Perspectives

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# Reinventing Radiology in the Digital Age Part I. The All-Digital Department[1]

For more than 25 years the vision of the all-digital radiology department has been a beacon guiding radiologists, computer scientists, and industrial developers in creating the equipment and the standards necessary to achieve this goal. Many all-digital or mostly digital radiology departments exist today (1) and serve as testimonies of the many breakthroughs that have been required to meld historically disparate imaging and information systems together under common standards, the most important ones being the Digital Imaging and Communications in Medicine (DICOM) (2,3) and Health Language 7 (3,4) standards.

There has not been a crisp point of demarcation between the technologic eras in radiology; no single point in time delimits the transition from the analog film hard-copy image era to the digital image era. The new methods and concepts that now shape the digital era of radiology began to be woven into the mix years ago, long before established ways of doing things could be feasibly abandoned. In particular, the demand for film hard copy on which to record and view images will persist, largely because of factors that are beyond the control of radiologists, such as the viewing preferences of the referring physician community. This is to be expected; after all, here and there, the horse and buggy still ply the same roads as the automobile.

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## The All-Digital Radiology Department: Why Did It Take So Long?

Although it seems obvious today in retrospect that the practice of radiology was destined to become digital, this advancement has been more than half of a century in the making since the time the first digital computers were invented in the 1940s (5). When astronauts from the United States landed on the moon in 1969, a feat largely enabled by computerized control of the Apollo spacecraft, there still was not a single clinically important application of computers in the field of radiology.

Cost is one obvious reason for the extended period between the recognition of the theoretic potential value of digital imaging and the substantial implementation of this technology. My first job position after high school was that of a FORTRAN IV programmer for an IBM 7090 (IBM, Armonk, NY) computer system. This monumental device—it occupied its own room—was the most powerful computer of its day and cost around $3 million in 1960. Today, the comparable cost would be more than $19 million, based on the interval change in the consumer price index (6). Initially, the cost of IBM 7090 systems effectively restricted their use to a limited number of high-value computational applications.

Another reason for the long interval before the notable development and use of digital imaging systems, apart from their high cost, was the fact that the computing power in 1960 did not come close to meeting the functional requirements of medical imaging. The IBM 7090 system (7) had 32 000 10-bit words of core memory. In comparison, the memory required to hold a single radiograph at the level of spatial resolution required for clinical applications is on the order of 5 MB. Moreover, there were no network connections: On the system with which I worked, all programs and data were entered via 80-column punch cards or magnetic tape.

Given the enormous feasibility gaps in the price and performance of early computer systems, the dawning of the digital age in clinical radiology practice was destined to be incremental. The first substantial wedge occurred with nuclear medicine in the late 1960s and the early 1970s. With the inherent spatial resolution of nuclear medicine scans at that time, a matrix of only 64 × 64 pixels by 8–16 bits per pixel or about 4–8 kB per image was required. Nuclear medicine computer systems (8) with core memory sufficient to enable scintigram acquisitions became available commercially, and nuclear medicine led the rest of the imaging world into the digital age for clinical applications a whisker ahead of conventional computed tomography (CT). Nuclear medicine applications were accelerated in the early 1970s by the invention of gated radionuclide ventriculography (9), which could be performed only with the use of computers. This technique enabled one to view movies of the beating heart throughout the cardiac cycle, an astonishing breakthrough for the time.

The pieces of the puzzle started to come together faster after CT was introduced in the United States in 1973. This imaging method inherently required a computer, and by the end of the decade, leading institutions in this country had computer systems for both nuclear medicine and CT applications. Radiologists were becoming used to the idea of working with computers, and the specialty of radiology began to be regarded with a certain cachet in medical circles as "high tech."

The invention and clinical implementation of magnetic resonance imaging in the late 1970s and early 1980s, of digital subtraction angiography in the 1980s, and of computed radiography in the middle 1980s and the adaptation of ultrasonographic systems for digital image capture put the potential to acquire any kind of radiologic image in digital form within reach by 1990. However, the development of systems that were sufficient for the direct digital capture of radiographs and mammograms took another decade. Thus, roughly 25–30 years elapsed from the introduction of the first practical clinical applications of digital imaging to the general availability of acquisition devices that were satisfactory for all clinical imaging methods.

The development of the networks, archives, workstations, and image management systems necessary for the practical and affordable clinical realization of an all-digital radiology department proceeded in parallel with the development of various image acquisition systems. The acronym PACS, which stands for picture archiving and communications system (3), had become common parlance in radiology circles by the late 1980s and is used as an encompassing term to refer to image management systems. The term *mini-PACS* was introduced to refer to single-modality applications. The rapid development of the components necessary to make PACS financially and operationally feasible was not principally driven by the medical marketplace but rather by the enormous demands of other commercial and consumer sectors for higher-performance, lower-cost computing power and associated workstations, networks, and archives.

A key milestone in the development of PACS was the establishment of a collaboration between the American College of Radiology and the National Electrical Manufacturers Association (3) to work together in developing a common standard for using medical images. The first American College of Radiology–National Electrical Manufacturers Association standard was published in 1985, but it was not until the third iteration (DICOM 3.0) was successfully demonstrated at the 1993 and 1994 meetings of the Radiological Society of North America that satisfactory networking capability and systems interoperability were achieved and were sufficient to persuade manufacturers of both imaging equipment and PACS to follow a common standard rather than use their own proprietary image-handling formats.

Along with the development of PACS and digital acquisition devices, the third key element required to implement all-digital radiology departments was the design of robust radiology information systems (RIS) to manage the complex data regarding patients and the operational and business functions of radiology—namely, patient identification, procedure scheduling, report generation, and billing. The RIS is the information management backbone of the all-digital radiology department. Although RIS devices do not require the ultra-high-performance computing power that is necessary for digital imaging systems or PACS, they still have been challenging to design from the standpoint of functional specifications and challenging to integrate with the other components of an all-digital department.

In the early 1990s, indecision among major incumbent vendors to the radiology community regarding whether to build PACS or even comply with DICOM standards was a factor that held back the progress toward the practical realization of all-digital radiology departments. The commitment to build PACS was something of an orphan project among the business plans of some major vendors to the radiology community, and at the time it was not at all clear which sector or sectors of the vending community among film companies, imaging equipment manufacturers, and RIS suppliers were the logical candidates to develop and sell PACS. Of the three major U.S. film vendors in the middle 1990s, two failed to execute a successful transition into the digital age and were forced to leave the business entirely. All of the four largest sellers of imaging equipment eventually developed PACS but were not early leaders, and none of the long-time RIS vendors has become a major contributor to PACS development. Apart from slowing the advance to all-digital departments, the lag in interest from established commercial players opened the door to numerous start-up companies and caused the commercial market for PACS to be heavily populated by new vendor entries.

## Systems Integration: The Achilles' Heel of the All-Digital Radiology Department

The biggest surprise during the assembling of components for all-digital radiology departments has probably been the realization that "all digital" is not synonymous with "all integrated." Although the individual digital components may be compliant with common standards, this compliance is far different from being fully integrated with each other. Since the components of an all-digital radiology department typically come from a number of vendors, each department is left to a greater or lesser extent with the problem of being the systems integrator. Moreover, in its original vision of an all-digital radiology department, the radiology community did not adequately anticipate the implications of having an all-digital health care enterprise or the monumental effect that the Internet would have on system requirements in radiology.

The level of integration within radiology departments is improving but still challenging. One useful way of understanding this issue is to simply follow the work flow as an examination is performed. Let us start by assuming that an examination has been scheduled in the RIS, with all the appropriate patient identification data having been input and all the desired study parameters having been designated. The first pivotal issue is whether there is a mechanism for transmitting the information in the RIS as part of a work list to the designated imaging device. Until just a few years ago, the software systems that controlled imaging devices were not designed to accept work lists, and there is still a substantial base of legacy equipment that cannot be directly integrated with an RIS. In this situation, a work list of the patient information for each imaging device must be printed out from the RIS. This list is typically given to a technologist, who must then re-enter the information at the device console before performing the examination. The estimated percentages of keystroke errors that occur during this step are as high as 15%–20% (3) on a per-patient basis.

The consequence of patient identification errors during the acquisition step is the inability to reconcile the patient data that are being downloaded to the PACS with the data in the RIS, and this failure to reconcile data leaves the imaging examination in a potentially irretrievable state until the miss-entry is corrected. Moreover, the awkwardness of establishing a real-time data exchange between DICOM-based PACS systems and Health Language 7–based RIS systems has necessitated the use of additional costly software modules in some PACS to handle the reconciliation of patient identification data (3). At Massachusetts General Hospital, before we replaced our pre-PACS-era imaging equipment with equipment that could accept work lists from our RIS, we encountered an average of 90 cases per day—out of a total of 1800 acquired cases per day—that required some kind of correction. We required a full-time employee to track down errors and perform the corrections.

Another common cause of discontinuity in work flow is the lack of integration between the PACS and the transcription system. Ideally, patient records should be automatically queued up on the transcription system as an examination is selected from a PACS work list. Without this feature, the radiologist must select or identify each case twice: once on the PACS and once on the transcription system. The inability to automatically queue up patient demographic data on transcription systems places an extra burden of work on system users and creates another potential source of error in matching reports with the correct patients. Now that the radiology community is truly committed to an all-digital practice environment, it should not tolerate these kinds of systems integration deficiencies, which are caused by the stand-alone specifications of components supplied by different vendors. The implications in terms of both quality and cost are too important.

Gaps in the integration of digital systems into radiology departments and into the information systems of host institutions also can limit the benefits of an all-digital radiology department. Integration of the hospital information system with the RIS is crucial. Each institution ideally should have a single "source of truth" for all patient registration data for the same reasons related to reconciling and retrieving of patient records discussed earlier. Without the technical capacity or the operational discipline to use only one master patient index as the source of truth, the consistent identification of patients between systems can rapidly deteriorate, rendering the institution a "Tower of Babel." Departments that have initiated PACS without either an RIS or the integration of the RIS with the hospital information system have quickly learned that imaging examination data simply disappear into the PACS owing to typographic errors and other name and registration number discrepancies between systems.

Another very basic integration factor that has prevented many institutions from reaping the operational and cost benefits of having an all-digital radiology department is the inability to ubiquitously share images with referring clinicians throughout the enterprise and to have images available in high-use clinical care units, including operating rooms and intensive care areas. This image-sharing capability typically hinges on three factors: a PACS design that supports enterprise-wide image distribution, the presence of suitable high-bandwidth hospital networks, and a large enough base of digital-image-viewing workstations that are installed outside of the radiology department.

Before Internet availability and the associated communication protocols made it practical to think otherwise, the focus of design for PACS was at a departmental rather than enterprise level. Consequently, many early PACS did not have the functional capability to readily send images to workstations or personal computers that were not a part of the self-contained departmental system. By the same token, before the advent of the Internet and the associated acceleration of distributed computing applications, most institutions did not have electronic medical records or other applications that required either high-bandwidth networks or sophisticated workstations for physicians. Without enterprise-wide integration of image distribution, some important benefits of PACS, such as lower operational costs due to reduced numbers of images printed on film and the ability of multiple users to view an imaging study simultaneously, are simply not possible.

At Massachusetts General Hospital, we were fortunate early on because the hospital administration, as part of an electronic medical records initiative, decided to provide each faculty member with a personal computer suitable for image viewing and had upgraded the hospital networks a year or so before the installation of a PACS, which included an enterprise-wide image distribution system, in 1996. These advancements allowed us to aggressively reduce our film use and costs and to demonstrate a positive return on our investment in the PACS. If the three components that enabled us to electronically integrate information within the clinician community—an enterprise-wide image distribution system, high-bandwidth hospital networks, and ubiquitously distributed workstations—had not been in place, we would not have realized a cost savings from reduced film use or the same gains in departmental and institutional operating efficiency. Failure to sufficiently integrate departmental and institutional systems continues to blunt the full benefits that are achievable with an all-digital radiology department.

## Early Benefits of First-Generation All-Digital Radiology Departments

Despite ongoing limitations in the integration of digital systems within radiology departments and between radiology departments and their host institutions, the early benefits of working in a digital environment are clear. From an operational perspective, the management of image data, the historical "bete noire" of radiology, has vastly improved. When we installed our current RIS at Massachusetts General Hospital in 1988, we learned to our astonishment and embarrassment that about 10% of the examinations being performed in the department were never reported by a radiologist. Records of some examinations were simply disappearing into the bowels of the institution, and without the RIS we had had no practical way of tracking them. After years of intensive effort with the RIS, during which we often combed the file room for delinquent cases, we reduced the percentage of unread cases to about 3%–4%. In the current PACS era, the number of unread cases has become miniscule. However, active data management is still required owing to limitations in automatically assigning a small number of imaging studies to the correct subspecialty work list prospectively for interpretation. The quality-of-care issues and the financial liabilities associated with lost or unread imaging studies have largely been resolved in the all-digital era; these resolutions represent a huge win for patient care and radiology.

The ability for multiple physicians and other caregivers to simultaneously access the same images from different locations has eliminated a historic element of contention and dissatisfaction among radiologists and their colleagues. An "either-or" decision with regard to the interpretation of an imaging study no longer has to be made before the study is released for urgent use to the operating room or emergency department. In addition, the corollary capability for remote viewing of images from home or elsewhere is a great benefit to radiologists and their clinical colleagues; it speeds patient care decision making and saves unnecessary travel time. Benefits in terms of both quality of patient care and quality of practice life are realized.

The productivity of radiologists in interpreting imaging studies on soft copy (digitally) versus hard copy (film) has been a subject of great interest in the digital age. The results are now evident, and soft-copy viewing is the undisputed winner (4,10–12). Although it is not possible to establish a one-to-one relationship between soft-copy viewing and increased productivity because of confounding factors other than soft-copy viewing, it is striking that the results of surveys (11,12) of radiologist productivity in both private and academic practices conducted during the past several years have shown increased productivity with digital image viewing.

Numerous other benefits have accrued from the first-generation implementations of all-digital radiology departments and all-digital radiology practices. Clinicians can access images and reports far more efficiently than ever before. Because technologists can assess image quality without having to leave their patients because films need to be developed, safety is improved. In addition, they no longer have to lug around stacks of cassettes, and, thus, the quality of their work life has improved. Radiologists can use a host of tools on workstations to adjust image contrast, rapidly measure structures, and make annotations. Teaching files and research databases can be readily assembled. The list could go on, so it is amusing for those of us who have lived through the birthing pains of evolving from a no-digital to an all-digital environment during the past 30 years to hear neophyte radiologists complain that "the PACS seems a bit slow this afternoon" as they blithely zoom through stacks of CT scans, reformat images into three-dimensional displays, apply quantitative measuring tools, fuse functional and anatomic data sets, and then send voice-generated reports in real time to their clinical colleagues!

## Conclusion

The magnitude of accomplishments to date that have been achieved with all-digital radiology departments has been enormous. Enumerable hurdles have been overcome and have led to improvements in quality of care, gains in productivity, and a myriad of other collateral benefits. Radiology, in fulfilling its digital initiatives, has become a leader in implementing the kinds of system solutions that have been identified by the Institute of Medicine as necessary to address the lurking gaps in health care quality that result in unnecessary patient morbidity and mortality (13–15).

If the progress stopped now, the story of the digital transformation of radiology would be compelling by any measure. But the story has really just begun: We now recognize that the original vision of an all-digital radiology department, as important as it was, was incomplete and really only a prelude to the substantial opportunities awaiting the field of radiology on the other side of its digital divide. It is now obvious that gaining the full benefits of an all-digital radiology practice will require better integration of systems within radiology departments, better integration of systems between radiology departments and their host institutions, the re-engineering of a wide variety of radiologic work processes, and the invention of entirely new applications and approaches to radiology that were unimaginable before digital systems were in place. To be a leader in radiology, an all-digital environment must be assumed and the question must become, "What else are you going to do with it?"

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