NORTH-HOLLAND

Available online at www.sciencedirect.com

SCIENCE DIRECT®

Technological Forecasting & Social Change
71 (2004) 267–285

Technological Forecasting and Social Change

Transforming radiology's workplace: Roentgen marries up with the digital world of IT and the Internet

George Mechling*

Department of Management, Western Carolina University, Cullowhee, NC 28723, USA

Received 21 June 2002; received in revised form 12 September 2002; accepted 17 September 2002

Abstract

Driven by technological developments in both medical imaging and information technology (IT), various institutional, demographic, and economic factors are making the teleradiology model increasingly attractive relative to the traditional radiology model that has been in place for the most part since medical imaging began. The emergence of teleradiology in the medical imaging industry is transforming the way radiologists do their work, and this paper shows why and how this is occurring. It further identifies a variety of issues that have arisen or are arising and their possible resolutions as radiologists engage in integrating their professional work with the new and novel settings (including radiology on-line) that recent developments in combining imaging and information technologies are creating.

Keywords: Teleradiology; Internet; Roentgen

1. Introduction

The American College of Radiology (ACR) defines *Teleradiology* as "*the electronic transmission of images* [in digital form] *from one locale to another for interpretation and/or consultation*" [1]. Teleradiology has come about as a result of combining know-how in

* Tel.: +1-828-227-3600; fax: +1-828-227-7414.
E-mail address: gmechling@email.wcu.edu (G. Mechling).

0040-1625/$ – see front matter
doi:10.1016/S0040-1625(02)00353-0

medical imaging and information technology (IT). This technological innovation is attractive for a variety of reasons that this paper will subsequently disclose. At the same time, however, this innovation is extensively transforming the radiology workplace. This obliges the radiologist to do his/her work in a new and for the most part, currently evolving technological environment. Are there issues that have arisen in this setting to which the radiologist and medical imaging industry as well, must effectively respond to ensure that professional standards cannot only be maintained but raised as well? Are there testable hypotheses one can frame that assess the impacts teleradiology's diffusion is having on the medical imaging industry that have given rise to these issues and the effectiveness of the industry's response to them?

The author has organized this paper into several parts in order to answer these questions. The first part briefly presents the basic teleradiology model and the various technological developments that make it possible for radiologists to implement that model. Part 2 compares the teleradiology model and the traditional radiology model by strategically profiling the two, and discusses how the teleradiology model can organizationally exploit its inherent strategic advantage over the traditional radiology model. It also advances an argument as to why the teleradiology model is potentially attractive to radiologists from institutional, demographic, and economic viewpoints vis-à-vis the traditional radiology model. The third part specifically devotes itself to the integrative issues that arise as radiologists attempt to adapt what they do to a teleradiology environment including an on-line teleradiology environment as well. The fourth and final part of the paper, the conclusion and summary, advances hypotheses to test to determine the effectiveness with which the medical imaging industry has beneficially exploited the innovation of teleradiology and avoided deleterious paths onto which it might have taken the imaging industry.

2. Part 1

2.1. The basic teleradiology model

Teleradiology is a special case of a more general innovation that has occurred from combining imaging and IT, PACS or picture archiving and communication system(s). A PACS is most often found in a single facility. There, it digitizes images, stores them on CDs, tapes, or hard drives and electronically retrieves and transmits them interdepartmentally for review via a local area network (LAN). Teleradiology, like PACS, also involves the digitization of images that are created at imaging stations and sent to or drawn from archives in which they are stored for viewing. In this respect, teleradiology and PACS are virtually identical. The difference between the two is that teleradiology involves the electronic transmission of digital imagery from one locale to another with networks substantially more flexible and less restrictive than a LAN. With PACS, the electronic transmission of digital imagery might be between an imaging center or archive and a radiologist who are at opposite ends of a hospital from each other. On the other hand, with teleradiology, the place where the image is originated or where it is archived and the radiologist who reads it can in principle be

on opposite sides of the globe from each other. Teleradiology's technological capability to decouple imaging centers, archives, and radiologists has economic, institutional, and strategic implications that reach far beyond what a PACS has to offer as merely but a better way to do radiology in-house. Support for this claim will be developed in subsequent sections of this paper, but first it would be well to describe the basic teleradiology model.

It is important to note, however, that the distinction being made here between teleradiology and PACS is now a somewhat artificial one from the users point of view. Anymore, users will use the term PACS to refer to both picture archiving, retrieval, and transmission be it local as well as remote due to advances in transmission technology, particularly web transmission technology. Making such a distinction in this paper between teleradiology and PACS is done merely to emphasize its focus on the significant implications that obtain as a result of possessing the technological capability of generating remote image transmissions.

Before proceeding to that discussion, however, it is appropriate to point out that this paper will center its discussion primarily around teleradiology's technological capacity to effectively and efficiently decouple radiologists, imaging centers, and archival facilities from each other as its unique feature and not so much on the fact that using digital data makes this practical. It is true, for example, that the technological capacity to computer enhance digital images for purpose of diagnoses constitutes substantial advantages in terms of time and cost for teleradiology over the traditional radiology (film) model [2]. Digitization of images also reduces storage space requirements. In addition, digitization eliminates the need for using and disposing of the toxic chemicals that are necessary to film processing and, with that, the costs, problems, and potential hazards associated thereto. These advantages are, however, the same advantages an in-house PACS has over the traditional radiology (film) model as well. So teleradiology is not unique in that regard. Comments about the advantages of digitization with respect to teleradiology can hardly be avoided from time to time in this paper. The reader should, however, not lose track of the fact that the "decoupling" phenomenon in teleradiology and the implications of that is what drives this paper. Hopefully, the author will not have lost track of that fact either.

The basic teleradiology model consists of three major components: a station that generates and transmits images, a transmission network, and a station that receives transmitted images for review [3]. The transmission station consists of scanners, imaging equipment, and modems that generate images, digitize, and transmit them. A transmission network can consist of wire, fiber optics, microwave, and, in some cases, satellites. Telephone companies have in the past, provided and continue to provide the most common transmission networks in the form of dedicated T1 and T3 lines. The transmission network is a key component of any teleradiology system inasmuch as the rate at which it can transmit images has been and continues to be a significant limiting factor in the organization and implementation of these systems. The receiving/image review station consists of some network interface device (most often a modem), a PC (with sufficient image storage space), high-resolution monitors, and an optional hard copy device printer. PC storage is most commonly associated with small, remote locations. These components are then combined into a point-to-point connection consisting of a sending station and receiving/image review station linked together by a dedicated transmission network. A LAN connection is an elaboration of the basic model in

which more than one imaging/sending station is linked to a receiving/image review station. LANs can be interconnected to form a wide area network (WAN). Both LAN and WAN elaborations of the basic model have been realized by different on-going teleradiology operations at the present time (Refs. [2,4]).

2.2. Technological issues and developments

While the basic teleradiology model and its more elaborate variations are conceptually simple and straightforward, a number of technological issues are associated with the implementation of teleradiology systems. The extent to which these issues are being resolved directly impact the rate at which teleradiology is diffusing through the medical imaging industry. Some of these issues have to do with resolution requirements, image transmission mediums, and, to a lesser extent now, equipment incompatibility.

The Food and Drug Administration (FDA) is the federal agency charged with the responsibility of insuring that the use to which digitizing, storing, retrieval, transmitting, and imaging equipment is put meets prescribed resolution requirements (i.e., so many pixels per square inch). Resolution requirements vary according to the different kinds of images that are to be read. Thoracic and orthopedic images, e.g., have the lowest resolution requirements while mammograms have the highest.[1] Thus, not all teleradiology operations may have the technological capability to do mammograms. They lack the technological capability to achieve the image resolution they must have to do diagnostically acceptable work. Consider, for example, Internet transmission. Massachusetts General Hospital (MGH), for example, is capable of transmitting images unrestricted as to type over the Internet, while other teleradiology operations may do only ultrasound and computed tomography in an Internet environment [5]. Thus, a wide range of capabilities continues to exist among teleradiology operations. It is also not uncommon for on-call radiologists to receive images for an initial review at, e.g., their homes. Depending on the severity of what is initially read and what the image is, the radiologist may then remove him/herself to the location originating the image to read its more highly resolved version in order to make a primary diagnosis [6].

Regardless of resolution requirements all digitized images consist of a substantial amount of information. Thus, transmission rates become an issue in terms of time and expense in addition to their resolution. Teleradiology operations make use of a number of different transmission mediums. The Department of Defense (DOD) has, for example, experimented with satellite transmissions of radiographs. Teleradiology operations elsewhere have extensively used dedicated T1 and T3 telephone lines to transmit their images instead of satellite transmission because the latter has proved too expensive to be practical. Despite their use, T1 and T3 lines have several disadvantages. First, they are expensive and represent a substantial investment on the part of a teleradiology operation. Teleradiology operations have sought to circumvent this disadvantage by leasing lines or employing on-demand Integrated Services Digital Network

[1] In addition, resolution requirements may be differentiated for primary and secondary review by a referring physician unless, of course, the referring physician requires the same resolution as the radiologist as is, for example, the case with neurosurgeons and orthopedic surgeons.

(ISDN) circuits wherever possible [7]. Second, T1 and T3 lines "hardwire" sites and centers together denying the operation further flexibility in the way it configures its network in the absence of substantial expense. Finally, transmission times, while reduced, may not be reduced enough to permit the kind of flow needed to comfortably offset the line investment. The development of lossy, lossless, and wavelet compression algorithms[2] including asynchronous transfer mode (ATM) transmission methods appear to have reduced transmission times to more satisfactory levels while not violating resolution standards (Refs. [4,10,11]).

Equipment incompatibility has also impeded the diffusion of teleradiology systems. In the past, original equipment manufacturers (OEMs) supplied service providers with equipment generally incompatible with the equipment other OEMs have supplied. A simple sales strategy motivated the perpetuation of this incompatibility at least for a while. If a salesperson could win an initial sale, this would virtually lock the customer into whatever additional digital imaging equipment that salesperson sold. As long as imaging sites were electronically isolated, equipment incompatibility was a viable manufacturing strategy for the OEMs.

Medicare, Medicaid, and the private health insurance industry have of late begun applying sustained financial pressure on medical practitioners in general in the form of a reimbursement squeeze. This has made it increasingly important to buyers of radiology equipment to have flexibility when evaluating capital investment projects as their radiology equipment ages or becomes obsolete and must be replaced [12]. They must be able to evaluate equipment on the bases of cost and performance needs. A practical strategy for forming or expanding any teleradiology operation is through mergers and acquisitions. Therefore, any thought of electronically linking incompatible equipment sites into a teleradiology system cannot be seriously considered. In response to the need for equipment compatibility, the ACR and National Electrical Manufacturers Association (NEMA) developed and established the Digital Imaging and Communications in Medicine (DICOM) standard in 1993 to which OEMs are to comply [13]. At this writing, DICOM's most current version is DICOM 3.0. However, the standard continues to evolve. To date, however, OEMs remain lukewarm with respect to their complying with DICOM. Their compliance to the standard too often results due to customer pressure and negotiations. Eventually, it would seem, however, as the teleradiology network continues to become denser; OEMS failing to comply with the standard in the manufacture of their imaging equipment will place themselves at a severe competitive disadvantage relative to their rivals.

The prospect of teleradiology transmitting images over the Internet is hardly a novel speculation. At least, nine leading vendors of medical imaging equipment recently "committed significant resources to porting their technologies to Internet protocols" [14]. Imposing issues do obtain, however, with respect to teleradiology using the Internet.

[2] Lossy compression cannot be decompressed with the date recovered exactly as it was before compression because in the very act of compression, data is eliminated. Lossless compression, on the other hand, looks for repeatable data patterns to efficiently encode that can be decoded at decompression. Decompressed data is recovered exactly as it was before being decompressed with a lossless algorithm. Wavelet compression emphasizes edges and details of an image while "glossing" over its smoother portions, thus, selecting what portions of the data to retain completely and what portions to not. See Refs. [8,9] for more on the most appropriate uses of each of these algorithms.

Certainly, there is the ever-present tradeoff issue between transmission speed and resolution quality that needs to be addressed. There is also some concern as to whether or not the privacy of a customer's images can be made secure from tampering and snooping when the Internet is the primary mode of transmission. It would appear that such transmissions are in the opinion of many more secure than when stored in a traditional film library (Ref. [15,p,49]). Furthermore, Dryer [16] notes, for example, that with Transmission Control Protocol/Internet Protocol (TCP/IP) in place a teleradiology operation can construct a firewall on the Internet that prevents outside access. This walled-off portion of the network creates an "Intranet" for the operation. The firewall does not allow external Internet users to gain entry to the operation's Intranet but does not hamper communication among facilities within the Intranet. Thus, a private area within a public space is set aside.

The Internet by its very nature thrives under open standards and "no one has figured out how to make much money by developing a nonproprietary product" [14]. Despite such an issue as this, Internet transmissions are currently being conducted (Ref. [15,p,56]) and, although it is not easily ascertained, it appears that a shift toward increased use of that medium is taking place [17]. Several teleradiology operations were questioned about their operations and Internet usage in connection with this study. Some operations were frankly, quite limited in what they did. Others, however, were not. Consider MGH in the Boston area. MGH is recognized as an industry leader in the development of its teleradiology capabilities including its use of the Internet. Sixty percent of its image traffic is on the Internet originating in four states, the Middle East, Greece, and Poland from rural and suburban hospitals, imaging centers, clinics, and mobile units. MGH is also capable of meeting resolution requirements for these images, including mammograms for which the resolution requirements are the highest. All of MGH's radiologists are subspecialists[3] of whom all now happen to reside in the Boston area although at one time some also resided in London [18]. Solutions depend on the needs of end users. On the one hand, low volume and on-call requirements may only need a point-to-point slow solution. On the other hand, large-volume teleradiology providing primary interpretations will most likely require high-speed lines with flexible distribution systems [16]. In this regard, MGH provides an example of what is possible and anticipates what is yet to come.

It is now possible with the Internet to send large volume teleradiology to any point on the globe as long as the referring site is connected to an Internet service provider. Thus, the Internet provides an ideal solution for integrating the physician demand for wider image distribution and issues of cost and ease of use as well [19].

Technological issues such as those discussed in this section that would thwart teleradiology's use of the Internet certainly exist but if MGH is any indication, these issues do not necessarily constitute formidable enough obstacles to significantly impede the increasing use of the Internet as a connecting medium. This may be due in part to a number of reasons. Technological capabilities in terms of infrastructure are not homogeneously distributed. An increasing volume of Internet transmissions for an increasing number of locales does not need

[3] The term subspecialists refers here to radiologists that specialize in reading certain types of images, such as mammograms or thoracic images as opposed to general radiologists that will read them all.

to rely on standard phone lines but can make use of technologically more efficient cable and satellite systems. Teleradiology networks with their operations in such locales and with sufficient capital can choose to invest in the kind of equipment that makes Internet use practical. There are strong incentives to do this. First, the opportunity to provide greater improved health care is a professional ideal to which the profession is committed. And second, there is monetarily just too much potentially at stake not to seize such opportunities as they come available.

3. Part 2

3.1. The teleradiology and traditional radiology model compared

Lovelock's service marketing typologies [20] provide a convenient way to differentiate the traditional radiology and teleradiology models from each other. His typologies comprehend a number of paired dimensions, for example, nature of the service act—performing actions on one's person or possessions and whether or not such actions are tangible or intangible; customization and judgment—are services customized or standardized and are customer contact personnel permitted to exercise judgment in meeting individual customer needs or not, etc. In all these typologies, five of which Lovelock advances that constitute and define an operation's service bundle profile, the traditional radiology and teleradiology models are virtually identical save for one.

This typology where the two models differ pertains to the method of service delivery. It has one dimension (nature of interaction between customer and service organization) that consists of delivery of services where the customer goes to the server, the server comes to the customer, or the server and customer transact at arm's length. The other dimension (availability of service outlets) consists of single or multiple sites. The radiologist and imaging center in the traditional model are in most cases in close proximity to each other because the images are on film and the films must to be physically conveyed to the radiologist after exposure and development for him/her to read. Therefore, the customer *goes to* where both the imaging equipment and the radiologist who provides the read services are proximally located to receive imaging services. This holds for a PACS operation as well if it lacks the capability to electronically transmit imagery offsite.

Some variations to this traditional model occur. In some locales, it becomes an issue as to whether or not imaging services can be provided in the traditional way. Customers cannot access an imaging facility and a radiologist that are both proximal to each other without great hardship or not at all. To accommodate their needs, the radiologist and imaging site are decoupled and couriers, 'circuit riding' radiologists, and/or mobile units are employed to traverse this gap. Couriers are dispatched to physically convey images to where a radiologist who can read them is located whether this travel involves merely a "cross-town" trip or is a trip of substantial distance. 'Circuit riding' radiologists associated with some service may also be used to frequent image generating facilities not staffed by radiologists, such as a rural hospital. Scheduled mobile unit visits can bring the imaging service proximally to the

customer when no local imaging facility is readily accessible and then performs a quasi courier service by taking the exposures back to where they can be read. Thus, the traditional radiology model tries to occupy all three categories of the interaction dimension of Lovelock's service delivery method typology. It is, however, only most efficient and effective in delivering its services when the customer has ready access to both imaging equipment and a radiologist that are not proximally decoupled. The problem in proximally decoupling the radiologist and the imaging facility where the traditional model is concerned and improvising with couriers, etc., is that there is no technological support for practically re-coupling them in a timely fashion for the sake of the customer.[4] Whether customers wait for imaging and readings or just readings to be done so that consultations can be conducted, the result is the same. The quality of healthcare is less than what it might otherwise be due to delays in diagnoses and possible subsequent treatments, limited opportunities to have more than one radiologist interpret the images generated, and the stress induced by the protracted suspense of waiting for a complete service delivery to be made.

The technical inability to efficiently and effectively decouple the imaging and read functions in providing radiology services impacts more than the delivery of those services to customers. It limits the traditional radiology model in the extent to which it can exploit the advantage of operating multiple sites—the other dimension of Lovelock's service delivery method typology. Services, in general, provide little opportunities for achieving economies of scale (EOS) and economies of scope (EOScope).[5] It is of course possible that multisite traditional radiology operations could generate some scale economies inasmuch as certain activities that would contribute to the overhead at all sites can be consolidated at one. However, such EOS would be minimal because of limited number of activities that could be so consolidated (Refs. [6,21]).

The teleradiology model has the technical ability to decouple the imaging and read functions in providing efficient and effective radiology services to its customers. The customer may still have to go to some location where the imaging service is provided or schedule him or herself for a mobile imaging unit coming through his or his locale but with little doubt such arrangements are more proximate and convenient for consumers in both rural and urban areas. Thus, from the standpoint of Lovelock's service delivery method typology and its customer and service organization interaction dimension, the teleradiology model focuses in part on arm's length transactions inasmuch as the radiologist is not necessarily near where the imaging occurs. This lack of the radiologist's proximity to where the imaging is done is of little, if any, significance as long as timely service can be delivered. However, it is worth noting that direct contact between patient and radiologist may sometimes be desirable and this could constitute a deficiency in the teleradiology model relative to the traditional model in the absence of some acceptable alternative.

[4] It is assumed that decoupling with respect to the traditional radiology model is done because it is cost effective for the radiology operation although such decoupling may not be cost-effective for the customer.

[5] The teleradiology literature advances the claim for the existence of EOS with teleradiology operations especially where multisite configurations are the case. This claim does not, however, appear to have been empirically substantiated at this time or the possibility that it is more precisely, EOScope that is enjoyed.

Given Lovelock's typologies, one would expect similar services to exhibit similar service bundle profiles. A service operation that departs from such a profile does so at its peril unless it possesses an uncommon technological input that enables it to depart from that profile so that it can enjoy competitive advantages over its rivals. Such is the case in teleradiology. Decoupling the radiologist from imaging stations and creating electronically linked multiple receiving/image review sites; a teleradiology operation can enjoy several competitive advantages over traditional radiology operations.

First, teleradiology reduces the lead-time for a customer to receive consultation or diagnosis (Refs. [22,23]). This reduces the period of time a customer must necessarily experience the stress of suspense (an obvious benefit) and in some cases preempts what could become a life-threatening situation. Linking radiologists at different receiving/image review sites in a single organization can also reduce lead-time by evening out the read-load each receiving/image review site in the operation must bear [2]. In this regard, stand-alone teleradiology systems could prove to be of immense benefit to small, rural, and remote hospitals.

Second, teleradiology should lead to better operations performance quality. Reading and interpreting an image is somewhat of an art as well as a science and the opportunity for a misdiagnosis is always present. Misdiagnoses can be time wasting, costly, and health threatening. Linking radiologists in a receiving/image review multisite teleradiology model to do multiple reads of a single image (like second opinions) drastically reduces the possibility of misdiagnoses [2].

Third, teleradiology exploits the *subspecializations* of its participating radiologists more efficiently and effectively than the standard radiology model can do (Refs. [2,24]). *Subspecialization* refers to the specialized skill of reading specific kinds of images, for example, mammograms. Subspecialists can read such images more quickly and accurately than a general radiologist reading the same images—both a cost and a quality issue. Subspecialists of a given kind can work at a single facility, a single facility of a multifacility operation, or be distributed among the various facilities of a multifacility operation without detracting from the accessibility, quality, and efficiency of the service provided because of teleradiology's technological capabilities. A thoracic image or mammogram, once in the system, can be simply forwarded electronically to the first available appropriate subspecialist.

Fourth, digitizing images means that one can computer enhance them to routinely bring out their detail. PACS places this technical capability directly into the hands of the interpreting radiologist. This is simply not an option in film based systems where a technologist at the acquisition workstation would perform these manipulations and print up separate sets of images that might prove satisfactory to the interpretive needs of the radiologist. Most often, therefore, such manipulations are not done because they can logistically stress a system in ways it is not particularly well equipped to meet. Furthermore, films to be interpreted often vary in size. Thus, light masking on film viewboxes can provide too little or too much back-lighting for the films to be interpreted. PACS automatically and correctly applies light masking to all images, which, over the long run, improves interpretation accuracy. Although such a technical capability is not a unique characteristic of a teleradiology system but is a characteristic of PACS, in general, no effectively competitive teleradiology system is without it [15].

Finally, the teleradiology model promises to provide services at a lower operational cost than the traditional radiology model for a number of reasons. A teleradiology operation requires less space than a traditional radiology operation of comparable capacity because it does not have to store and retrieve film within its facility and dispose of toxic chemicals. This is also true of some multifacility teleradiology operations where one facility may store digitized images for the rest of the facilities in the operation to retrieve. Furthermore, many teleradiology operations can outsource to meet their storage needs using facilities designed to specifically perform that service. Also, the opportunity to achieve scale economies with the teleradiology model and enjoy cost advantages therefrom is less limited than with other radiology operations [2]. Finally, the greater production pace the teleradiology model can maintain compared to traditional radiology operations lowers operations cost from a time-value point of view [2]. Such competitive cost advantages have yet, however, to be decisively established. To the extent such cost advantages exist, it is relatively easy to anticipate how they would be exploited. Their exploitation would probably not lead to reduced consumer cost since contractual arrangements and federal/state government regulations generally set and cap the fee structures and revenues would ostensibly stay the same. Rather, inasmuch as these cost advantages would contribute to the relative widening of a teleradiology operation's margins, the operation has more of its margin to allocate to improving consumer services and thus make the operation more competitive service-wise.

3.2. The emergence of a setting conducive to the adoption of teleradiology

Teleradiology as an alternative imaging service delivery method has become increasingly attractive for a number of institutional, demographic, and economic reasons in addition to the strategic advantages it has over the traditional radiology model. Medicare and Medicaid have set stricter limits on what can be claimed for various procedures as well as reconsidering and restricting the procedures for which claims can be made. The same can be said of private healthcare insurance carriers as well who at the behest of their subscribers have confronted the healthcare industry as a quasi-united front using their buying power as leverage to obtain concessions from healthcare practitioners [25]. The increasing determination of payors to restrict the healthcare industry to what it can charge for its services has, therefore, put great pressure on the industry to contain its costs if it wishes to maintain even opportunity cost margins. At the same time, the healthcare industry is also experiencing this squeeze on its margins, it is also experiencing increasing pressure to make its services accessible to more of the population (Ref. [25, pp. 1–4]). Teleradiology provides the technical means for accomplishing these two objectives.

As a consequence of these developments, many radiologists are motivated to attempt increasing the number of reads they do in order to maintain their income levels and offset the revenue lost by the fee structure imposed upon them. Teleradiology provides two ways of accomplishing this. Since rural folk receive imaging services, on average, less frequently than persons in more urban settings, if at all, rural areas constitute a potential market waiting to be developed [26]. Teleradiology has the technological means to effectively and efficiently tap into such markets. Market expansion is not, however, limited to the development of the rural

side of the radiology market. Teleradiology's competitive advantages over the traditional radiology model can lead to the capture of urban market share at the expense of traditional urban radiology operations as well (Ref. [15, pp. 29–34]).

The economic attractiveness of the teleradiology model resides in its potential to improve the efficiency of resource allocation relative to the traditional radiology model while accessing markets previously untapped or those that can be further exploited. Heitoff reports that as a result of electronically linked multiple receiving/image review sites and the subspecialization strategy that such linkages can pursue, teleradiologists of one operation read on average 50 scans per 8-h day. General radiologists on the other hand will average less than two-thirds that rate with a higher probability of misdiagnoses [2]. The higher productivity rates of the teleradiologists combined with increased efficiency in image routing reduce overhead in the form of fewer staff personnel required per unit of output and reduced supply costs [27]. While these reductions may be regarded as good from the point of view of cost efficiency, one should not overlook the fact that in the Lundberg study that jobs that did not disappear were changed and in many cases, radically. The higher productivity rates of the teleradiologists combined with increased efficiency in image routing also lead to higher utilization of fixed investment in the form of equipment and reduced space and storage needs (Ref. [25,pp,1,ndash,4]). Unfortunately, few cost studies of teleradiology operations have been done. Some results have been inconclusive leaving the justification for such operations only on equity and quality grounds [22]. Other results have, however, suggested that teleradiology operations in some aspects possess a distinct cost advantage over the traditional radiology models [28].

4. Part 3: integration issues

The identification and examination of issues that arise primarily for the radiologist but also for administrators, and support personnel as well is organized as follows. First, the results of a study measuring IT's impact on the workplace as it and imaging technology become thoroughly integrated are summarized. Next, issues that arise in many different settings in which teleradiology occurs are presented. Finally, speculations are made as to what it might well mean for teleradiology operations and its teleradiologists when those operations go on-line.

4.1. Integrative dynamics: job and IT in radiography

Lundberg [27] conducted several studies of Swedish hospital radiology departments with respect to work process and staffing requirements over time as radiology operations became more fully networked into the health care system as a result of their increasing use of IT. Lundberg categorizes this integration on the basis of three stages of development: conventional radiology operations, partially networked radiology operations, and fully networked radiology operations. Conventional radiology operations do not have any electronic communication support systems within their operations nor do they have any such systems that

link them to any other hospital operations. Information in the forms of images (films) and documents are manually conveyed. Partially networked radiology operations digitize films and information. Some conveyance of images and documents is done electronically with a necessary number of diagnostic workstations to serve requesting units. Fully networked radiology operations traffic exclusively in digitized images and information both within and without their operations and communicate electronically to the entire population of physicians associated with all the several operations the radiology operation serves.

Lundberg found that in evolving from a conventional through a partially networked radiology operation to a fully networked radiology operation that for secretaries, on average, 100% of their tasks were abolished. On average, 71% of the tasks assisting nurses perform were abolished and 6% of their tasks changed. On average, 40% of the tasks radiology nurses perform were abolished and 20% of their tasks changed. On average, none of the tasks radiologists perform were abolished, but 75% of their tasks were changed. On average, 100% of the tasks file-room staff performed were abolished. The conventional radiology operation involves performing, on average, some 30 different tasks (some of which are repeated) in order to complete imaging services for a patient. The number of tasks in the fully networked radiology operation is drastically reduced, on average, to eight. This occurs as the result of extensive changes in way the personnel in a fully networked operation who remain, perform their work. See Ref. [27] for details.[6]

4.2. Integrative dynamics: radiologists, their practice, and IT

The different teleradiology applications currently found in the imaging industry consist of military, rural, urban, large private practice, and international applications. A number of issues associated with these applications obtain. Some of these are performance issues personnel (particularly radiologists) must confront as they engage in tasks that are now doable as the result of technological advances in both imaging and IT. Selected issues of this kind will be the focus of what immediately follows.

The issues that appear to be most frequently identified throughout the teleradiology literature are licensing, security, workload distribution, subspecialization, virtual interaction, computer skills, physical work demands, and technology selection.[7]

Licensure in the practice of teleradiology has been one of the more vexing issues facing radiologists [15]. The fact that a radiologist is electronically enabled to do reads for customers located in different jurisdictions (states) obliges the radiologist to also be licensed in these jurisdictions to do so. Radiologists not so licensed are of little use to a teleradiology operation because they limit what it can do in terms of the capability it is specifically intended to exploit. This is true of rural and urban applications and university applications to a lesser extent. It is particularly true of large private practices that aggressively market their services

[6] The extent to which costs of retraining and/or or revising compensation schedules for the new sets of skill levels that are required of personnel could well offset the gains in reduced costs due to the feasible sizing down in the number of personnel required to staff the operation. Lundberg does not speak to that possibility.

[7] Almost every bibliography entry touches on at least one of these issues.

wherever opportunities present themselves. They obviously can consider only those opportunities for which they have the resources. Therefore, they must avoid pursuits that such intrinsic limitations as inadequate licensure would thwart. This means that radiologists coming on-board such organizations as well as organizations providing rural and urban services are under increasing pressure to upgrade their qualifications by obtaining licenses to practice in jurisdictions other than those in which they reside.[8]

The security of image transmissions is a topic that is raised as a cause for concern somewhat regularly in the trade literature. Most teleradiology operations, however, appear to be quite secure about the security of their image transmissions. Teleradiologists appear to be of the view that gaining access to a customer's images is more likely when hard copies of those images exist than when they are in digitized form (Ref. [15,p,49]). Nevertheless, HIPAA (the new patient privacy and record security regulation now in force) is now providing standardization to the way required layers of security are being added to the electronic medical record. This further insures that the privacy of one's electronic medical records can be maintained.

Subspecialization, among a cadre of radiologists in an imaging operation, will be increasingly important as teleradiology becomes more commonplace [29]. Decisions as to which subspecialties a radiologist should acquire are of course always best informed by knowledge of market needs. As the subspecialties portion of the market for radiologists proportionately increases, the margin for error in making the optimal decision may narrow. Thus, a radiologist would be obliged to exercise heightened care in deciding which specializations he/she should acquire in order to maximize his/her chance of securing the most gainful employment.

Misreading an image is a serious service quality failure that can be costly to life, health, and professional practice. It is understandable, therefore, that from time to time a radiologist would find it advisable to have additional reads performed by other radiologists to critique his/her initial interpretation. Such a practice drastically reduces the possibility of service quality failure. The frequency of such critiques performed per initial read in teleradiology exceeds the frequency with which such critiques are performed in traditional radiology operations because the practice is a desirable one and can be pursued more efficiently [2]. Thus, teleradiologists will have to collaborate with each other and be willing to bear the opportunity cost of having to pass up their own initial and primary reads to do critiques at possibly lesser compensation or none at all. Furthermore, teleradiologists may eventually also have to be willing to subject themselves on a regular basis to a peer review of their read skills since service checks can be conveniently performed by randomly inserting "test" images for them to read into their work flow. Heitoff suggests something on this sort with quality benchmarking of his staff's interpretive skills by means of blinded surgical correlation studies

[8] Military and international applications, on the other hand, do not place such requirements on their radiologists. Being licensed to practice at all is sufficient in the military given that its jurisdiction is worldwide. International operations seek to exploit potential markets of underserved throughout the world. Consequently, the issue for their clientele is merely that the services received be from someone who is licensed by some professionally recognized licensing authority.

[2]. However, the implementation of such a practice as the random insertion of images into a radiologist's workflow unbeknownst to him or her in order to "test" his or her interpretive skills remains for the time being a daunting administrative professional undertaking even if it might seem a good idea to some.

Being expected to do reads in addition to the initial or primary reads they do in order to assure higher service quality suggests that teleradiologists face greater and more compressed workloads than traditional radiologists. Heitoff [2] notes that each of the teleradiologists in his operation will on an average read 50 images in an 8-h day. This exceeds the count traditional radiologists confront over a longer period of time, typically 40 in 10 h.[9] Furthermore, this higher count presumes that in the case of an operation consisting of more than one read facility, workloads are distributed among the teleradiologists in the various read facilities so as to insure that perishable capacity is minimized and lead times do not exceed an acceptable length [2]. Thus, teleradiologists must be willing to accept an equitable distribution of work between each other where and when appropriate for the sake of the operation's benefit and not necessarily one's own. How collaborating radiologists are duly compensated for their work must be negotiated and legitimated by widespread agreement from the parties affected. Finally, and particularly with urban applications, the "duty" teleradiologists must pull in some operations makes physical demands on them that older teleradiologists are generally regarded as incapable of bearing. According to Lightfoote, "...the stress of working alone entirely by computer and phone through the night can escalate over many nights. Consequently, *nighthawks*[10] must be young and able to tolerate the disruption of normal circadian biorhythms" (Ref. [15,p,32]).

Lightfoote's comment about the physical demands that can be made on teleradiologists and the need for *nighthawks* uncovers another issue that radiologists confront as they enter a teleradiology environment. For want of a better term, the author refers to this issue as a *virtual interaction* issue. Lightfoote's operation consists of 30 radiologists resident in six electronically linked hospitals. During daytime hours, emergency room (ER) physicians receive interpretations done by radiologists resident at their own hospital. During the nonbusiness hours and especially in the late hours of the night and early morning, any one of the operation's radiologists could pull duty as a teleradiologist for the operation's six ERs. Physicians in the various ERs, however, were uncomfortable with interpretations from any one of 30 unseen radiologists, 80% of whom were unknown to the ER physicians at any one time. To ease this discomfort, the number of radiologists working the swing shift was reduced to four to ease the ER physician's burden of getting acquainted with them (Ref. [15,p,32]). Thus, to ameliorate the ER physicians' discomfort with virtual interaction, fewer radiologists

[9] It is important to note, however, that Heitoff is unclear as to what sort of images constitute the 50 per day each of his radiologists can generate in an 8-h day. Are they mammograms, orthopedic, thorasic images, or some mix of these and others? Were they done with ultrasound, MRI, CT, or a mix of such equipment? Both the reader and author have no way of knowing for sure based only on Heitoff's claim. The time it takes to read an image is in good part a function of what the image is and the kind of equipment that generated it. So, Heitoff's claim could be more impressive if it was better clarified.

[10] Lightfoote's name for a group of radiologists selected from an operation's cadre of radiologists to pull swing shift as teleradiologists for the network's ERs.

were subjected to physical stress at a greater intensity than might have otherwise been necessary.

Virtual interaction also brings into being new interactions identified by those involved in both rural and university applications that also challenge radiologists. Franken,[11] when speaking of a university medical center's involvement in teleradiology, notes that it is not uncommon that different expectations across the network can lead to some discord, particularly between the university hospital and the rural hospitals it serves. The source of this discord becomes a bit clearer when Franken suggests, "we can't be arrogant here [at the university] and assume that personnel at the small rural hospitals don't know what they're doing. They just have different health care objectives than we do" (Ref. [15,p,48]). Consequently, Franken attends weekly and monthly staff meetings at sites where the university provides teleradiology services to "obtain a better understanding of . . .[their]. . .si-situations" (Ref. [15,p,48]).

Another issue for radiologists is becoming accustomed to working strictly in a computer environment. Consider how radiologists traditionally do their reads. More often than not, a secretary or clerk in radiology hangs the films up on a backlit screen or viewbox and the radiologist comes into the room to interpret what the films show to him or her. The extent of his/her contact with electronic devices may well be limited to merely reporting what he/she sees into some recording device from which a secretary then transcribes a report. The electronic transmission of images means that radiologists must accustom themselves to doing "soft" (monitor) reads instead of "hard" (film) reads that in appearance are not quite the same and are harder to read (Ref. [15,pp,26,and,41]). They also must acquire skill-reading images while paging through screens if they do not have banks of several monitors by which to sequentially array the images they intend to view. Furthermore, they need to be able to capitalize on the manipulative power of computer technology so as to permit them to enhance the images they read and, thus, improve the quality of their diagnoses (Ref. [15,p,26]). According to some, becoming accustomed to effectively working in a computer environment will become so critical in the near future, that "the radiologist [who is not] will not have a job" (Ref. [15,p,50]).

4.3. Integrative dynamics: internet usage

As presented earlier in this paper, increasing teleradiological use of the Internet has taken place throughout the decade of the 1990s. The expectation is that this use will continue to increase as the innovation further diffuses through the medical imaging industry as technological capabilities for doing so improve and as Internet use becomes economic and strategic imperatives. Many of the current teleradiology applications make only limited use of the Internet, at least for the moment. Others, however, such as MGH, are almost state-of-the-art showcase examples of Internet usage and anticipate what could well become the norm in the not too distant future. The expectation is that the Internet will become an increasingly

[11] Edmund Franken, MD, is a Professor of Radiology at the University of Iowa and involved with its *virtual hospital* including the direction of its teleradiology operations.

important means of image transmission. The implications of increased Internet use for radiologists, support staff, and administrators and how they will do their work are significant in terms of how the imaging industry eventually organizes itself.

Previous configurations, for the most part, have imaging/sending stations tied to one or more receiving/viewing stations by dedicated lines (T1 and T3 and various ISDN systems). Where more than one receiving/viewing station is involved, a WAN configuration exists. Once on-line, however, the Internet itself becomes in principle, the WAN for any teleradiology operation on it. Given such an environment, it is not unreasonable to envision imaging/sending stations operating independently of any receiving/viewing station. Decoupled from receiving/viewing stations because dedicated lines are no longer necessary, imaging/sending stations would be free to transmit their images to the receiving/viewing station of their choice. Factors affecting such a choice would more than likely be based on the cost, quality, capabilities, and turn-around time of the receiving/viewing stations whose read services for which they shop. Such a reorganization of the medical imaging industry and teleradiology itself in such a highly dynamic environment will oblige radiologists to constantly reassess their competitive strengths and take adaptive organizational actions in light of those reassessments. This is not to say that relationships of convenience and stable expectations between imaging/sending and receiving/viewing stations would not develop, but they would be informal relationships not formal ones that hopefully are dictated by the ultimate end-user to whom the services are provided, the healthcare consumer.

5. Summary and conclusion

This paper has identified some technological developments that in combination with various institutional, demographic, and economic factors are in the process of changing the way radiologists now and will eventually do their work. The demand for subspecialty radiologists will increase as the relative demand for general radiologists declines. Radiologists working in a teleradiology environment will also find it necessary to become licensed in many jurisdictions in order to pursue individual practices because the operation to which they belong will more than likely do business across jurisdictional boundaries. Also with the proximal decoupling of read and imaging functions, site-specific credentialing will become a necessity. The need to engage in multiple reads in order to assure the quality of their product will require radiologists in an operation to coordinate their activities with each other even though they more than likely are located in different facilities. Since such multiple reads will likely be the rule and not some mere professional courtesy, maintaining acceptable lead times while not disadvantaging one radiologist relative to the others in terms of primary read responsibility and compensation will be an issue to which all concerned will be sensitive. Furthermore, their competitive environment if anything will become more dynamic requiring the organizations of which they are a part to learn and adapt more rapidly than was ever required of them with the traditional radiology model. They will not only have to contend with health maintenance organizations (HMOs), the government, and other payors, but each other as competitors—something they have always had to do except it will intensify. Finally,

the time of small independent operations will likely come to a close because they will not be able to compete with their cyberspace counterparts.

As a result of work done preparing this paper, however, a number of questions has emerged that can be identified at this time as topics for future investigation and hypotheses testing.

According to Brown [30], few formal cost analyses have been done for any telemedicine operation (Refs. [22,28]). Given the cost advantages, the teleradiology model claims to have over the typical radiology model, additional studies are obviously needed. To what extent does the size of the population served, utilization rates, travel distances, and the relative magnitude of the cost components impacting either model determine where the cost advantages lay? There are also numerous claims made about the scale economies achievable with the teleradiology model. To what extent do scale economies exist? Are economies of scope achievable with the model as well? Do ways of configuring the teleradiology model favor one economy over the other? How do such considerations drive mergers and acquisitions of teleradiology operations?

Questions of organization and operational focus also obtain. How well will teleradiology (the combining of radiology and IT) and those it impacts (radiologists, physicians, consumers, administrators and staff, and the healthcare reimbursement industry-institutional players, e.g., the government and private/public insurance firms) adapt to each other's requirements and needs? Will this integration lead to increased quality in this segment of healthcare? Given the ability of payors to monopsonystically bargain down health care costs charged against them, will teleradiology operations eventually become radiologist "sweat shops" as radiologists clamor to maintain their standard of living by increasing their read rates given that the technological support available makes it operationally possible to do so? If this occurs, how will the quality of service provided be affected? Given the probability of dramatic changes in the jobs support staff perform are there ways of converting to teleradiology and PACS for that matter that can ease the burden and stress of that conversion and improve performance?

Much has been made of the fact that digitization of images radically reduces storage space requirements relative to those where film is used. While this is true, several questions arise given the realization that if the technical capacity to do something exists, it is usually done. The generation and management of digital images are so far quite unencumbered relative to film generation and management. Combining these capabilities with a stakeholder system consisting of, but not necessarily limited to, patients and family, physicians, OEMs and vendors, government, and the legal profession, could and maybe already are leading to an ongoing explosive proliferation of digital images because of the increasing technological empowerment of a system with a mind of its own over which no one stakeholder was or is capable of exercising restraint.

Are vendors, for example, proposing to lease off-site long-term electronic storage for PACs image overflow or to provide redundancy in the event of data loss? This has yet to be determined but would be an indication of the extent to which digital images are being proliferated as well as providing an example of it being encouraged. The cost associated with such storage would then be one monetary manifestation of the economic impact such proliferation is having on the industry's cost structure.

Are there other indications of technologically induced proliferation of digital images? What about the teleradiologists themselves? Certainly, additional reads mean additional compensation and is desirable. However, these persons are professionals and one assumes that filling their time with images of situations they judge to be trivial or unnecessary and energy sapping when time and energy could be devoted to images of more serious situations could be professionally distressing. Thus, there could well be a bit of a dark side to the implementation of teleradiology in terms of a society's institutions that deserves some investigation.

Finally, questions about industry structure and healthcare recipient welfare also surface. Will concentration ratios in the industry increase on a global scale as teleradiology becomes more diffused through the imaging industry? Will the possibility of an increased sense of isolation obtain among the actors involved in the unfolding technological drama given the "virtuality" of their reality? How will the issues these questions would investigate affect the supply of radiologists? Finally, how might an increased use of the Internet as a sort of "wildcard" impact the answers to the above questions? Will a trend toward decoupling imaging operations and read operations lead to increased competition and a subsequent increase in consumer benefits as is so often presumed to be the case given such a development? Or, could it lead to a situation where the images generated become commodities that may or may not go to the lowest bidding read station like a contractor bidding on a construction job depending on what is to read and the backlog of work already in the queue [31]?

These questions focus on issues the introduction of technological change has brought about in an important industry. The study of such issues and their connection to technological change is interesting in its own right. These questions are, however, hardly mere academic questions. They are far more than that. They are also quite personal. We all will eventually face health issues, some of us sooner than others—in the midst of life and certainly, at the end of it. Teleradiology could easily have a role to play in dealing with those issues. The effectiveness and grace with which that role is played can no doubt be anticipated as a function of the sorts of answers to those questions posed in the paragraphs immediately above one uncovers.

References

[1] A. Allen, Teleradiology: I. Introduction, Telemed. Today 4 (6) (1996) 7.
[2] K. Heitoff, Reinventing the wheel, Decis. Imaging Econ. 11 (2) (1998) 12–16.
[3] C. Ruggiero, Teleradiology: a review, J. Telemed. Telecare 4 (1) (1998) 25–35.
[4] G. Wachter, N. Brown, A. Allen, Teleradiology service providers, Telemed. Today 4 (6) (1996) 14–15, 30.
[5] J. Thrall, Meeting stakeholder expectations in radiology through internet PACS, Decis. Imaging Econ. (2001) 5–7 (December Supplement).
[6] Market Assessment Report: Teleradiology, Sun Health Alliance, Charlotte, NC, 1995.
[7] D. Schwartz, Techtalk, Telemed. Today 5 (5) (1997) 28–32.
[8] J. Ladino, Data compression algorithms, www.ccs.neu.edu/groups/honors-program/freshsem/19951996/jnl22/jeff.html, 1996.
[9] M. Orchard, I. Daubechies, R. DeVore, R. Sharpley, T. Yu, Image compression, www.waveletidr.or/compression/compression.html, 1999.

[10] M. Goldberg, Application of wavelet compression to digitized radiographs, Am. J. Roentgenol. 163 (1994) 463–468.
[11] H. Huang, Asynchronous transfer mode technology for radiologic image communication, Am. J. Roentgenol. 164 (1995) 1533–1536.
[12] L. Aron, To merge or to acquire, Decis. Imaging Econ. 11 (2) (1998) 26–31.
[13] S. Horiil, F. Prior, W. Bidgood, C. Parisot, G. Claeys, DICOM: The Value and Importance of an Imaging Standard, Radiological Society of North America, www.rsna.org/practice/dicom/index.html, 1997, Pennsylvania State University.
[14] A. Allen, Cutting edge Internet teleradiology from 9 leading vendors, Telemed. Today 6 (3) (1998) 20–25.
[15] C. Jaffe, T. Harle, Handbook of Teleradiology Applications, Radiological Society of North America, IPC Communications Services, St. Joseph, MI, 1997.
[16] K. Dryer, Enterprise-wide image distribution, Decis. Imaging Econ. (2000 January/February) 3–4, 17 (Supplement).
[17] A. Gropper, The internet as a disruptive technology, Decis. Imaging Econ. (2001) 3–4 (December Supplement).
[18] J. Bernard, Response to an Inquiry by this Paper's Author, Massachusetts General Hospital, JBERNARD@PARTNERS.ORG, 25 March 2002.
[19] G. Boland, Internet image distribution, Decis. Imaging Econ. (2000) 4 (January/February Supplement).
[20] C. Lovelock, Classifying services to gain strategic marketing insights, J. Mark. 47 (2) (1983) 9–20.
[21] S. Dwyer, B. Stewart, J. Sayre, J. Honeyman, Wide area network strategies for teleradiology systems, Radographics 12 (3) (1992) 567–576.
[22] P. Halvorsen, I. Kristiansen, Radiology services for remote communities: Cost minimization study of telemedicine, Br. Med. J. 312 (1996) 1333–1336.
[23] S. Uldal, J. Stoemer, T. Sund, Considerations on time and use: Teleradiology experiences from Northern Norway, Telemed. Today 5 (5) (1997) 26–27, 39.
[24] E. Franken, K. Berbaum, W. Smith, P. Chang, D. Owen, G. Bergus, Teleradiology for rural hospitals: Analysis of a field study, J. Telemed. Telecare 1 (4) (1995) 1995.
[25] World Medical Image Management Markets, Frost and Sullivan, Silicon Valley, Mountain View, CA, 1994.
[26] E. Franken, K. Berbaum, Subspecialty radiology consultation by interactive telemedicine, J. Telemed. Telecare 2 (1) (1996) 35–41.
[27] N. Lundberg, How network technology changes the work process at a radiology department, http://www.internet.adb.gu.se/publications/3/pub.html, 1997 (IRIS 19 Publication).
[28] T. Bergmo, An economic analysis of teleradiology versus a visiting radiologist service, J. Telemed. Telecare 2 (1996) 136–142.
[29] A. Allen, J. Patterson, Annual survey: Teleradiology service providers, Telemed. Today 5 (5) (1997) 24–25.
[30] N. Brown, 20 selected teleradiology references, Telemed. Today 4 (6) (1996) 16–17, 28–30.
[31] C. Proval, The convergence factor, Decis. Imaging Econ. 13 (7) (2000) 5 (November/December Supplement).

George Mechling is an Associate Professor of Management in the College of Business at Western Carolina University in Cullowhee, NC 28723. Professor Mechling teaches courses in quantitative methods, production and service operations management, and management of technological innovation. His published research has consistently dealt with issues involving the interaction between organizations and their application and adoption of continuous and disruptive technologies.