify individual capabilities and manage the internalisation process. Therefore, a recognised location in the hospital for informal interactions offered an important opportunity to uncover the limits of one's knowledge, communicate the problem to others by, for example, pointing to the area on the computer screen that required interpretation, and to ask others for help. Over time, the clinicians got better at using PACS and these types of interactions became less important, until technical changes or regulatory changes occurred again.

PACS had a different meaning for every user group in the hospital. The learning of PACS in the hospital was interpreted by some individuals as an opportunity to modernise and improve services, and by others as an imposition on their existing practice, making their work more difficult. Some clinical staff, in particular consultant radiologists, who had a superior position in the hospital hierarchy, resisted direction. The opportunity for staff to gather in the PACS department, and voice complaints and at the same time be supported in their problem-solving by others, made it easier to integrate the system into their work practices. The informal location in the PACS department made collective interpretation easier, and helped in the creation of a community of practice of PACS users in the hospital. The informal interactions that occurred in the PACS department allowed for individuals with different functions in the hospital to share their interpretations of the technology, and build an understanding of PACS interpretations and functions in the hospital, helping their own learning and routinisation of different aspects of the technology.

For the manager, it was a system that needed to be integrated into radiologists' work practices as quickly as possible at the lowest possible cost. For several of the nurses interviewed, in the first phase it was a source of many problems that at first they did not know how to solve, or work around. The way in which digitisation had impacted directly on their work tasks was through logging of scanning requests and logging of scans. Previously the nurses had done this on paper. They had had many problems and crashes with the system, with the result that they kept both written logs and digital logs. PACS had doubled their workload at first. Later on, they became more confident in PACS and no longer needed the paper back-up of logs.

For radiologists in the hospital, PACS changed their ways of interpreting scans and the 'ritual' of the radiologist interacting with patients. For example, prior to PACS the radiologist visited the patient with the paper image of the scan as part of the patients' file, so they could look at the image while they were talking with the patient. Now the clinicians in the hospital were annoyed that they could no longer do that: "*I can't possibly have all the images in my mind of all the patients I am visiting in the ward, it is much harder now, I have to go back and forth between the computer and the patient, it all takes a lot longer*" (consultant radiologist interviewed).

The creation of a PACS community in the hospital changed both individual and group understanding of what radiology is in the hospital. Certain aspects of radiology changed from being a centralised service within the hospital with a distinct hierarchy and department, to possess elements of a service that incorporated different groups of people in the hospital, changing radiology from a relatively vertical to a more horizontal structure and with emerging aspects of a decentralised and generic technology (but still requiring highly specialised skills). This process involved unlearning of what radiology is, of individual tasks in the hospital, and making new interpretations of what was previously known of IT systems (for example, the evolution of interpretations of IT systems as data storage and communication to an understanding of IT as a diagnostic tool replacing more centralised functions of the X-ray regime).

Interpretation in the early phase of PACS institutionalisation changed the forms of interaction between individuals. In the main, it increased communication between previously relatively disconnected social groups. Communication was relatively unstructured and more trial-and-error, before a collective meaning of PACS was created through communication and management between individuals familiar with specific technical processes (for example, technicians, managers and nurses) and the shaping of this function by individuals who had more power in the process (for example, managers and radiologists).

Unlearning was characterised by two main stages: first, directed radical adjustments to rules of operation (directed from outside the hospital and the manager); and second, incremental adjustments based on feed-back about what worked and what did not work (from inside the hospital). The manager of the PACS department was the main actor who changed some important rules in PACS imaging in the hospital, and drew his information from NHS guidance for PACS implementation (for example, the rule to shift from film to digital images). When he had set this rule in the hospital, the learning and organisational changes required became apparent, and he had to set up a location for the transfer of PACS know-how in the hospital so that radiologists and other users could learn and inform the manager of further changes required.

Interpretation at the individual and group levels was affected by industry interpretations of PACS and interpretations of the formal healthcare regulatory authorities. In this hospital, the main users had had little experience with PACS changing existing radiology functions. However, most users had information on PACS and were familiar with some of its potential functions in the hospital, but did not know the precise details of how it would change their work. Over time, context-specific interpretations were created, stabilising PACS within the various groups. However, actors in the external technical system continued to be important. For example, rules for accessing PACS images were under negotiation and changed several times during the interview process (for example, whether family members can view each other's digital images), as did the technical specificities of which images would be transferred via hospital PACS (just CT or both CT and MRI images).

Integrating

To understand learning through integration and the relationship between PACS features and group action in the hospital, I focused on the groups where I was told changes in learning and operational processes were happening, namely in the radiology group, the nurse group in the hospital, and the broader emerging PACS user community.

In the radiology group, integration was mainly associated with radiologists using PACS to analyse images and produce diagnostic reports. This involved the accumulation of PACS-specific skills, which were learned through trial-and-error and interaction with other hospital users, and the application of previously acquired diagnostic skills and IT skills. In the hospital, the majority of radiologists had not been trained to perform their tasks using IT, and this was a radical change for them (they had been trained to use film images and were long into their career by the time they had to use PACS). As stated previously, the PACS manager created a separate physical structure for learning PACS skills. In this space the main users of the system were localised in one part of the hospital which was centrally accessible to them, and it emerged as an area within which people could ask each other and help each other to solve problems, and thus replace and unlearn elements of the X-ray regime.

Certain norms changed over time, with doctors becoming less and less resistant to using PACS, although it had a personal cost to them. An advantage of PACS was that the throughput of diagnostic information was much faster, but radiologists had a lot more information to deal with per patient because the images were far more detailed: "*your eyes don't get a break. Before with film you could get approximately 10 images and had to look at each one in detail. Now you get one image with CT and MRI side-by-side on workstations and you can manipulate images and its 3D so there is a lot more work for us* *and information and [it's all] very detailed, which takes a very long time to go through.",* was what one radiologist stated.

Nurses emerged as an important user group in terms of gaining knowledge and spreading it to other clinicians in the hospital. Unlike the hospital radiologists, the majority of nurses had had experience with hospital IT systems from previous programs, and were able to use and transfer these skills to radiologists and other PACS users. Their familiarity with individual clinicians, regular direct contact with patients, and overall organisational processes made them very important in supporting change.

PACS integration was helped by the creation of a PACS user community in the hospital. This process had two main features which helped in integration, an informal one internally created and a formal one which was created externally from outside the hospital. The informal norm, the localisation of PACS users in the PACS department, has already been described. The formal norm was the externally led institutionalisation of multi-disciplinary team meetings (MDTMs) involving weekly meetings (depending on the clinical specialty area) on patient diagnosis in which PACS was a central tool for the presentation and discussion of individual patient cases. Overall, PACS increased interactions between diverse staff in the hospital and helped in changing internal relationships and structures for integration. However, many other behavioural and structural adjustments are still in process. As the radiology manager stated: "*What has changed with these meetings is the increased workload; radiologists now spend many more hours looking at images and preparing for the meetings. (Making diagnosis about patients) has become much more imaging driven and imaging dependent; all of them (clinicians participating in the meetings) will be looking at the images and finding the areas to treat. Previously a report would land on a desk and no conversation would take place.*"

Integration processes were affected by wider systemic features of the technology. First, PACS has specific components which, in order to work as a system, need to be compatible with other components both within the hospital and within the wider healthcare sector. IT more generally but PACS specifically made radiology a systemic rather than a comparably stand-alone hospital service, and changed both the structure of radiology and the structures of other hospital services such as nursing and management. Second, PACS emergent systemic aspects were closely related to decision-making structures external to the hospital organisation. At times, for example when access allowances were being given out in this hospital, this created a dichotomy between what had been decided outside the hospital and what would work within the hospital context.

Integration was difficult because decision-making structures either fitted elements of the X-ray regime (for example, when devices were not very different from one another, were more stand-alone, and their role had been stabilised for almost a century) or they had been pre-determined at a very early stage of PACS implementation. This restricted the emergent nature of learning and integration, by narrowing choices and restricting context-specific flexibilities that were required for learning processes to occur. It also imposed unrealistic expectations on doctors, who said that PACS had increased the time they required for each patient, rather than decreasing it, but they were paid to spend the same amount of time on the patient as before.

The creation of a user community helped in developing a shared understanding of what is going on with PACS technology in the hospital but challenged existing structures. Confirming the relationship between technology and organizational structure (Barley 1986), PACS implementation was delayed because of "*professional boundaries*" (interviewee CBR1[56]). At first, the PACS hierarchy reflected the traditional radiology hierarchy of radiologists as the main users, and all other staff as subordinates. A few months after the initial formalization of its use through hospital management, it became clearer that individuals who used PACS on a day-to-day basis, building up their tacit skills, were those that were most frequently asked for help with the system. The PACS manager soon drew attention to the nurses and technicians who had gained the expertise, re-labelled them as 'super-users' and thereby named a different social group for what was at first considered an area of expertise for radiologists. The process of redefining individual roles, along with the unpredictable nature of where knowledge will be accumulated and how tacit

[56] Consultant Breast Radiologist 1.

know-how will be transferred, is a feature of technology areas at early stages of development in organisations.

Integration was helped by the small size of the hospital with relatively few specialists and more generalists, which helped in the creation of a relatively large PACS community in the hospital. Access to patient images, for example, was not restricted to radiologists, but other staff members could have access to them because radiologists were not always available. There were far fewer specialists so, in order to deliver the service, doctors had more responsibilities in the process, and had to be more flexible in the application of their skills. As a consequence, learning in PACS was more widespread, and many more people were involved in the routines and in the development of the technology. Less emphasis on specialists was also reflected in another part of the process, which meant that there was a limit to what could be done in the hospital. Some of the diagnostic areas are highly specialised, such as MRI musculoskeletal, and in this hospital these images would never be made or looked at, because the specialist to perform the service was not part of the hospital. A radiologist interviewed stated: *"there is a good average of widespread skills (in the hospital), but highly specialised areas are not represented. Size matters because with size you get more diverse specialisations, but you have to be careful that the diversity does not cause separations between them so that technologies such as PACS are limited to certain (departmental) areas as well."*

Integration was to some degree slowed down by regulatory changes in external financing of PACS, and the greater dependence of the hospital on these changes. This was one of the first hospitals in the region to introduce PACS, but this was not perceived as favourable, since according to one interviewee: *"in the end we paid for parts that everyone else got for free. This makes us more careful in making other changes because we might later find that there could be more money coming in."* Thus, individual motives to support internal adaptation to an externally changing technical environment were dampened by changing forms and outcomes of mediation.

Institutionalising

Institutionalising involves the organisational-level exploitation of what has been learned at the individual and group levels. Two main phases of learning underpinning institutionalisation were recognisable. In the first phase, organisational goals and rules were set externally by the healthcare regulatory authority and contracting firm before hospital capabilities were created. Problems arose from the misfit between external norms and internal learning requirements to meet them. One radiologist interviewed expressed his frustration as follows: *"potentially there is value in IT in healthcare but you need to change it to something that produces value for us. For that, you need to talk to us, to include us, not just the vendor – they don't know what we do."* Similarly, another radiologist stated: *"people [decision-makers implementing the NPfIT program] have this vague idea about IT technology, that IT will improve the kind of care that we can provide. But mostly it has been a disaster because doctors were not consulted; people were not asking us what we want. Maybe we would have said the PACS system, but they never asked us – they never ask anybody. They just gave the contracts to the major vendors."*

In the second phase, supports for learning were created within the hospital, enabling the emergence of an internal community of practice by changing conditions for knowledge exchange. In this phase, various features of technology stabilisation were visible, such as unchanging rules for access and usage, a designated physical space for communication across professional and departmental boundaries, and inclusion in rule-making for internal hospital PACS processes. Hospital PACS capabilities were highly embodied in individuals, and thus individual learning played a very important part in organisational-level institutionalisation, more so than learning at the group level.

Feed-forward and feedback

Feed-forward learning processes involve the flow of ideas from the individual to the group to the organisational level. In contrast, feedback learning processes occur from the organisational to the individual level, which requires changes in the institutional order to allow individual intuition to emerge . In the case explored, individual- to group-level learning processes followed feedback processes of externally-led institutionalisation. The impetus for change was an institutional system external to the hospital (for example, the national healthcare sector programme for PACS implementation, firms, and other regional and national hospitals which had built up PACS capabilities) for changing from aspects of the X-ray regime, such as paper-based imaging, to a digital imaging and communication system.

Feed-forward learning was, in part, a directed process of rule-setting, communication support and inter-disciplinary meetings, and partly an informal process of localised problem-solving in the hospital supported by the emergence of a community of practice of PACS users. Shared understanding of PACS was cultivated through the localisation of PACS devices in one part of the hospital, aiding interactions between users, the sharing of problems, and the construction of a shared identification, and also helping in the collective transition from the X-ray to the IT-based diagnostics regime that emerged, gradually replacing the previous atomistic radiology structures.

Section summary

This section described the learning processes and technological changes that occurred in the hospital during PACS implementation. To sum up, intuiting was helped by the PACS manager’s previous seven years of experience in PACS implementation in another hospital, which made him better able to understand personal resistance against PACS by radiologists. Intuitive insights by the PACS manager were shared with nurses who did not feel threatened by the changes, and had a certain familiarity with radiologists in the hospital, and acted as boundary spanners between different professional groups in the hospital. Radiologists’ intuition for the direct implications PACS had for their work at the time (in particular for image analysis and interaction with patients) was helped by previous experience with analogue imaging and IT systems. Intuiting at the individual level was also helped by previous experience of the PACS manager with private industry, for understanding product and system dynamics external to the hospital.

Interpreting of PACS technology in the hospital was helped by the localisation of PACS users in one physical area. This aided interaction between individual PACS users, the exchange of tacit components of know-how (they were otherwise difficult to locate in the hospital), and for the exchange of interpretations of the systems technology by different user groups, increasing their social connectedness within the technology space. Choice restrictions helped direct interpretation and joint-problem solving, because it created problems, on the one hand, and provided an opportunity for exchange, on the other. Overall, interpretation was aided by rules and supports for unlearning via choice restrictions, behavioural guidelines, human agency, and interpretations that flowed into the hospital from external firm agents.

Integration was helped by different factors for different user groups in the hospital, because PACS rules, systems and operational constraints had different implications for every group. For radiologists, PACS meant more information on diagnosis, more time spent per patient, and changes in the doctor-patient relationship. This was helped by the local area in which radiologists could examine images and ask for help with visualisation, network or wider IT problems with the system. Changes in the doctor-patient relationship were demanding on radiologists' time, and the change of certain rituals, such as visiting patients in wards with paper-based images on file, were seen as an inconvenience by the doctors. Nurses felt the transition through changes in the way they logged scanning requests, and integration of PACS in this process was helped by practice and by slowly gaining trust in the system. Integration was helped by the creation of a PACS user community in the hospital, which improved inter-disciplinarity by crossing departmental boundaries. Integration was further helped by the small hospital size, which required generic skills and flexibility in operations, social norms which were a legacy from other changes that occurred in the hospital over time. Integration was made more difficult by requirements for technical compatibilities with other hospitals in the region, and the separation of where these adjustments were required and where the decisions were made.

Aspects of PACS processes were defined in the hospital and stabilised after long periods of intensive communication, decision-making, and knowledge accumulation by individual specialists. Learning was made more difficult by the dependence on external aspects of decision-making, continuing changes in regulations, and regulatory mediation of changes in products and systems restricting technical search processes and technical choices.

7.2 Changes in learning conditions for PACS institutionalisation in a large teaching hospital in a city

This case analyses aspects of the creation of PACS capabilities in a large urban teaching hospital. The process I traced with my interviews involved the changes in learning conditions that the interviewees recalled from the first beginnings of PACS usage in place of paper-based imaging in the hospital, and the later phase which was defined by the national programme for PACS implementation (NPfIT). The case shows the importance of individual enthusiasm and leadership, informality and unpredictability in the accumulation of knowledge, and the difficulties in changing informal internal structures with externally created social norms.

Intuiting

Intuiting played an important role in the first learning and integration phase of PACS in the hospital, which occurred before the externally-led programme for PACS implementation. The origins of the development of PACS within the hospital were traceable to the motivation, commitment, and intuitive capacities of one particular medical physicist. He was a forerunner in investing his time in the installation, technical compatibility checks and trouble-shooting in the hospital. The medical physicist began to lead the development of PACS based on his own previous knowledge of IT systems and network development, and the support of hospital management to buy-in specific components from outside.

His intuition had been supported by several key aspects of his practices that arose from the position and nature of the medical physics service to the hospital and the region. First, medical physics was a central service to the hospital and to regional radiology and nuclear medicine based on providing informational support services to the radiology community. Thus, it had a relatively high degree of IT and systems technology components integrated within its processes already. Second, by providing services to the hospital and the region, the medical physicist had knowledge of the social norms of the actors who were assumed to be most affected by the transition from the X-ray regime to the PACS regime. This helped in intuiting where there might be problems with PACS, for example with regards to the technical requirements of image transportation, access, and individual radiologists' preferences. Third, the medical physicist had experience with existing institutionalised communication procedures with radiology and nuclear medicine in the hospital, which supported quick and frequent testing of intuitive notions complemented by user information feedback.

Interpreting

Interpretation processes had different characteristics before formal PACS implementation was initiated by the NPfIT program, and after. Before NPfIT, interpreting was helped by the individual commitment of the medical physicist to collaboration in PACS interpretation, technical support by the medical physics department, use of existing knowledge and communication structures, experience with the procedural order involving changes in general hospital IT systems, and physical proximity and established relationships with the radiology department. Interpretation was also helped by communication with the wider medical physics community outside the hospital, and the practice of inter-disciplinary knowledge accumulation, which revolved around existing social norms within the medical physics community. Interpretation was also helped by communication between radiologists and medical physicists, who cooperated in the integration of PACS in work processes.

The second phase of PACS learning was initiated by changes in learning structures marked by the creation of an entirely new hospital PACS department, a new PACS manager, and contracts and timelines negotiated with a private firm. This changed the existing decision-making structure and formalised different social norms from the ones that had been previously informally created (through feed-forward learning processes), and launched a new learning phase for the hospital. In this phase, interpretation processes occurring in the PACS department, the medical physics department, and the radiology department were central for changing existing procedures. In the PACS department, interpretation was helped by the previous knowledge of staff of hospital IT systems (though not in this hospital) and the overlap between the knowledge of the regional IT network, IT know-how, and the formal requirements of PACS in the hospital. However, this knowledge alone was insufficient to overcome the existing structure of the medical physics department as the main department underpinning PACS capabilities in the hospital. The PACS department lacked knowledge of social groups in the hospital whose processes and structures had been affected by PACS previously, and who had already built up systems and operational routines through feed-forward processes.

The most important processes of interpretation involved dialogue and communication between the new PACS department, and the existing PACS community of medical physicists and radiologists in the hospital. This was difficult because it took a long time for the two groups to become aware of each other and to understand their respective roles. Dialogue between the two groups was difficult to establish because the medical physics and radiology community did not at first include the PACS department in its processes, and, on the other hand the PACS department made decisions without consulting them. The two social groups had different cognitive maps of the processes of integration of PACS in the hospital. The PACS department focused more on rules and formal technical requirements of the programme, whereas medical physics focused more on what worked within the existing hospital processes, and made changes according to those.

Integrating

Integration involves coherent and collective action . The first learning phase underlying collective tasks was characterised by continuous interaction between the definition of technical system requirements, task learning requirements, and task specification leading to integration. These processes were at first led by the individual medical physicist, and later by the medical physics department.

Definition of system technical requirements involved acquiring specific details of existing IT and network systems in the hospital, the different imaging devices and size of images that needed to be transported via PACS, and defining roles for who could access the information, and who could change it. Commitment by medical physicists to acquiring this information, testing the possibilities of the systems, making changes to them, supporting radiologists in problem-solving, and communicating with other hospital users were important for PACS integration within radiology and the wider IT regime in the hospital. As a nuclear medicine physician interviewed stated: "*nuclear medicine and medical physics have always been inter-disciplinary, we have to be*, *but radiology only now has to be (because of PACS, MRI and CT).*"

Task learning requirements and task specification were supported by existing social norms of intra-hospital and extra-hospital interactions. Internal to the hospital, integration was supported by the existing central service function of medical physics and its inter-departmental and inter-hospital communication, search processes, and service provision. As such, medical physics mediation of PACS requirements and possibilities in the hospital built upon its existing mediatory function for hospital-wide technical and radiology support. PACS integration was also helped by existing norms associated with external aspects such as working with private industry (for example, in the maintaining of diagnostic devices and obtaining up-to-date software), and with regulatory agencies (for standard-setting for radiation doses, for example). Moreover, nuclear medicine and medical physics experts were few in number compared to radiology, so there were already many user networks in place before PACS, and reliance on them for hospital problems and questions was common. This kind of networked structure with communication links outside the hospital was very useful for PACS implementation in the hospital. This is different from the social norms in radiology, which is a much bigger professional community nationally, and does not rely as much upon IT-based user networks for problem-solving.

In the second learning phase, after NPfIT, decision-making structures and goals changed in the hospital. The PACS department was not able at first to establish itself as an organisational leader or authority on PACS in the hospital because of the existing learning structures that had been built previously. Procedural capabilities for PACS (image analysis and sharing by radiologists) had already been created by existing users in the hospital, but the programme brought with it different rules and goals for the organisation, which disrupted integration processes. A radiologist interviewed stated: *"I have never had any contact with the PACS department, only medical physics, for PACS questions. I wasn't even aware of their existence until recently. But the PACS department made all the decisions, with no communication, with us nor with nuclear medicine. This created many problems for us, for example now the PACS system cannot take images produced by gamma cameras which we have two of in this hospital. The images are too big (to transport) for the (existing PACS) system."* This external definition of technical system requirements started off a new process of interaction with learning requirements and task specification, but without the supporting relational structures in the previous learning phase.

Institutionalising and feed-forward and feedback learning

Similarly to the previously discussed learning processes, factors and conditions supporting PACS institutionalisation in this hospital can be categorised into before and after the NPfIT programme was implemented in the hospital. The first learning phase, characterised by feed-forward learning from the individual to the group and organisational level, began with informally motivated and managed individual and group level dialogue, communication, experimentation and rule-creation within the existing hospital structures in the medical physics department. Conditions for learning such as previous IT know-how, established relationships with pre-defined user groups such as nuclear medicine and radiology, relationships and norms of working with wider IT user networks, and time resources (medical physicists primarily provide a service to other clinicians and technicians in the hospital and the region; they do not treat patients, so they repeatedly stated that they had the available time to commit to PACS integration) to devote to learning PACS skills, system compatibility requirements, and to solving problems as quickly as they came up, supported the development of PACS in the hospital. Over time, the stable and predictable aspects of PACS were specified in terms of tasks and procedures, and a relatively informal user community emerged in the hospital.

The phase following NPfIT was characterised by conflicts between how rules on aspects of PACS were created and managed and the existing PACS routines in the hospital. Important changes were the externally defined power granted to the newly formed PACS department, which was in conflict with the already established role of medical physicists in the hospital who used a more emergent, incremental, inclusive and consultative process for rule-setting. This created a condition in which decision-making power on, for example, technical specificities on the size of image to be transported and stored in the PACS system, handling of patient information, access to the PACS system, search options, saving of past scans, rules on who could request a scan, which groups got PACS training, accountability for accuracy and changes of patient reports, and degree of confidentiality of patient information, were defined without including the main groups who were affected by these changes.

Section summary

This case explored aspects of the creation of PACS capabilities in a large urban teaching hospital. Intuiting was helped by previous experience with IT systems in the hospital with medical physics, and by the medical physicist's familiarity with other individuals and groups in the hospital and communicated via established relationships. Before NPfIT, interpretation was aided by localised dialogue and communication in the medical physics department, time for trial-and-error experimentation, and social norms of knowledge exchange with the wider medical physics community outside the hospital, and the existing norm for inter-disciplinarity within this community. After NPfIT, interpretation was held back by the new social group of the PACS department, externally determined social norms for decision-making, and the difficulty of replacing existing norms in the hospital. Integration before NPfIT was supported by the individual commitment of medical physicists for acquiring information, testing, communication with radiologists and nuclear medicine staff through informal social processes supported by social norms of interaction between the main PACS user groups in the hospital of medical physics, radiology and nuclear medicine. Integration was also helped by the long-standing norms of medical physics as a central service function for the radiology and nuclear medicine departments in the hospital and the region, and supported by social norms and experience of working with industry (important for fast-changing products and systems in PACS), wider practice communities, regulatory agencies, and the small size of the national medical physics community, making communication easier. After NPfIT, integration processes were slowed down by the external creation of internal structures and decision-making rules, the establishment of the PACS department as a leader, and low levels of communication between this department and existing users, and a misunderstanding within the PACS department of the incremental nature of the PACS development process in the hospital. Overall, stabilisation of PACS was well under way in the hospital before NPfIT, and was slowed down by it. Feed-forward learning processes led by medical physics were relatively successful because of individual knowledge, communication, and interactions with other social groups inside and outside the hospital. The existing processes of capabilities creation were delayed by the external programme, which imposed rules in the hospital that were in conflict with existing learning structures and processes.

7.3 Chapter summary

In section 7.1 the case study explored the accumulation of knowledge and the creation of organisational routines as part of a managed process of hospital learning and change. Intuiting at the level of the manager was helped by previous experience in PACS learning in another hospital, in particular on technical aspects and on pre-empting personal resistance to changes in the behaviour of radiologists. Insights were shared by a relatively neutral social group, that of nurses, who were sympathetic to the change requirements and knowledgeable about the operational needs of radiologists, and who could act as boundary-spanners between the social groups. The manager also relied upon his intuition when making internal decisions that were likely to be affected by changes in products and systems by private industry and by regulatory authorities. Individual intuition was also important for radiologists, who relied upon their PACS experience in other hospitals, and on skills acquired from the analogue regime (in particular for image interpretation through pattern recognition). Interpreting was aided by constructing a physical space for knowledge exchange (a designated room with high-resolution monitor screens) which allowed for interaction between individual PACS users, and for communication, trouble-shooting, and the creation of an understanding of PACS and its meaning to different user groups in the hospital. Choice restrictions (for example, no more X-ray film, just digital visualisation) helped in directing efforts for interpretation by creating problems, and at the same time opportunities for solving them. Integration was helped by communication of the meaning of PACS for different user groups in the hospital, the creation of a physical learning space, and the small hospital size and the requirement for individual flexibility in roles. Overall, technology stabilisation was made more difficult by the dependence on external aspects of decision-making, continuing changes in regulations, and regulatory mediation of changes in products and systems, restricting search processes and flexibility in technical choices.

Section 7.2 focused on informal aspects of the creation of PACS capabilities in a hospital, and the organisational changes in learning conditions which occurred following the implementation of a national programme for PACS implementation (NPfIT). PACS routinisation was initiated by a medical physicist and the medical physics department, and specifically their commitment to PACS installation, to the solution of technical problems, and to the collection of information for the definition and realisation of tasks and procedures. These processes were supported by existing social norms for facilitating inter-disciplinary communication, and knowledge exchange with hospital user groups, and the wider PACS user community outside the hospital. Following NPfIT, learning processes were obstructed by changes in decision-making structures and their conflict with existing norms associated with PACS in the hospital.

The table below summarises the main findings of the chapter.

Table 8: Summary of changes in learning conditions in PACS clinical practices examined

PACS clinical practice	*Organisational learning processes*	*Knowledge factors*	*Social factors*	*Other factors*
PACS Town				
Brief description of case: This case describes aspects of PACS routinisation in a large urban teaching hospital. It shows how integration processes led by rules and institutions external to the hospital were mediated via internal management through choice restrictions and support for tacit learning and inter-disciplinary communication structures.	Intuiting	Manager: Previous skills acquired through tacit experience for PACS systems integration in another hospital by the manager; intuition for pre-empting resistance to change by social groups; previous experience for understanding and pre-empting external changes in regulation and industry. Individual radiologists: experience with analogue pattern recognition.	Manager: testing of insights with nursing group, building familiarity with group less threatened by change; relationships with informal regulatory bodies; relationships with industry.	
	Interpreting	Physical proximity and designated hospital space for tacit knowledge exchange and communication.	Horizontal social structures in physical problem-solving space; technical choice restrictions; externally directed changes in rules of operation; creation of a community of practice supported by changes in norms of social group interaction; different interpretations of PACS by each user group.	
	Integrating	Radiologists: accumulation of skills through trial-and-error learning and interactions with other hospital users; repeated practice, changing	Creation of a structure (a physical space) for communication supporting integration; nurses emerging as an important social group, acting as	

		behaviour and keeping up to date with changing technical requirements through interaction with other users; divergence of decision structures and internal demands for learning of processes underpinning changes in routines; small size of hospital and norms give rise to advantages such as flexibility of staff in performing diverse tasks.	boundary spanners between previously disconnected groups in the hospital; nurses' familiarity with different groups, patients and organisational processes; integration supported by emergence of hospital PACS community of practice; changes delayed by legacy of X-ray regime such as rigid professional boundaries obstructing development of systemic features of technology.	
	Institutionalising	Externally defined goals and rules, and differences between them and internal capabilities; changes in conditions for knowledge exchange.	Supports for the creation of a hospital PACS community of practice; inclusion in internal rule-making; changes in internal decision-making structures.	
	Feed-forward and feedback between the learning processes	Feed-forward: radiologists and nurses learning through practice; group learning supported by long-standing familiarity between staff, especially with nurses. Feedback: management-level supports for knowledge exchange and problem-solving; management mediation of external regulatory changes affecting clinical practices and rule-setting.		Feedback: National programme for PACS implementation; changes in regulation of clinical practices; changes in technical requirements mediated by firms, regulatory authorities, and other hospitals.

PACS City	***Organisational learning processes***	***Knowledge factors***	***Social factors***	***Other factors***
Brief description of case: This case explores PACS learning phases before and after NPfIT in a large teaching hospital in a city.	Intuiting	IT systems and operational service skills; commitment to problem-solving.	Individual agency and motivation; structure (position of medical physics within hospital and regional healthcare system); understanding of social norms of radiology and nuclear medicine users.	
	Interpreting	Phase before NPfIT: Individual commitment to collaboration and inter-disciplinarity in defining rules and procedures; technical support of medical physics department; reliance upon existing communication and decision-making structures within and outside the hospital. Phase after NPfIT: change in and external imposition of a new decision-making structure; conflict with existing social norms and procedures. PACS department supported by externally instituted decision-making power; knowledge of regional IT network structures and NPfIT program requirements.	Phase before NPfIT: existing norms and structures for dialogue and communication between user groups. Phase after NPfIT: change in organisational decision-making hierarchy in conflict with existing structure and obstruction of inter-group interpretation processes by exclusion of existing user groups from decision-making process; and new external meaning of hospital PACS performance and distance between programme goals and actual hospital achievements.	
	Integrating	Phase before NPfIT: Medical physics: commitment to leading the	Phase before NPfIT: Supported by existing social norms of medical	

		interaction process between definition of system technical requirements, task learning requirements, and task specification; testing; supporting radiologists in problem-solving; leading and enabling knowledge exchange with other hospital user groups. Phase after NPfIT: change in decision-making structure with externally defined actors, rules and goals; disruption of existing learning processes and structures.	physics for inter-departmental mediation and inter-disciplinarity, hospital-wide search processes, and external interactions with firms and regulatory authorities. Phase after NPfIT: disruption of learning processes through changes in structure and lack of internal relational structure and support.	
	Institutionalising and Feed-forward learning processes	Interaction between individual, group learning and institutionalising: Individual intuition, motivation and commitment to problem-solving, dialogue, and testing. Interaction with and support from medical physics and gradual emergence of their role as main actors enabling technical change elements to PACS regime; supported by existing IT capabilities, existing inter-departmental relationships. Gradual stabilisation and definition of individual and group tasks and procedures		

	Institutionalising and feedback learning processes	through a joint communication process. Conflicts with existing internal learning structures and externally defined decision-making structure and norms; separation of control (goals and rules) from social groups involved in carrying out PACS routines; disruption of learning because of lacking relational structure of PACS department in hospital; gradual acceptance of users of changes in rule-making procedures, with continued reliance on medical physics department for problem-solving.		

Source: Author's own analysis.

Chapter 8

Conclusions

The aim of this thesis was to explore innovation in hospitals. Using a framework for technological learning in organisational practices, this thesis set out to uncover processes of innovation in CT, MRI and PACS. Based on six empirical case studies in UK hospitals, this research found that learning in clinical practice is diverse, incremental, and shaped by complex processes of multi-level mediation and technological problem-solving in operational routines.

Section 8.1 summarises the main findings and presents the key features of medical innovation discovered in the individual case studies on clinical practice in CT, MRI and PACS. In section 8.2 the theoretical implications of the research are presented, making explicit the reinforcement and contradiction to existing theory on organisational learning and technological change based on the research results. It also provides a critical analysis of the study’s limitations, and makes some suggestions for future research. Section 8.3 makes policy inferences based on the research evidence gathered in this study and, where appropriate, suggests some changes to existing health technology policy. Section 8.4 presents the final conclusions.

8.1 Summary

This thesis explored innovation in clinical practice in UK hospitals. Innovation in hospitals is considered an important topic for policy. Current policy approaches to healthcare innovation were reviewed in Chapter 1, which revealed reliance upon scientific evidence of efficacy and cost-effectiveness to inform policy, and formulation and implementation practices built on a rather linear, narrow and atomistic view of medical innovation.

This was confirmed by a review of some of the main scholarly literature on change in healthcare practices in Chapter 2, which found conceptualisations of hospitals as adopters of external ideas, products and services. The main approaches to organisational learning were then reviewed, and a framework for studying learning processes, learning levels, and learning outcomes in hospitals was presented. While organisational learning approaches offer extremely valuable insights into learning in clinical practices, their relationships with aspects of technological evolution were understudied. This chapter then argued that deeper understanding of technological processes *underpinning* learning in hospitals may help us understand how hospitals innovate and why some innovate more readily than others. Following on from the deduction of the rationale for studying learning in hospitals and its relationships with technological change, this chapter presented the theoretical framework and research questions guiding the study.

Research design choices were discussed in chapter 3, which argued for the choice of an exploratory case study design for the collection and analysis of novel empirical data. The justification for the selection of clinical practice as the unit of analysis, and CT, MRI and PACS technology areas was presented. The chapter discussed the use of interviews, observations and archival searches for data collection, the reasons for choosing the specific hospital sites, as well as the analytic techniques used for interpreting the data. The shortcomings of the methods, and the ways in which I tried to ameliorate their effects on the study, were also described.

Chapter 4 argued that an investigation of hospital innovation requires an understanding of details of the scientific discovery and historical development of the specific technology areas. The chapter reviewed literature demonstrating that diagnostic imaging evolved through complex interactions between the science system, technology and the healthcare sector of which they were part. This chapter described important sectoral aspects such as the distribution, procurement and regulation of these technologies in the UK NHS, where the empirical study was carried out.

The theoretical framework presented in Chapter 2, which defined the organisational learning concepts at the individual, group and organisational levels (intuiting, interpreting, integrating and institutionalising) and their interactions with evolutionary aspects of technology (such as regimes, technological systems, cumulativeness, and complexity) used to explore the findings presented in Chapters 5, 6 and 7. The analyses have shown that clinical practice innovation is characterised by incremental, inter-disciplinary, emergent and contextualised features of technological learning in operational routines. These points are expanded upon in the sections that follow.

8.1.1 Learning in CT clinical practices

Chapter 5 explored innovation in CT practices in two cases of hospital learning. In the first case it was found that learning conditions were altered by changes in the complexity of pelvic cancer, extra-hospital changes in values and expectations (mediated by changes in patient preferences and changes in medical guidance). It was also found that transformation in CT artefact complexity, an increase in ambiguity in the interpretation of diagnostic data, and alteration in artefact 'systemness' properties all influenced interpretive requirements in different and previously disconnected parts of the hospital.

Integration of CT diagnosis activities and their operational routinisation in the hospital were transformed by change in certain technical aspects and the functional role of CT information over time, and changes in medical guidance and their reinforcement of existing individual values in the hospital. The increase in CT-based diagnostic information affected hospital skills requirements and their accumulation by influencing individual searches for more information (with limited changes in learning conditions) and by increasing the pressure on clinicians for diagnostic accuracy.

An important feature of the CT regime was an increase in the variety of decisions and decision-points (for example, technical aspects, diagnostic decisions, decisions on information access, and of inclusion). Emergent and systemic aspects of CT were reflected in the far reach of individual decisions on individual tasks, procedures, and communities in other parts of the hospital.

Incremental steps towards transformation in the CT regime such as ‘multi-disciplinary team meetings’ occurred in parallel with a retention of the division of labour under the X-ray regime (for example, divisions between radiologists and oncologists in accessing of diagnostic information), producing a ‘layering’ of technological systems (Hughes, 1989).

CT diagnostic information had no obvious cognitive or social boundaries, so it was difficult to locate relevant know-how. Certain communication structures in the hospital became more collaborative, flexible and inclusive of clinicians and technicians with diverse skills. Despite these changes, some structural rigidity remained (such as decision-making rules, and rules on access to the amount of diagnostic information available to non-radiologists).

The second part of this routine involved the development of CT capabilities in the oncology department of the hospital. It was found that the learning environment of the oncology department was transformed by the acquisition of the CT device, supported by learning processes and the gradual formation of a community of practice. Integration of CT technology aspects were supported by addition of individual with diverse skills and resources to the department (for example, IT skills, radiation therapists, and medical physicists). Interpretation was slowed down by hospital social norms of departmental divisions (hindering communication and tacit knowledge exchange) between the oncology and the radiology department, and divisions between the oncology department and the CT devices firm.

Integration of CT into oncology practices was hindered by the continuing separation of decision-making from the locus of learning, and insufficient time being made available for clinicians to learn new tasks. Integration was helped by the replacement of patients by ‘phantom’ planning software and hardware, which removed the need for patients to lie for long periods of time while their cancer treatment was being planned.

Within the same context of capability-building in the oncology department, CT institutionalisation was helped by skills accumulation and collective learning over time at the departmental level, and hindered by elements of structure, such as norms reinforcing departmental divisions which supported the ‘old’ X-ray regime. Routinisation benefited from physical flexibility provided by the systems technology, such as making the same type of diagnostic information available at different hospital sites. Routinisation was supported by the gradual creation of a community of practice in the oncology department, a common goal in the department, and a low level of existing relational norms within the department, which made it easier to achieve feed-forward learning processes underpinning the creation of the new routine.

The second case revealed that capabilities creation in a CT department in a small town hospital depended upon tacit knowledge accumulation supported by social norms of mentoring and imitation. Interpretation was supported by staff in ‘higher grades’ mentoring staff in ‘lower grades’ to perform task elements of the CT regime. This social norm had the effect of empowering staff, and creating more incentives to practice, acquire skills, and learn.

An important aspect of CT capabilities was found to be the ability to integrate various tasks and procedures in a short span of time. Integration was supported by continuous repetition of tacit elements of tasks and procedures, observation of other members in the department, continuous, predictable patterns of communication, and the uninterrupted availability of core radiography, nursing and technical staff in the department, which helped to build trust, familiarity and behavioural certainty.

Institutionalisation processes were helped by the above-mentioned factors, as well as by other stable elements of the routine such as interactions with the contracted CT manufacturing firm, the long-standing experiences of the CT manager with the exact same CT device, the uncertain availability of radiology staff (which created the need to routinise without them), recognition of learning through staff promotions, and the small hospital size requiring flexibility in roles to meet departmental performance goals.

Part of the departmental capability in CT scanning was reflected in the codification of its practices in the form of a CT scanning protocol. In addition to the above-mentioned factors supporting learning, codification was influenced by factors such as the merger of the hospital with another hospital, creating conditions for the transfer of CT practices, and the overall increase in demand for CT scans which affected both hospitals (both from patients and from changes in radiologists' preferences for CT scans).

Institutionalisation via feed-back learning processes was attempted with the transfer of the protocol to the second hospital site. It was argued that institutionalisation processes were hindered by contextual differences between the two hospital sites such as how they had scans booked, which staff were available, and the differences in social norms for mentoring staff in lower staff grades, differences in level of experience with CT devices, differences in CT devices, differences in individual radiologists' preferences for CT, and limited choices and decision-making powers in the receiving department to ameliorate the effects of these differences on changes in the CT regime.

8.1.2 Hospital innovation in MRI

Chapter 6 analysed two cases of change in learning conditions underpinning MRI routinisation. In the first case it was found that the hospital learning environment was transformed by knowledge resources, commitment, and strategic reorientation. Specialised individual experience and skills in MRI research and operations were a basis for individual intuition. Characteristics of the hospital context, such as its recent change to a teaching hospital, changed learning conditions by expanding the search and problem space in the hospital.

Individual and group interpretation of MRI in the hospital was supported by individual commitment to dialogue and incremental step-wise problem-solving, and the open and flexible cognitive map of the neurologist scientist leading inter-departmental communication in the protocol formulation process. Interpreting was helped by a clear and specialised goal, awareness of its translational complexity, and the subsequent inclusion of diversely skilled individuals to meet the knowledge, process, and organisational requirements of routinisation in the phases of individual and group learning.

Conditions for technology interpretation and integration were changed by the creation of hospital norms in support of teaching, research, the expansion of neurological diagnostic imaging services, and the distribution of power and resources in favour of scientific experimentation and discovery in parallel with the provision of more diversified patient services. Integrating was supported by the strategic change intensifying the role of the hospitals neurological services at the regional level, both increasing demand and changing the patient population (from chronic to acute cases), and by the accumulation of knowledge through repeated practice.

Familiarity between individuals and detailed knowledge of how they performed their individual tasks helped in the execution of the new operational routine in MRI in the hospital, because of the high importance of individual clinicians' capabilities within organisational procedures. Routinisation was helped by the historically important central function of diagnostic imaging within neurology, and the networked way of carrying out neurological services, structures that overlapped to a certain degree with the institutionalised MRI research practices.

The second case explored aspects of MRI innovation involving the formulation of a set of guidelines at the regional level for its implementation in the local hospitals. Essential for the learning process was a definition of the diversity of MRI devices, skills and procedures in the local hospital population. This informed the codification process by supplying information on the behavioural modifications that were possible in the hospitals.

Intuiting was, as in the previous case, supported by experience in the specialised diagnostic area. Scientific evidence and insights into MRI capacities for breast imaging helped influence experienced clinicians' ideas for codification. Interpretation processes were based on past knowledge accumulation in MRI for breast diagnosis, as well as on skills acquired through experimentation with different MRI devices in the distant past when connections between the advantages of MRI over other imaging techniques were less explicit. Interpretation was also helped by individual experiences in the translation of scientific evidence to clinical practice.

Interpretation and integration processes were central requirements for institutionalisation, and these relied upon individual capabilities, and an understanding of the rapid technical change in MRI devices, which increased heterogeneity between local hospitals. Fast-paced external changes to the devices put pressure on language and learning capacities within local hospitals to keep up with changing knowledge demands created by external changes in MRI devices.

Learning depended upon knowledge exchange and task coordination between different social groups with divergent goals, resources, and power. A crucial social group were patients, who increased pressure on clinicians' performance in diagnosis and changed their preferences towards non-invasive diagnostic techniques such as MRI.

Overall, regional-level institutionalisation was supported by knowledge of how and why individual devices in hospitals were different, and knowledge of the MRI capabilities of local hospitals, the increase in resources that were brought into the region with the creation of a local medical school and teaching hospital, the increase in scientific evidence on the medical value of MRI for breast cancer diagnosis over existing diagnostic techniques, a supportive attitude at the individual clinician level of medical guidance, the creation of a regional governing body for the improvement of regional cancer services, and an orientation of national-level priorities towards cancer diagnosis and treatment channelling resources for this area to the region.

8.1.3 PACS innovation

Chapter 7 described aspects of PACS institutionalisation in a city and in a town hospital. The first case found that PACS learning was supported by incremental step-by-step behavioural restrictions and changes in the conditions for knowledge exchange. Modifications underlying the transition to a digital from an analogue diagnostic regime were helped by unlearning features such as interactions between diverse specialists, and rule changes informed by external regulatory requirements and technical support of the local PACS firm.

Managerial skills acquired through tacit experience in PACS systems integration in a previous hospital helped learning through intuiting. Specifically, awareness of possible resistance to externally led change by internal social groups, and insights into pre-empting external changes in regulation and industry, reduced uncertainty in the innovation process.

Experience with analogue pattern recognition aided individual radiologists in intuiting what was required for learning tasks that formed part of the PACS regime. Testing of insights into solutions to problems benefited from the manager's and radiologists' familiarity with boundary-spanning individuals, such as nurses, a comparably stationary and neutral social group in the hospital who historically had an important role in inter-departmental functions and communications.

Changes in conditions for tacit knowledge exchange, such as a designated physical space for high-resolution PACS equipment, fostered inter-disciplinary communication between PACS users in the hospital, to address problems such as technical choice restrictions (from film to digital scans), changes in the 'ritual' of visiting patients with a stack of film, and operational aspects such as logging scans. Such processes contributed to the collective interpretation of PACS, and to an awareness of different perceptions of the technology by the various social groups, as well as creating a foundation for the formation of a community of practice.

Integration of rules and tasks in the radiology group was supported by the accumulation of skills through trial-and-error learning, interactions with other users in and outside the hospital, and by repetition. Interaction with users outside the hospital helped in keeping practices up to date with rapidly changing software and hardware elements (which, for example, changed the types of devices in other hospitals the clinicians visited) influenced by private industry. Integration was supported by an understanding of diversity in hospital goals, and by changes in decision-making structures influencing operational routines. Staff flexibility in performing diverse tasks, partly because of the shortage of resources such as specialists due to the small hospital size, helped in the integration of systems components of PACS because it was impossible to know where in the hospital such skills might be needed and when.

The creation of operational routines (for obtaining scans, logging scans, delivering diagnoses, and monitoring and interacting with patients) characterised the change towards a PACS regime in the hospital. These aspects of the regime change were supported by ‘feedback’ learning processes such as codified knowledge provided by the national NPfIT programme, and managerial mediation of it to the wider user community in the hospital through the creation of a hospital-wide PACS community of practice, and their inclusion in internal rule-making, focusing efforts towards both internal learning processes and their connectedness to external organisations and systems.

The second case, that of PACS implementation in a city hospital, showed that individual and group-led changes to an internal regime can be jeopardised by social power structures, technical specifications, rules and procedures defined by external organisations addressing the same or similar conditions and objectives. In the first phase of hospital learning (before the national programme), PACS innovation was led by the medical physics group in the hospital. Intuiting was helped by knowledge of hospital IT systems, hospital service skills derived from the centralised service function of medical physics within the hospital, which involved both an understanding of procedures and social norms and perceptions of the main hospital PACS users (radiology and nuclear medicine). Essential to regime change were aspects of social agency, specifically individual commitment to problem-solving and motivation, and actions that were enacted from there on.

The creation of a PACS regime in the hospital context required periods of individual and collective interpretation. Before NPfIT, interpreting was supported by individual commitment to collaboration and inter-disciplinarity in defining elements of the routine (rules, tasks and procedures), the norms and structures of the medical physics department such as their knowledge of existing communication and decision-making structures within and outside the hospital that overlapped with knowledge and social requirements of PACS technology.

Individual commitment to inter-departmental communication, hospital-wide search processes, collaborative and incremental definition of rules (for example for access and image transportation) benefitted the building of socio-technical aspects of the PACS system in the hospital. Learning was supported by task execution, testing, supporting radiologists in solving network and access problems, and mediating between previously disconnected groups. External imposition of rules (for example through the NPfIT programme) resulted in some disruption of these emergent and painstakingly accumulated learning structures (for example, the directed uni-lateral nature of some of the programme's decisions were in conflict the comparably open structures for dialogue and communication between PACS user groups in the hospital).

In parallel, the staff in the new PACS department helped in the hospital's integration within the regional PACS systems through their knowledge of regional IT network structures and NPfIT programme requirements, and external interactions with the contracted firm and with the primary regulatory authority, which over time emerged as important rule-making aspects of the hospital PACS regime.

In summary, routinisation of PACS was supported by emergent feed-forward processes and obstructed by decisions made separate from the practice locus of learning, systems usage and development. Feed-forward processes were reliant upon individual intuition, motivation, and commitment to problem-solving, inter-disciplinary dialogue and testing, and incremental stabilisation of technology through a joint communication framed by existing relational structures for the definition of tasks, rules and procedures, which were difficult to maintain under the externally-led PACS regime.

8.2 Theoretical implications

Hospital innovation in diagnostic imaging technologies is very important for the improvement and delivery of healthcare services, and many investments have been made to support it. However, hospitals differ in their innovation processes, and important explanations have been provided by scholars of diffusion, communication, and evidence-based medicine, as well as scholars on organisational behaviour and management.

This thesis has focused on organisational learning processes shaped by evolutionary accumulation of technological knowledge. This thesis found that important aspects of learning and innovation processes in hospitals are underpinned by technical change and group-level technological regimes, such as communities of practice.

The results in this thesis support the view that technological accumulation is an important underlying feature of innovation in hospitals. Organisational learning processes were found to be interdependent with aspects of technical change such as cumulativeness, emergence, systemness, and unpredictability, such as has been suggested by evolutionary approaches to technological change (Rosenberg 1982; Hughes 1989).

This thesis used an organisational learning framework to explore technical change in hospital organisations. The findings suggest that technological learning processes occur simultaneously at the individual, group and organisational levels, and that the barriers, supports and outcomes are variegated and difficult to predict.

Innovation in hospitals is a dynamic process involving changes in regimes such as building novel interpretations of individual and departmental roles and functions. This finding confirms Barley’s (1986) work on the interdependent relationship between technology and organisational structure. This thesis has also revealed that an important aspect of regime change is the proximity between decision-making and the locus of learning, and that larger distances between them (whether cognitive or physical) make learning more difficult.

The empirical chapters showed that hospitals cannot innovate on the basis of evidence of efficacy or on the basis of medical guidance alone. Important for operational routinisation are regime aspects such as behavioural restrictions for decision-making and rules for inter-disciplinarity in problem-solving.

This thesis suggests that regulation (based on codified knowledge) is insufficient in harmonising operations across hospitals because of the partial tacitness of operational routines (Zollo and Winter 1999). Contextual features such as departmental management of scanning requests, skills availability, group learning norms, and access to knowledge sources are difficult to shape and control, as are their interactions with externally defined changes in organisational goals.

Problems in changing technological regimes (for example, from X-rays to IT-based diagnostic imaging such as CT, MRI and PACS) demanded out-of-routine knowledge and relational patterns which were localized and context specific, confirming Gibbons et al.'s (1994) conceptual advances regarding 'Mode 2' knowledge production. Hospitals with resources (individuals, time) and social norms supporting communication and learning processes across departmental, and other cognitive and social boundaries were better at solving problems posed by new technologies than those hospitals that had few such resources or norms.

Learning requirements (such as understanding, defining and making choices with unpredictable outcomes, transforming work practices and ways of relating to other clinical groups and patients, and building novel and unexpected individual specialisations within the same learning infrastructures) associated with complex systems devices are group, organisation, and time-specific, and they take a long time to accumulate and to be applied. It was found that medical devices such as CT or MRI scanners are not static stand-alone products, but rather systems technologies which have idiosyncratic, emergent and systemic developmental patterns within hospital contexts that may create conflicts with structural legacies of older regimes. This finding supports the earlier work of Hobday (1998).

Hospital innovation is strongly guided by external and internal social values of technology which are also dynamic. The emergence of positive public attitudes to non-invasive diagnostic procedures, the motivation of clinicians to provide the best service to patients, and the increasing threat of being sued for making a diagnostic mistake, spurred on individual and group learning efforts in the technology areas. The evolution of social values and their interrelationships with advancements in imaging echo Hughes (2004) work on the relationship between technology and culture.

Learning in hospitals is an uncertain and complex process (for example in which social groups will be affected in diagnostic procedures, and the extent and degree of ambiguity that will be introduced with more diagnostic data). Technological uncertainty in hospital contexts is reduced by processes of agent involvement in decision-making and codification, and that this involvement needs to continue throughout the entire learning process. These findings confirm Oudshoorn and Pinch’s (2005) research on the importance of user involvement in innovation.

Innovation in clinical practice is supported by the creation of communities of practice (Wenger 2000). Communities of practice form around technological problems (Rosenberg 1982) for which solutions, and the processes to arrive at them, are partially or wholly unknown. The same problems may occur in different parts of the hospital and this may also be unknown to all parties.

Hospitals, like firms, have organisational boundaries which are open to external knowledge sources. Learning processes do not only arise from and interact with other learning processes within the organisation, but that they co-evolve with technological changes that occur outside the organisation, confirming Dosi’s (1982) contributions on technological paradigms.

For the medical devices studied, interactions with firms are important for medical innovation. CT and MRI devices in particular were found to embody diverse technology elements such as electromechanical knowledge, engineering knowledge, and IT and software knowledge, and ‘hidden’ knowledge on their bundling within the device. Interactions with firms supported understanding of such intrinsic artefactual complexities, confirming Pavitt’s (2004) view of innovation. In turn, firms benefited from these interactions by obtaining knowledge on aspects of the device as they interacted with the hospital innovation environment.

Changes in environmental complexity, such as changes in diseases, patient populations, and in societal expectations of healthcare services, influence hospital innovation. Modes of mediation of external technology aspects are highly variegated and structured, perhaps for hospitals more so than for other organisations (for example, via guidance, regulatory authorities, national and local healthcare strategies, research organisations, and patient groups). As a result, hospitals seem to have less power and flexibility within large technical systems (LTS) than firms do.

Increase in knowledge in hospitals is incremental and it is supported by step-wise restrictions of technical choices which are managed and proximate to the locus of learning. Knowledge growth is supported by individual commitment to discovery, problem-solving and the expansion of search and problem spaces via the inflow of technology ‘elements’ as found in Bell and Pavitt’s (1993; 1995) studies of technological capabilities.

An aspect of the evolution of systems technologies in organisations is that they increase the complexity of organisational procedures before they simplify them. Complex products such as CT and MRI place different knowledge and structural demands on hospitals which take a very long time to discover and learn, connect previously disconnected parts of the hospital, and change existing connections. This confirms Hobday’s (1998) theory of complex products and systems and their contextualised, unpredictable and incremental evolution in organisations.

Hospital technological capabilities are sometimes embodied in single individuals. Organisational-level learning is in such cases highly dependent upon individual experience, skills, availability, motivation, and individual persistence in technological knowledge accumulation.

Hospital routines are highly tacit, and regime changes benefit from mentoring and imitation and the accumulation of tacit skills. It was also found that tacit knowledge accumulation across the organisational hierarchy ameliorates negative consequences of the sporadic availability of resources such as individual capabilities. For example, highly skilled clinicians move around hospitals on a daily or weekly basis, and the difficulty in predicting their accessibility was lessened by the accumulation of know-how for less mobile staff.

The empirical results in this thesis show that hospital learning is cumulative and that it can take a very long time to be translated into services for patients. As noted by Bell and Pavitt (1993), knowledge accumulation and production involve different conditions and processes. Growth in hospital services can occur with little learning (for example, the increase in CT scans), but innovation cannot (for example, improvements in the accuracy of diagnosis require comparably more learning).

The findings in this thesis can be generalised to the UK national healthcare sector, as well as to other healthcare sectors internationally with similar approaches to the governance of technological change (for example, publicly financed healthcare sectors in other European countries). The findings may also be generalisable to privately financed healthcare systems, which have high degrees of regulation.

Other aspects which are generalisable are the close relationship between organisational learning and changes in conditions for the accumulation of technological knowledge, and the development of systems technologies, which is also important for private sector firms. In such cases innovation in systems technologies, such as changes in specialisation, may pose similar structural challenges in meeting changing knowledge requirements.

The findings would appear to be less generalisable to sectors where the creation of new organisational forms and modes of interaction are less institutionalised and more easily possible, such as many private sectors including the manufacturing sector. In such sectors, processes may be more freely outsourced, and learning and production strategies more quickly transformed. Moreover, in such a sector the creation of systems and changing of processes may not be as constrained by regulation and a multitude of decision-points or risk to individual patients. In such cases, generalising the results of this thesis to these sectors may be more risky.

The aim of the thesis was to provide a sufficiently comprehensive exploration of learning in clinical practice in CT, MRI and PACS and make accurate and plausible analytic generalisations. Although the research met the overall project aims, it has important limitations. Shortcomings of the thesis are due to its scope, the complexity of the phenomenon of learning and the data available for analysis. A further set of limitations are the potential of biases, such as researcher bias and current events bias.

My preconceptions about the phenomena of learning and technical change in clinical practice changed throughout the course of the study. During the exploration of processes and sub-processes of learning in hospitals it quickly became clear that these were much more complex and detailed than I had initially assumed. The theoretical framework provided perspective but in reality the boundaries of individual practices and processes are undefined. This was somewhat improved upon by my carefully designed theoretically informed interview schedule to keep the focus on the important details and maintain consistency in the findings.

Learning is very difficult to detect and measure and the interpretation of what counts as learning, how much detail is required to capture and explain it, and what information to omit, is influenced by the researcher. In acknowledgement of this I kept the analysis as close to the details of the case as possible (idiographic approach).

Clinicians in the NHS organisations I visited were difficult to contact and interview. I took steps to collect high quality data using face-to-face interviews with the main people involved in the individual practices and tasks, as well hospital and Trust managers, and regional decision-makers to collect data on the ‘big picture’. I also attended some official meetings (multi-disciplinary meetings providing first-hand information in another practice context) in the search for multiple sources of information for triangulation purposes.

The effect of the researcher on the interview is not easily controlled. I tried to minimise any effect by asking neutral questions, by using an interview guide, and by asking interviewees to speak from individual experience to minimize researcher effects. During the analysis I tried to reduce researcher bias by keeping the analysis as close to the empirical data as possible. Overall the use of a case study, qualitative data and producing contextualised theory was appropriate for this exploratory research. The results of the study achieved its aim of providing a contextualised analysis of learning in clinical practice in specific technology areas.

Future research could go more deeply into the examination of conceptual relationships which emerged as particularly important during the course of the exploratory study. For example, a closer look at the co-evolution of specific social components of technological systems such as practice traditions (values, common problem themes, and testing procedures) (Constant 1989) and operational routines in clinical settings. A further line of inquiry is to pose the same or similar research questions in another empirical context (for example, the same sector in a different country) and through comparative analyses explore international differences in sectoral ‘technological style’ (Hughes 1983).

8.3. Policy implications

Several policy inferences can be drawn from the findings of this thesis. Current health technology policy in the UK NHS does not adequately acknowledge the importance of technological learning for innovation as examined in the case studies. Health economists advocate the use of cost-efficiency and cost-effectiveness indicators of hospital performance, and making the healthcare sector more like a market in order to improve medical innovation. Science-based healthcare regulation maintains the view that scientific evidence of efficacy is an objective and suitable way to transform healthcare practices and ensure certainty in healthcare outcomes. The importance of creating conditions for the accumulation of technological knowledge, and the inherent uncertainty of innovation in healthcare remain undeclared and unaddressed.

An over-reliance on medical guidance and large-scale government programmes in which rules are specified far away from their integration context can mean that the importance of individual, group and organisational learning processes and structures for innovation is ignored. Similarly, current policies tend to neglect the unpredictability of how technology elements evolve in hospitals. For example, part of the NPfIT programme in the South East region has been the external specification of diagnostic images that may be transported. While this may seem a suitable issue to focus on for the purpose of regional systems harmonisation, outsourcing such a decision to external agents can create operational problems (such as inadequate allowance for the size of diagnostic images that need to be communicated) for hospitals themselves.

Agent involvement in guidance formulation, such as NICE are doing, is important, but it must also be acknowledged that technological change has persistent elements that are uncertain and highly differentiated across organisational contexts and over time. Hospitals may not possess the required resources to meet regulatory aims, and policies need to take into account such differences (not just inputs and outputs), as well as the considerably long time spans that are required to accumulate technological knowledge and improve performance.

In their technological learning requirements hospitals have some important resemblances to firms. For example, they differ from one another in their internal processes of communication, collaboration, knowledge exchange, and mentoring, as well as in their inter-relationships with other organisations (such as with universities and with producers of diagnostic devices). Their knowledge bases, social norms, and connectedness with other parts of the healthcare system are more likely to reveal whether they will engage in qualitative change, than changes in economic incentives, which may bring about quantitative changes without qualitative improvements in services. Policies need to support the creation of an integrated healthcare innovation system that includes hospitals and their broader scientific and technological environments.

The use of productivity targets for hospitals needs to be reconsidered because they obscure and hide the importance of incremental technological accumulation for the development of healthcare services. For example, an increase in CT scans and a reduction in waiting times do not necessarily mean an increase in diagnostic accuracy. Similarly, time lines for externally governed processes such as NPfIT need to be more realistic. Current programmes continuously underestimate the complexity of NHS transition to the IT technological paradigm (Clegg and Shepherd 2007).

In hospitals it is difficult to predict who the end-user of a particular diagnostic technological product or service is likely to be. For example, in the case of CT, the user may be the radiologist or radiographer, while the end-user is the patient. The main elements that in economic theory define the user (for example, choice) are not really present in the hospital context. Similarly, the emergent nature of systems technologies such as the evolution of user groups and the creation of user groups must be acknowledged if innovation is to remain a goal.

Current policies suggest that innovation drivers and outcomes for hospitals can be identified ex ante. This thesis has shown that in the case of diagnostic imaging technologies it is very difficult to see which factors are driving the process of innovation and what their outcomes are because hospitals are complex and open, not simple and closed systems. It needs to be acknowledged that while certain policy instruments may work for some hospitals, they will not work in others. To remedy this, health technology policy targets should aim at creating and sustaining learning conditions for technological accumulation.

8.4. Final conclusions

This study has explored innovation in clinical practice using a framework for organisational learning and technological evolution. In the case studies on learning and change in CT, MRI and PACS practices it was shown that that there exist a number of underlying features of technology such as complexity, cumulativeness, and unpredictability, which shape innovation in hospitals. Policy needs to address the activities required by hospitals to deal with this complexity and learn.

Policies directed at health technologies should take into account that hospitals differ in their practices, norms and resources, and if this heterogeneity is not acknowledged it can cause inefficiencies in the innovation process. In conclusion, medical innovation can be improved by policies that are informed by explicit support for technological learning in clinical practice.

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