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Overview of Medical Imaging Informatics

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8.1 Introduction

Medical imaging informatics is a relatively new multidisciplinary field arising out of the combination of biomedical and clinical informatics with imaging science. Advances in informatics, including further development and integration of digital imaging modalities, *Picture Archiving and Communication Systems (PACS)*, healthcare information systems, advanced image processing and other information technology tools, will play a central role in bringing about the rapidly approaching era of filmless, paperless, and errorless imaging in medicine.

8.1.1 Overview of Imaging Informatics

The term *informatics* refers to the discipline that deals with the collection, classification, storage, retrieval, and dissemination of recorded knowledge and is treated both as a pure and as an applied science. Major informatics functions include knowledge representation, extraction and structuring, information distribution and retrieval, data management architectures, and communication of knowledge and information. It also includes efforts to understand the impact that information technology has on people, the development of new uses of that technology, and its application in the context of other fields (Indiana University 2005).

Biomedical informatics is the interdisciplinary science that deals in particular with biological and medical information, its structure, acquisition, and use (Vanderbilt University 2005). It is grounded in the computer, information, cognitive, and social sciences, and in statistics and engineering, as well as in the clinical and basic biomedical sciences.

The subfield of *clinical* or *health informatics* occurs where the health sciences and the information sciences come together. Its focus is on the skills, tools, and systems that enable the sharing and use of information to promote health and to deliver health care, and it includes the study, invention and implementation of structures and algorithms to improve the understanding, management, and communication of medical information (UK Health Informatics 2005). Its objective is to coalesce the necessary data, knowledge, and tools in the clinical decision-making process at the time and place that they are needed to address a specific, perhaps unique, medical situation—whether it involves a single patient at risk or a population.

In general, a primary role of informatics is to attempt to answer the question “how, what data is delivered where and when.” In the context of medical informatics, “What?” may refer to the patient’s entire medical record or a subset related to the current illness, laboratory values, clinical history, allergies, etc. “What” may also include general biomedical knowledge, pharmaceutical references, practice standards, the current literature, and so on. “How?” relates to the way in which the data or information is represented: as an image, for

example, or a graph, a value, a color, or a sound. “Where?” reflects the location of data delivery—to the operating room, the intensive care unit, a radiology reading room, or on a personal digital assistant hand-held device at the point of care. “When?” refers to the time or point in a process at which data is to be delivered—immediately upon request, for example, or only when the test result is abnormal. It also refers to the length of time that data persists at a location—such as for the life of the patient, as part of the legal medical record, while the patient is hospitalized, or until it is viewed by the requestor.

8.1.2 Biomedical Imaging Informatics

Biomedical imaging informatics is a composite of the biological, clinical, imaging, and information sciences, along with medical physics and engineering. The biological sciences include bench sciences such as biochemistry, microbiology, physiology, and genetics. Health services science encompasses what is often referred to as bedside research and includes outcomes and cost-effectiveness studies and public policy. The intersection of bench and bedside research is called *translational research*, and biomedical imaging informatics research often falls into this category.

Imaging informatics touches every aspect of the imaging chain from image creation and acquisition, to image distribution and management, to image storage and retrieval, to image processing, analysis and understanding, to image visualization and data navigation. Concepts in imaging informatics will enable medical imaging to achieve filmless, paperless, and perhaps even errorless operations, ultimately reducing cost, increasing efficiency, and improving the quality of healthcare.

8.1.3 Major Areas of Research and Development

Major research topic areas in imaging informatics span a spectrum similar in scope to those of mathematics, physics, and engineering. They include scientific endeavors ranging from theoretical model construction to the building and evaluation of applied systems. Consistent with a broad definition of imaging informatics, research can focus in the areas of image creation, image management, image display, technology assessment, knowledge management, and evidence-based imaging.

Some researchers are examining methodologies for improving or expanding imaging modalities, and for measuring and enhancing image quality. Others who focus on image management design, develop, implement, and assess the use of information systems in formatting, distributing, storing, and retrieving imaging information in the clinical, research, and teaching environments. Still others direct their efforts on the development of standards, databases and integration, storage and distribution architectures, and point-of-care delivery devices. The ultimate aim of all these activities is to provide

an efficient and reliable filmless and paperless digital medical imaging operation.

The spectrum of imaging informatics research spans everything from methodology-based basic informatics research, to applied informatics research, design and development, engineering evaluation, and clinical evaluation. Methodology or basic informatics research encompasses efforts in content-based image retrieval, image processing, decision support, and evidence-based imaging. Applied informatics research examples include the exploration of new graphical user interfaces, unique data visualization techniques, and computer-aided detection. Design and development research involves work on standards, benchmarks, and technical guidelines. Engineering evaluation assesses the information systems themselves, while clinical evaluation examines workflow management and health outcomes as a result of the utilization of information technologies.

Research on various aspects of medical image display covers software and hardware devices for image presentation, graphical user interface design, image processing and analysis, computer-aided detection, and three-dimensional visualization, as well as aspects of visual perception and image quality. Data mining and decision support tools to assist in reducing medical errors are also active areas of study, as is technology assessment, including outcomes research and cost-effectiveness studies.

8.1.4 Challenges

Scientists specializing in the evolving field of medical imaging informatics are professionals involved at the intersection of information science, imaging technology, and healthcare. In contrast with other scientists who tend to practice one type of research, imaging informaticists have historically been engaged in all aspects of the field, including the research, development, and evaluation side, as well as in studying and teaching the theoretical and methodological basis of data applications and information systems in medicine. This has arisen largely because early on, scientists in the field were challenged by the hardware and by technical limitations. Research thus focused on overcoming these limitations. Today with many of the hardware obstacles resolved, these same scientists are now able to investigate the application and impact of informatics concepts and tools in the clinical arena.

Several special challenges exist, as is often the case for newly established fields of study. Imaging informatics research is often of the translational type requiring a multidisciplinary team effort. There is a need to embrace a collaborative culture, often a foreign concept in other fields of research. Historically, traditional research funding sources have not targeted translational research and often work in this area has been overlooked by academia in the past. This attitude is beginning to change, however, and more sources of research support are becoming available.

Imaging informatics research is difficult to carry out because it requires access to a sophisticated technology infrastructure and often has high initial developmental costs. It is often necessary to perform informatics research and testing in the clinical arena, further complicating the implementation, validation, and impact assessment process. In addition, the imaging informaticist requires a unique educational and training background covering several very disparate scientific fields of endeavor. Research in the field also requires a clinical acumen as well as an expert understanding of technology.

Today's imaging informaticists have come from a wide variety of fields including those trained in medicine with an interest in computing technologies, those trained in computer science, engineering, and physics with an emphasis on applications in healthcare, as well as those established in other fields entirely such as the aerospace, entertainment, and business industries. Today a few fellowships exist for training medical imaging informaticists of the future. In time perhaps more formal educational programs will be available to train scientists in this new field.

8.2 Picture Archiving and Communication Systems (PACS)

A PACS is a medical image management system, or a collection of electronic technologies, that enable the digital filmless imaging department. By means of a PACS, images can be acquired from any of a number of modalities, stored and retrieved, transmitted, as well as interpreted digitally on soft-copy display.

8.2.1 Historical Overview

In the analog world, even images that were created by inherently digital modalities are printed to film for display on a light box or alternator, and for image archival as the legal record, where films are stored in large rooms of filed film jackets. Imaging examinations on film must be transported from one location to another by foot or mail for viewing by radiologists and referring clinicians. Films are retrieved and re-archived manually by film library personnel. With a PACS, images are acquired as digital computer files, stored on computer disks or other digital media, transmitted across computer networks, and viewed and manipulated on computer workstations.

The benefits of PACS are numerous and include rapid and remote data distribution within and between health care enterprises. Digital archival is more permanent than film with regard to media degradation, and does not suffer the problem of lost films. A PACS gives multiple users in distinct locations simultaneous direct access to the same examinations. And the digital nature of the data allows for image manipulation and processing, which may lead to enhanced visualization of radiological features and improved interpretation of imaging studies. A PACS can lead to more expedient

care, more efficient workflow, greater cost-effectiveness, and overall higher-quality care.

PACS have come about via a convergence of technological and economic factors, including a dramatic improvement in computing power, the advancement of network capabilities and storage devices, the development of imaging standards, and systems integration. PACS applications posed serious challenges to computer hardware in the 1990s. Today PACS applications are only a subset of what computers can do. PACS and filmless radiology are now considered by many to be a better way to carry out medical imaging and may in fact be necessary. The number of images per study has grown beyond what is feasible for viewing on film. However, only about 20% of healthcare enterprises have implemented PACS.

Early PACS

In 1979 the earliest paper proposing the concept of a PACS was published by Heinz Lemke, entitled “Applications of Picture Processing, Image Analysis and Computer Graphics Techniques to Cranial CT Scans” (Lemke et al. 1979). In the early 1970s, M. Paul Capp, Sol Nudelman, and their colleagues at the University of Arizona Health Sciences Center organized a digital imaging group that developed the first digital subtraction angiography (DSA) device that was the precursor to what has become modern clinical digital imaging. They introduced the notion of a “photoelectronic radiology department” and depicted a system block diagram of the demonstration facility they had built (Capp et al. 1981).

Samuel Dwyer III predicted the cost of managing digital diagnostic images in a radiology department (Dwyer et al. 1982) and along with Andre Duerinckx, organized a landmark conference at which the acronym “PACS” was coined. This meeting sponsored by the International Society for Photo-Optical Engineering (SPIE) and titled “The First International Conference and Workshop on Picture Archiving and Communications Systems (PACS) for Medical Applications” was held in Newport Beach, CA, January 18–21, 1982. It continues today as the Annual SPIE International Symposium on Medical Imaging. Two panel discussions “Equipment Manufacturers’ View on PACS” and “The Medical Community’s View on PACS” that took place at the first conference were captured in the proceedings (Duerinckx 1982). There was talk of linking imaging modalities into a single digital imaging network and the recognition that for this to be practical, standards would be required. Steven Horii participated in those beginning discussions and has been instrumental in bringing about the creation and implementation of a standard for digital medical imaging, now known as the *Digital Imaging and Communications in Medicine* (DICOM) standard.

Numerous PACS pioneers have brought digital medical imaging to its current form through their efforts in research and development, design, implementation, testing, analysis,

standards creation, and education of the technical and medical communities. In 1982 and 1983, Dwyer oversaw construction of what is often considered the first PACS. In 1983, H. K. Bernie Huang published the first of many papers detailing the PACS efforts at the University of California Los Angeles (UCLA), which culminated years later in a clinically operational, filmless radiology department (Huang et al. 1983). G. James Blaine and R. Gilbert Jost at Washington University in St. Louis, MO focused their efforts on the development of utilities enabling PACS research and development (Blaine et al. 1983). In the mid- to late-1980s, several researchers described their prototype PACS hardware and software efforts (Seshadri et al. 1987; Kim et al. 1988; Horii et al. 1989; Arenson et al. 1990).

Similar activities were taking place in Europe and Asia. Hruby opened a completely digital radiology department in the Danube Hospital in Vienna in 1990, setting the tone for the future (Hruby and Maltsidis 2000). Several academic radiology departments in the United States began working with major vendor partners to further the technology and its clinical implementation. Such academic-industry collaborations continue the advancement of PACS today.

Development of the DICOM Standard

The development of standards in medical imaging is one of the facilitating factors that has enabled PACS, and medical imaging in general, to mature and become more widely utilized. Foremost among them is the DICOM standard (DICOM 2004), which was created to promote an open architecture allowing interoperability among systems for the transfer of medical images and associated information.

Clinical applications of computers were becoming widely accepted in the 1970s. X-ray computed tomography (CT) and DSA were introduced, followed by other digital diagnostic modalities. Before DICOM came into being as an exchange protocol to bridge differing hardware devices and software applications, information sharing was difficult. Devices manufactured by different vendors employed a wide variety of incompatible digital image formats.

The American College of Radiology (ACR) and the National Electrical Manufacturers Association (NEMA) formed a joint committee in 1983 to develop a standard to promote communication of digital image information, regardless of device manufacturer. It was felt that this would facilitate the development and expansion of PACS, which could also interface with other hospital information systems, and allow the creation of diagnostic information data bases that could be interrogated by a wide variety of geographically distributed devices.

The ACR-NEMA Standard version 1.0 was published in 1985, and v2.0 three years later. ACR-NEMA 2.0 required a file header followed by the image data. The file header contained information relevant to the image, such as matrix size

or number of rows and columns, pixel size, gray-scale bit depth, etc., as well as information about the imaging device and technique, (i.e., Brand X CT scanner, acquired with contrast). Patient demographic data such as name, date of birth, etc., were also included in the image header. ACR-NEMA 2.0 specified exactly where in the header each bit of information was to be stored, so that any device could read the standard required image information needed by going to its designated location in the header. It also included new material to provide command support for display devices, to introduce a new hierarchy scheme for identifying an image, or for adding data elements for increased specificity when describing an image. These standards publications specified a hardware interface, a minimum set of software commands, and a consistent set of data formats. The Standard unified the format of imaging data, but it had no networking capabilities and it functioned only as a point-to-point procedure.

At the 1994 Annual Meeting of the Radiological Society of North America (RSNA), a variety of imaging vendors participated in an impressive demonstration of the new and evolving imaging standard (ACR-NEMA 3.0). Participants attached their devices to a common network and transmitted their images to one another. In addition to the image format of ACR-NEMA 2.0, the revised Standard, now designated DICOM, included a network communications protocol, or a common language, for sending and receiving images and relevant data over a network. The Standard continues to evolve, with significant updates yearly.

The current version of DICOM contains a number of major enhancements over previous versions of the ACR-NEMA Standard. The first is that it is applicable to a networked environment, requiring a *Network Interface Unit (NIU)*. Operation in a networked environment is supported today using the industry standard networking protocol *TCP/IP (Transfer Communication Protocol/Internet Protocol)*. Thus in addition to the format of the data being exchanged between medical imaging devices, the DICOM standard also specifies how the devices themselves should communicate using simple commands such as Find, Get, Move, Send, Store. These commands operate on objects such as images and text, which are formatted in terms of groups and elements. The hierarchy of data is of the form patient, study, series or sequence, and image.

DICOM specifies, through the concept of Service Classes, the semantics of commands and associated data and also the levels of conformance. The DICOM standard language structure is built on *information objects (IO)*, *application entities (AE)*, and *service class users (SCU)*, and *service class providers (SCP)*. Information objects include, for example, the image types, such as CR, CT, MRI, etc. The application entities include the devices, such as a scanner, workstation or printer. The *service classes (SC*)* define an operation on the information object via *service object pairs*

(*SOP*) of IO and SCU and SCP. The types of operations performed by an SCU-SCP on an IO include storage; query-retrieve; verification; print; study content notification;; and patient, study, and results management. A sample DICOM-formatted message is written in terms of a Tag (consisting of a group and an element) followed by the Length of the tag, followed by the Value: 0008,0020-8-20050402 represents group 8, element 20, which corresponds to the study date given as an 8-character field.

Architectures

The two basic architectures used in PACS today are *distributed (cached)* and *centralized (cacheless)*. Data are acquired by the PACS in the same manner for both architectures, from the imaging modality via a DICOM send to a network gateway. Demographic data are verified by interfacing to the *radiology information system (RIS)* and/or *hospital information system (HIS)* through an IS gateway. Studies are permanently archived by a DICOM store to an electronic archive device.

In a distributed system, images and other relevant data are automatically routed to the workstation(s) where the studies are expected to be viewed and cached or stored on the local display station disk (Figure 8-1a). The best distributed PACS also pre-fetch relevant prior examinations from the long-term archive and automatically route them to the pertinent display for immediate access for comparison purposes. Studies not automatically routed to a workstation can be queried for and retrieved upon request. A centralized architecture is easier to implement and maintain, and it uses a simple on-demand data access model, but it also has a single point-of-failure in the central server component (Figure 8-1b). It is also bandwidth-limited, requiring a fast network connection from display stations to the central server. The distributed architecture, by contrast, requires more complex workflow logic to implement, such as auto-routing and pre-fetching of data, but it may have more functionality and may be more easily scalable. Early PACS were predominantly distributed systems; but with the increasing availability of high bandwidth networks and large amounts of inexpensive storage media, most PACS today follow the centralized architecture. Future PACS may evolve to be a combination of both distributed and centralized architectures, encompassing the best of each design.

If a PACS operates with a cached architecture, in which data are automatically distributed to and stored at the display station, then the on-line storage capabilities should include space for maintaining all the pertinent examinations for a given episode of current care, (i.e., 3 days for outpatients and 6 days for inpatients). Space for pre-fetched relevant historical examinations should also be included in the anticipated storage requirements. If the PACS operates as a cacheless centralized system, then it is important to have adequate capacity to store a patient's clinical encounter on the server.

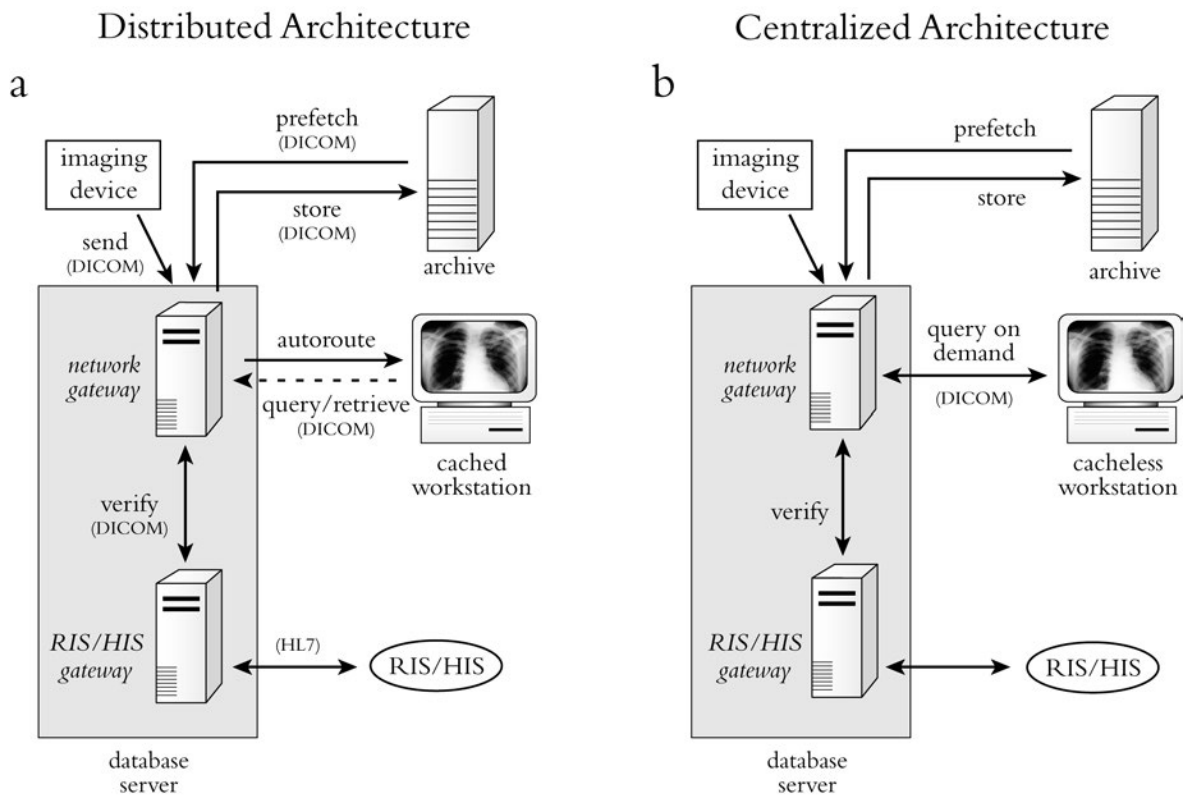


Figure 8-1. PACS Architectures: (a) Distributed vs. (b) Centralized.

In this case, it is important to have large amounts of on-line *redundant array of independent disks (RAID)* at the central server instead of large amounts of local storage at each display station. RAID capacity should also encompass relevant prior examinations pre-fetched to the server.

8.2.2 Medical Image Acquisition and Manipulation

Digital acquisition of data from the various imaging modalities for input to a PACS is the first step in eliminating film. Essential features for successful clinical implementation include conformance with the DICOM standard, radiology information system–hospital information system (RIS–HIS) interfacing, and workflow integration.

Integration with PACS

Image acquisition is the first point of data entry into a PACS and, errors generated here can propagate throughout the system adversely affecting clinical operations. General predictors for successful incorporation of image acquisition devices into a digital imaging department include: ease of device integration into the established daily workflow routine of the clinical environment; high reliability and fault tolerance of the device; simplicity and intuitiveness of the user interface; and device speed (Andriole 1999).

DICOM. Imaging modality conformance with DICOM is critical. DICOM consists of a standard image format as well

as a network communications protocol; compliance with it enables an open architecture for imaging systems, bridging hardware, and software entities, allowing interoperability for the transfer of medical images and associated information between disparate systems. The DICOM standard is used, for example, to negotiate a transaction between a compliant imaging modality and a compliant PACS workstation. The scanner notifies the workstation, in the language that both understand, that it has an image study to send to it. The workstation replies to the modality when it is ready to receive the data. The data are sent in a format known to all, the workstation acknowledges receipt, and then the devices end their negotiation. Data are formatted in terms of groups and elements; Group 8, for example, pertains to image identification parameters (such as study, series, image number), and Group 10 includes patient demographics (such as patient name, medical record number, date of birth).

Prior to DICOM, the acquisition of digital image data and relevant information was extremely difficult, often requiring separate hardware devices and software programs for different vendors' products, and even for different models of devices made by the same manufacturer. Most of the major manufacturers of imaging devices currently comply with the DICOM standard, thus greatly facilitating an open systems architecture consisting of multivendor systems. For many legacy devices purchased prior to the establishment of DICOM, an upgrade path to compliance can be performed.

For those few devices that do not yet meet the standard, interface boxes consisting of hardware equipment and software programs that convert the image data from the manufacturer's proprietary format to the standard form are available.

RIS–HIS interfacing for data verification. Equally essential, particularly at acquisition, is integrating the RIS and/or HIS with the PACS. (The RIS maintains radiology-specific data such as imaging examination orders, reports, billing information, etc. The HIS typically includes more general patient information and may contain laboratory results, patient histories, etc.) This greatly facilitates input of patient demographics such as the name, date, time, *medical record number (MRN)* uniquely identifying a patient, *accession number (AccNum)* uniquely identifying a particular imaging examination, exam type, imaging parameters, etc. It also enables automatic PACS data verification, correlation, and error correction with the data recorded in the RIS–HIS. Most imaging modalities are now tightly coupled with the RIS, providing automatic downloading of demographic information from the RIS, via barcode readers or directly to the scanner console (via modality worklist capability) and hence to the DICOM header. This eliminates the highly error-prone manual entry of data at acquisition.

Health Level 7 (HL7). This is the RIS–HIS standard and compliance with it is desirable. RIS–HIS databases are typically patient centric, enabling query and retrieval of information by the patient, study, series, or image data hierarchy. Integration of RIS–HIS data with the PACS adds intelligence to the system, helping to move data around based on “*how, what data should be delivered where and when,*” automating the functions performed traditionally by the film librarian.

Modality worklist. Many modality vendors now provide the capability to download RIS–HIS schedules and worklists directly to the imaging device. In these circumstances, the imaging technologist need only choose the appropriate patient's name from a list on the scanner console monitor, such as by pointing to it on a touch-screen pad, and the information contained within the RIS–HIS database will be downloaded into the PACS header and associated with the image data for that patient examination.

The general DICOM model for acquisition of image and relevant data from an imaging system involves the modality device acting as an SCU (service class user), and storing it to an SCP (service class provider) device such as a PACS acquisition gateway or an image display workstation. In the modality worklist function, however, the image device receives the pertinent patient demographics and image study information from a worklist server, such as a PACS, RIS, or RIS–HIS interfaced device.

There are two modes for accomplishing the RIS–HIS data transfer to the imaging modality. The first involves data being transferred automatically to the modality based on the occurrence of an event trigger, such as examination scheduled, patient arrived, etc. The second involves a query from the modality to the RIS–HIS; this may be initiated by entry of some identifier at the modality, such as bar coding of the study accession number or the patient medical record number from the scheduling card. This initiates a request for the associated RIS–HIS information (patient name, date of birth) to be sent from the worklist server on demand.

The benefits of the DICOM modality worklist cannot be overstated. Incorrectly (manually) entered patient demographic data, such as all the permutations of patient name (e.g., James Jones, J Jones, Jones J) can result in mislabeled image files and incomplete study information, and can undermine the integrity of the PACS database. Furthermore, the improvements in departmental workflow efficiency and device usability are greatly facilitated by modality worklist capabilities. For those few vendors not offering DICOM modality worklist for their imaging devices, several interface or broker boxes are available which interconnect PACS to RIS–HIS databases translating DICOM to HL7 and vice versa. Figure 8–2 indicates how RIS, HIS and PACS systems might interact upon scheduling an examination for image acquisition into a PACS (Andriole et al. 2000).

Digital image acquisition

Approaches to the generation of digital x-ray images include the digitization of existing analog film; computed radiography (CR) scanners with photostimulable storage phosphors; digital radiography (DR) and fluoroscopy (DF) devices based on flat-panel imaging technology; and CT. All of these were described in earlier chapters. Other clinical modalities, which by now are virtually all built on digital technology, are nuclear medicine, including single photon emission computed tomography (SPECT) and positron emission tomography (PET), magnetic resonance imaging (MRI), and ultrasound (US).

Image acquisition from these devices should be a direct digital DICOM capture. Direct digital interfaces allow capture and transmission of image data from the modality at the full spatial resolution and full bit depth of gray scale inherent to the modality, while analog (video) frame grabbers digitize the video signal voltage output going to an image display, such as a scanner console monitor. In the frame-grabbing method, as in printing an image to film, the image quality is typically limited to just 8 bits (or 256 gray values), while most modalities have the capability to acquire in 12, 16, or even 32 bits for color data. Capture of only 8 bits may not allow viewing in all the appropriate clinical windows and levels or contrast and brightness settings.

For example, when viewing a CT of the chest, one may wish to view both with lung window and level settings and

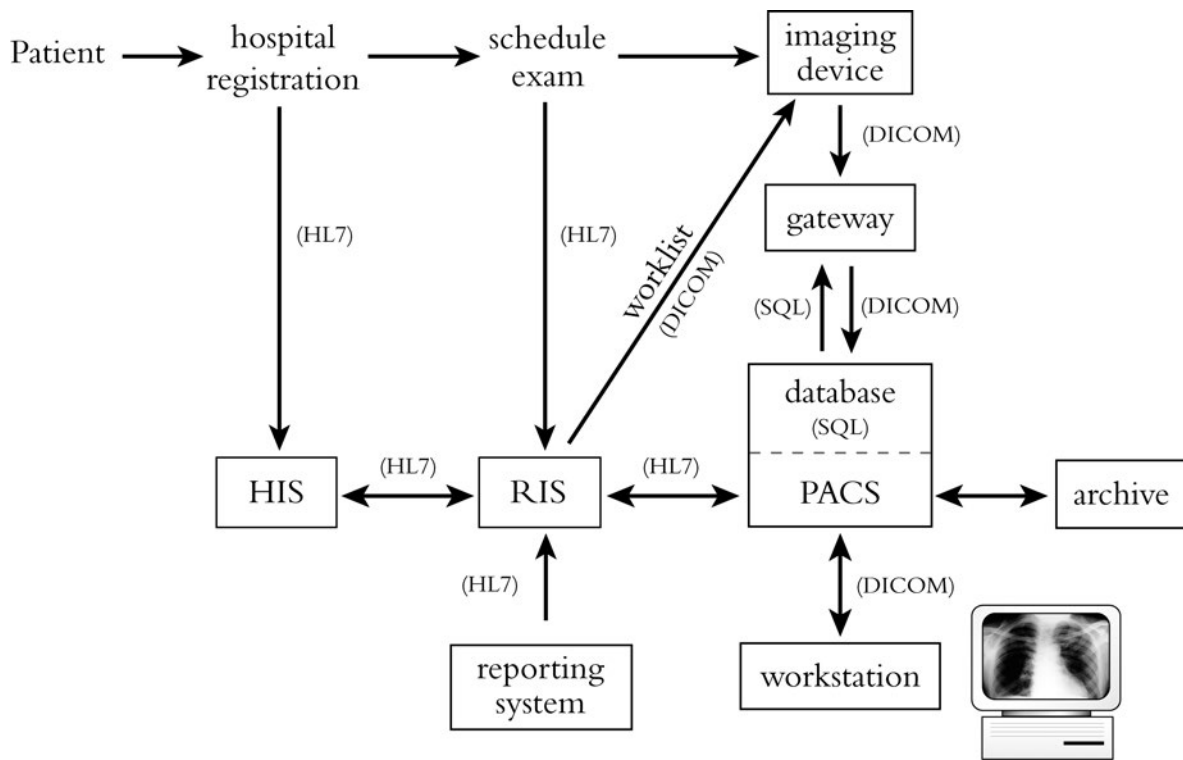


Figure 8-2. The interaction between a Hospital Information System (HIS), Radiology Information System (RIS), and Picture Archiving and Communication System (PACS), beginning with examination scheduling, followed by image acquisition, examination review, report generation, and communication of results back to the referring physician.

with mediastinal and bone windows and levels. Direct capture of the digital data will allow the viewer to dynamically window and level through each of these settings on-the-fly (in real-time) at the softcopy display station. Whereas, to view all appropriate window and level settings on film, several copies of the study would have to be printed, one at each window and level setting. If one performs the analog acquisition or frame-grabbing of the digital data, the viewer can only window and level through the 8 bits captured, which may not be sufficient. Thus, direct capture of digital data from the inherently digital modalities is the preferred method. Table 8-1 lists the modalities commonly interfaced to PACS along with their inherent file sizes and bit depths.

Typical image processing (using CR as an example)

Processing of an image is commonly performed to optimize it for display. Each manufacturer has a set of proprietary algorithms that can be applied to the image for printing on laser film or display initially only on their own proprietary workstations. Prior to the DICOM standard, only the raw data could be directly acquired digitally. Therefore, to attain the same image appearance on other display stations, the appropriate image processing algorithms (if known) had to be implemented somewhere along the chain from acquisition to display. Now image processing parameters can be passed in the DICOM header, and algorithms applied to images dis-

Table 8-1. The modalities commonly interfaced to a PACS, and their inherent file sizes.

Modality	Image Matrix Size (pixel)	Grayscale Bit Depth (bits)
CT	512×512	12-16
DR, DF, DSA	512×512, 1024×1024, or 2048×2048	8-12
MRI	256×256	12-16
NM, SPECT, PET	64×64, 128×128, or 256×256	8-32
US	64×64 or 128×128	16-32

played on generic workstations, though advanced real-time manipulation of images can typically only be done on each manufacturer's specific processing station. In general, the digital image processing applied to CR, for example, consists of a recognition or analysis phase, followed by contrast enhancement and/or frequency processing. Note that the same general types of image processing applied to CR can also be applied to DR images.

Image segmentation. In the image recognition stage, the region of exposure (as defined by the collimation edges) is detected, a histogram analysis of the pixel gray values in the

image is performed to assess the actual exposure to the CR plate, and the appropriate look-up table specific to the region of anatomy imaged and chosen by the x-ray technologist at the time of patient demographic information input is selected. Proper recognition of the exposed region of interest is extremely important as it affects future processing applied to the image data. For example, if the bright white area of the image caused by collimation at the time of exposure is not detected properly, its very high gray values will be taken into account during histogram analysis, increasing the “window” of values to be accommodated by a given softcopy or hard-copy display device. The effect would be to decrease the overall contrast in the image.

Some segmentation algorithms, in addition to detecting the collimation edges, enable users to blacken the region outside these edges in the final image if so desired (Bogucki, Trauernicht, and Kocher 1995). Removing this bright white background in images of small body parts or pediatric patients tends to improve image contrast appearance (Figure 8–3).

Contrast enhancement. Conventional *contrast enhancement*, also called *gradation processing*, *tone scaling*, and *latitude reduction* is performed next. This processing amounts to choosing the best characteristic curve (usually a nonlinear transformation of x-ray exposure to image density) to apply to the image data. These algorithms are quite flexible and can be tuned to satisfy a particular user’s preferences for a given “look” of the image (Gringold, Tucker, and Barnes 1994). Look-up tables are specific to the region of anatomy imaged. Figure 8–4a shows a default adult chest look-up table applied to an image, and Figure 8–4b presents the same image but with high-contrast processing. A reverse contrast scale or *black bone* technique in which what was originally black in the image becomes white, and what was originally white in the image becomes black, is sometimes felt to be beneficial for identifying the location of tubes and lines. The contrast reversal algorithm has been applied to the image in Figure 8–5a, resulting in the image in Figure 8–5b.

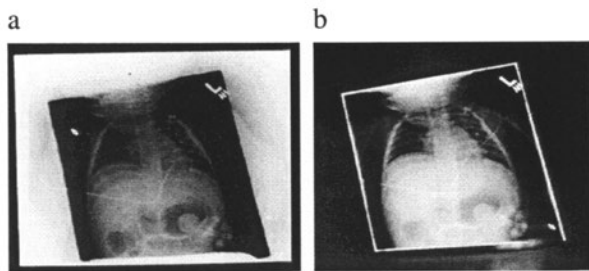


Figure 8–3. Image segmentation: (a) Algorithm detection of (white) collimation edges of exposure region; (b) with “blackened surround” applied, resulting in improved overall contrast.

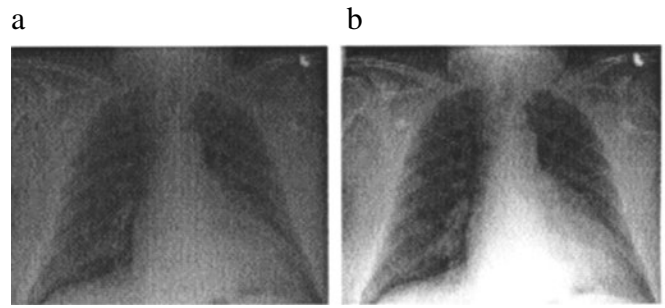


Figure 8–4. Chest image processed with (a) default mode, and (b) high-contrast algorithm applied.

Spatial frequency processing. The next type of image processing usually performed is spatial frequency processing, one type of which is known as *edge enhancement*. These algorithms adjust the frequency-response characteristics of the CR images, essentially implementing a high or band pass filter operation to enhance the high spatial frequency content contained in edge information. Unfortunately, noise also contains high spatial frequency content and can be exacerbated by edge enhancement techniques. To lessen this problem, a nonlinear unsharp masking technique is typically implemented to suppress noise. Unsharp masking is an averaging and smoothing technique that begins by creating a blurred copy of the image; when the blurred version is subtracted from the original, the effect is one of noise suppression. Specific spatial frequencies can be preferentially selected and emphasized by changing the mask size and weighting parameters. For example, low spatial frequency information in the image can be augmented by using a relatively large mask, while high spatial frequency or edge information can be enhanced by using a small mask size (Matsuda et al. 1993).

Dynamic range control. An advanced algorithm for selective compression or emphasis of low-density regions in an image,

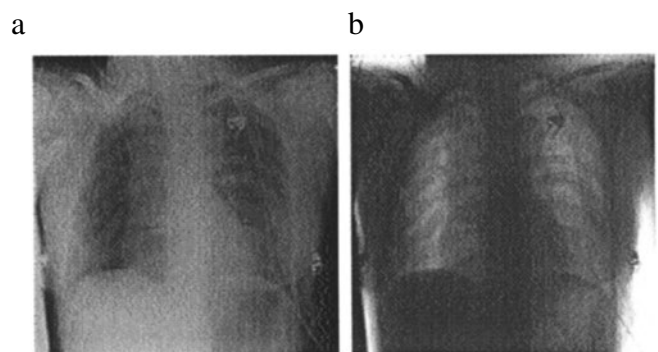


Figure 8–5. Chest image processed with (a) default mode, and (b) blackbone/contrast-reversal algorithm applied.

independent of contrast and spatial frequency, is known as *dynamic range control (DRC)* processing (Ishida 1993). The algorithm consists of performing an unsharp mask for suppression of high spatial frequency information, then applying a specific look-up table mapping to selected low optical density areas. This mask is then added back to the original data, with the overall result being improved contrast in poorly penetrated regions, without loss of high-frequency and contrast emphasis. In a clinical evaluation of the algorithm for processing of adult portable chest exams, DRC was found to be preferred by five thoracic radiologists in a side-by-side comparison, providing improved visibility of mediastinal details and enhanced subdiaphragmatic regions (Storto et al. 1995).

Multiscale image contrast amplification. *Multiscale image contrast amplification (MUSICA)* is a very flexible advanced image-processing algorithm for local contrast enhancement (Agfa 1994; Vuylsteke, Dewaela, and Schoeters 1997). It is based on the principle of detail amplitude or strength, and on the notion that image features can be striking or subtle, large in size or small; its processing is independent of the size or diameter of the object with the feature to be enhanced. The method decomposes the original image into a set of detail images, each of which represents an image feature of a specific scale. This set of detail images, or basis functions, completely describes the original image. Each detail image representation and the image background are contrast-equalized separately; some details can be enhanced and others attenuated as desired. All the separate detail images are recombined into a single image, and the result is diminished differences in contrast between features regardless of size, such that all image features become more visible.

8.2.3 Medical Image Archival

Digital image archives were once thought of as costly, inefficient impediments to moving toward (PACS) and digital imaging departments (Pratt et al. 1998). However, current trends in archival technology have shown the cost of digital storage media decreasing steadily with capacity increasing, while analog devices such as paper and film continue to increase in overall cost (Chunn 1996). Improvements in storage devices along with the use of intelligent software have removed digital archives as a major stumbling block to implementing PACS. The following discussion of electronic archival technologies for medical images covers available digital media, PACS system architectures, and storage management strategies.

Digital image archival can be more efficient than the manual data storage of the traditional film file room. A study of image examination retrieval from a PACS versus a film-based system showed statistically significant reduction in times for the digital method, in many cases down from hours to minutes (Horii et al. 1992). The improved retrieval times

with PACS were particularly striking for studies between 6 months and 1 year old, and for studies greater than 1 year (Horii et al. 1992).

An informal survey of 75 radiologists operating in a traditional film-based radiology department found that 70% experienced delayed access to films, which caused them and their staff money in terms of decreased efficiency. Rarely did this delayed access to films result in repeated or unnecessary studies, or result in longer hospital stays. However, inaccessible or lost films did result in time spent, often by the radiologist or clinician, looking for films.

Digital archives are generally less people intensive, eliminating the physical handling of films, and are therefore less expensive and less subject to the errors in filing and lost films that often plague film stores. Electronic archives can improve the security of stored image data and related records, assuring no loss of exam data while offering simultaneous case availability to many.

Digital archives must have an intelligent patient-centric system database interface to enable easy retrieval of imaging examinations. They should conform to the DICOM standard format and communications protocol by being able to accept and return DICOM format files. Many archive systems reformat the data once inside the storage device to a more efficient schema appropriate for the specific archive architecture.

Medical image data files are large compared to text-based clinical data, and are growing in size as new digital applications prove clinically useful. A single view chest x-ray, for example, can require 10 megabytes (MB) of storage space. With the expanding availability of multidetector CT scanners and increasing use of magnetic resonance angiography examinations, thousand-slice studies are not uncommon. Imaging activity continues to increase significantly as it becomes a key diagnostic triage event, with most diagnostic imaging departments showing an increase in overall volume of cases. A typical 500-bed healthcare enterprise performing approximately 200,000 examinations, for example, can generate on the order of 5 to 6 terabytes (TB) of data per year (Siegel and Shannon 1997).

Compression can be used to reduce both image transmission time and storage requirements. Lossless (or bit-preserving) compression at 2:1 is done by most PACS archive systems already. Lossy or non-bit-preserving compression by definition does not provide an exact bit-for-bit replica of the original image data upon decompression. Numerically, lossy compression can produce visually lossless images at compression ratios of 5:1 to 30:1, depending on modality (Erickson et al. 1998; Savcenko et al. 1998; Avrin et al. 2001). Compression at these levels can achieve much greater space savings and appear to be of adequate image quality for image comparison and review of prior studies. For perspective, without compression only 50 two-view digital projection x-ray examinations at approximately 10 MB per image can

be stored on a single gigabyte (GB) optical disk. With 25:1 compression, approximately 1250 examinations can be stored on a single GB disk.

Digital archival media

The digital storage device media used in PACS today include computer hard drives or magnetic disks (MD), the redundant array of independent or inexpensive disks (RAID), optical disks (OD), magneto-optical disks (MOD), and tape. Newer technologies such as digital video disks (DVD) and ultra density optical (UDO) disks are being introduced. The properties and attributes of each storage device including capacity, performance, and relative cost are compared and summarized below. Table 8–2 summarizes the relative cost of digital archive media per capacity or number of GB that can be stored per dollar, in addition to typical capacities and retrieval times.

Magnetic Disk (MD). The standard computer hard drive or magnetic disk, also known as a direct access storage device (DASD), is the fastest medium from which to retrieve data. Retrieval times are on the order of 1 to 50 milliseconds (msec). However, magnetic disks have the lowest capacity, typically hundreds of MB to tens of GB, and the highest cost per amount of data storage of all the archival media used in PACS today, though prices are continuing to decrease rapidly. As a result of the relative high cost in the past, MDs have historically been used for local on-line storage at the display workstation where fast access was required, yet large capacity was not cost-effective. Today it is becoming cost-effective to use spinning media for all stages of storage—the trend toward everything-on-line.

Redundant Array of Independent or Inexpensive Disks (RAID). RAID devices consist of multiple MDs with high performance and larger capacity (now TB worth per device). These devices can offer redundancy, lessening the concerns with a single point of failure, and have hot swappable components that can be replaced as needed without bringing the entire archive system down.

RAID has traditionally been used for “near line,” intermediate short-term storage, or clinical-operational storage cache to minimize the number of transactions hitting the

deep or long-term archive. It is becoming cheap enough per capacity to consider using RAID in larger configurations for high-performance, longer-term storage. In these configurations, a higher percentage of studies, perhaps accounting for several years or more, can remain available on-line for immediate access.

Optical/Magneto-Optical Disk (OD/MOD). Optical disks and magneto-optical disks are of the removable spinning storage media class typically stored in an automated media movement device or jukebox, giving them total device storage amounts equal to hundreds of times the individual media capacity. ODs and MODs have higher capacity than magnetic disks, typically GB to tens of GB yielding hundreds of GB to tens of TB total device storage. They are lower cost per capacity than RAID, on the order of a half dollar (in 2005) per GB of storage. ODs are a slower medium than RAID, on the order of seconds to minutes for data retrieval in both batch and random seek modes.

ODs are also known as *write once, read many (WORM)* disks, with data permanently written onto them. MODs are erasable, reusable platters and are able to hold more data per unit than ODs. Due to the slower performance and lower cost per capacity, ODs and MODs have traditionally been used for long-term, permanent PACS storage.

Tape. Tape is also a removable storage medium typically kept in a jukebox or tape library. The magnetic tape type most often used for PACS is digital linear tape (DLT). It has very high capacity, tens to hundreds of GB for many TB per tape library, and low cost on the order of a quarter dollar or less per GB of storage. It is a slower medium than MOD in random retrieval times because of its sequential nature. However tape performance is competitive with MOD for retrievals of large files using very high batch read-write rates. Even random retrievals of very large files (on the order of 50 MB) can be transferred faster with DLT than with MODs. Tape has historically and is currently being used for disaster backup, as well as for long-term, permanent storage.

Digital Video Disk (DVD). Newer technologies such as digital video disks appear promising but have failed to move significantly into the medical arena due to their high cost

Table 8–2. Digital archive media capacity, retrieval times, and relative costs per GB of storage (2005).

Archive	Storage Capacity	Retrieval Times	Cost/Capacity
Magnetic Disk	100s MB – 10s GB	1 to 50 msec	\$1.00/GB
Optical Disk	1–10s GB for TB devices	sec to minutes	\$0.40/GB
Tape	10s–100s GB for 10s TB devices	10s sec to minutes	\$0.25/GB
RAID	10s–100s GB for 10s TB devices	100–300 msec	\$10.00/GB
DVD	GB for TB devices	sec	\$2.50/GB
UDO	30 GB for 10s–100s TB devices	sec to minutes	\$2.00/GB

and slow performance. DVDs use dual-sided storage, thus achieving greater amounts of storage (GB) than MODs fairly inexpensively. However, the cost of the drives still remains quite high, and the lack of a universal standard read-write format currently limits the use of DVDs for PACS.

Ultra Density Optical (UDO) Disk. Recently released ultra density optical (UDO) disks use a blue laser recording technology to achieve much greater data storage densities, on the order of 30 GB capacity per disk, and this is predicted to double within 6 months. UDO is a WORM disk technology with a 50-year life span and a current cost of approximately \$2 per GB. While this is just a first-generation device release in the medical arena (other fields including the defense industry have used UDOs), it may prove to be a useful technology for PACS.

Figure 8–6 graphs the capacity versus performance characteristics of the MD, RAID, OD, and tape. Note that tape and OD are relatively similar in their trade-off between capacity and performance.

Archival strategies

Data migration. Medical images have a life cycle in which early on, quick access to the data is critical and often needed by several people in many different locations simultaneously. After a patient has been treated and discharged, however, that same imaging study may rarely need to be accessed again, and if it is, taking minutes or even hours to retrieve it may be acceptable. This pattern of use suggests that hierarchical or staged archival strategies can be implemented for optimum cost-effective use of storage technologies, particularly for the older distributed PACS architectures.

The stages or terms of storage include on-line or local storage, short- or intermediate-term near-line storage, long-term or off-line storage, and disaster recovery or backup storage. On-line storage contains information that must be available to the user immediately at the display station, and therefore requires high-speed access. Since this performance is costly, on-line storage is usually reserved for clinically critical data needed during a single episode of current care, i.e., 3 days for outpatient clinical encounters and 6 days on average for a typical inpatient stay. The medium best meeting on-line local storage needs is the standard computer magnetic disk.

Short-term or near-line storage is used to provide relevant prior or historical imaging studies for comparison during a patient's return visit. This does not require immediate access, particularly if the data can be automatically pre-fetched with advanced notice of scheduled appointments. Most patients who do not return for continuing care within 18 months of the acute visit are unlikely to return at all. In other words, a large percentage of imaging examinations performed will never be re-reviewed after the original clinical episode, so slower access may be acceptable. As such, RAID devices work well as short-term or near-line storage.

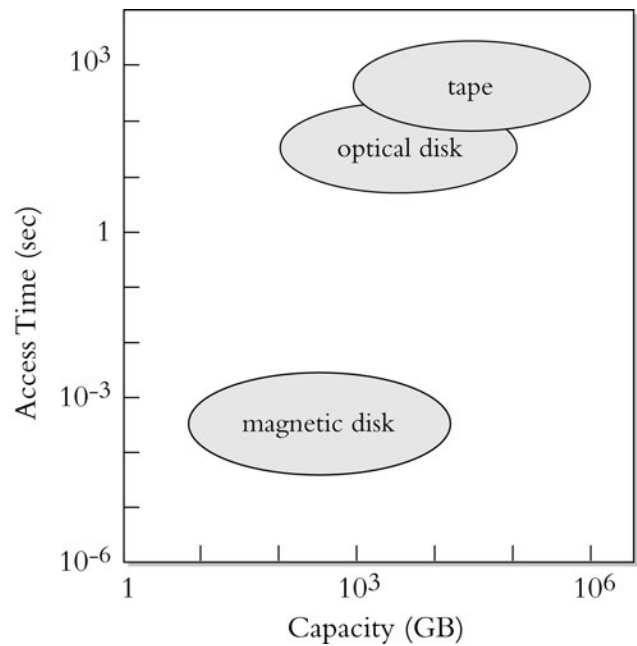


Figure 8–6. Capacity vs. performance characteristics of digital archive media.

Long-term or permanent storage provides availability to data with advance notice for retrieval, especially when long-term storage is off-line or on-the-shelf. Removable storage media devices such as OD, MOD, or tape jukeboxes are typically used for long-term storage due to their high capacity per cost characteristics. Long-term archives must cover an institution's entire medico-legal storage requirements, which vary from state to state (i.e., 5 years for general adult studies in Massachusetts, 21 years for pediatric studies, and life for mammograms and images with orthopedic appliances).

The requirements for fast retrieval of images initially followed by slower retrieval later, if at all, suggests that different types of storage devices could be used over time to archive images with cost savings. As fast retrieval times grow less important, images could be migrated to less costly, higher capacity, slower storage devices (Figure 8–7). Software is used to handle the movement of data from one medium to another and the strategy makes the actual physical storage device transparent to the end user. Such a strategy is known as a *hierarchical storage management (HSM)* scheme.

Hierarchical storage management and compression. Data compression can be used to maximize the amount of on-line or near-line storage available to a PACS. While the full resolution image data can be viewed originally for primary diagnosis, a losslessly compressed version can be sent off-site to an inexpensive tape backup archive. The original data can also be wavelet lossy compressed and stored on a large RAID device for maximum cost-effective on-line storage and retrieval of images for review and comparison (Figure 8–8) (Avrin et al. 2001).

An HSM scheme utilizing short-term archival of uncompressed DICOM data for primary diagnosis, in an on-site RAID, coupled with a very deep long-term archive of diagnostic quality wavelet compressed data in an on-site optical jukebox, cost effectively maximizes on-line storage for immediate image retrieval. Lossy compressed data (at ratios of 25:1 for CR, 10:1 for CT, and 5:1 for MRI) grows the on-site review jukebox by 10 times depending on the mix of cases, making 20 or more years available on-line (Avrin et al. 2001). This effectively maintains the entire legal record worth of original plus two relevant prior examinations all on-line.

A hierarchical storage management scheme such as this provides a solution for maximum intermediate storage and retrieval through the use of on-site lossy compression, and off-site tape backup of losslessly compressed data for the legal record and disaster recovery of data. The use of compression in this HSM scheme provides a cost-effective, high-performance archive system. This HSM can be tailored to a given healthcare enterprise's needs to provide clinically and economically beneficial digital archival of medical images.

Scalable solutions

Everything-on-line (EOL). With the dramatic decline in the cost and increase in capacity of RAID devices, it may become feasible to have all studies with their relevant prior

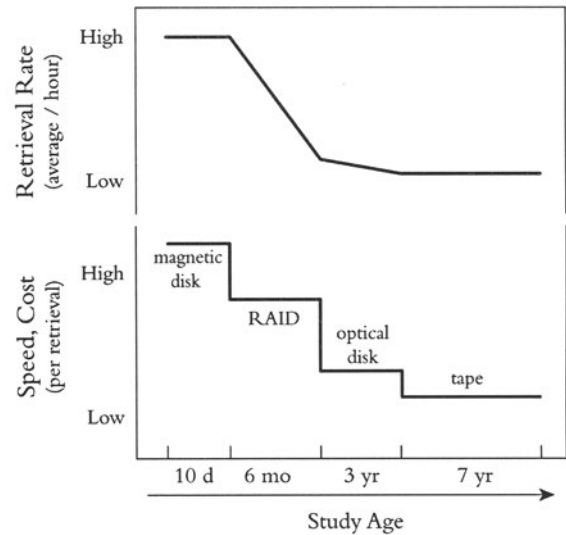


Figure 8-7. The life cycle of an image examination showing migration strategy and retrieval requirements vs. cost over time.

examinations accessible on-line. This is particularly important for centralized or cacheless PACS architectures. On the other hand, imaging volume and study sizes continue to increase and may continue to overburden archive technolo-

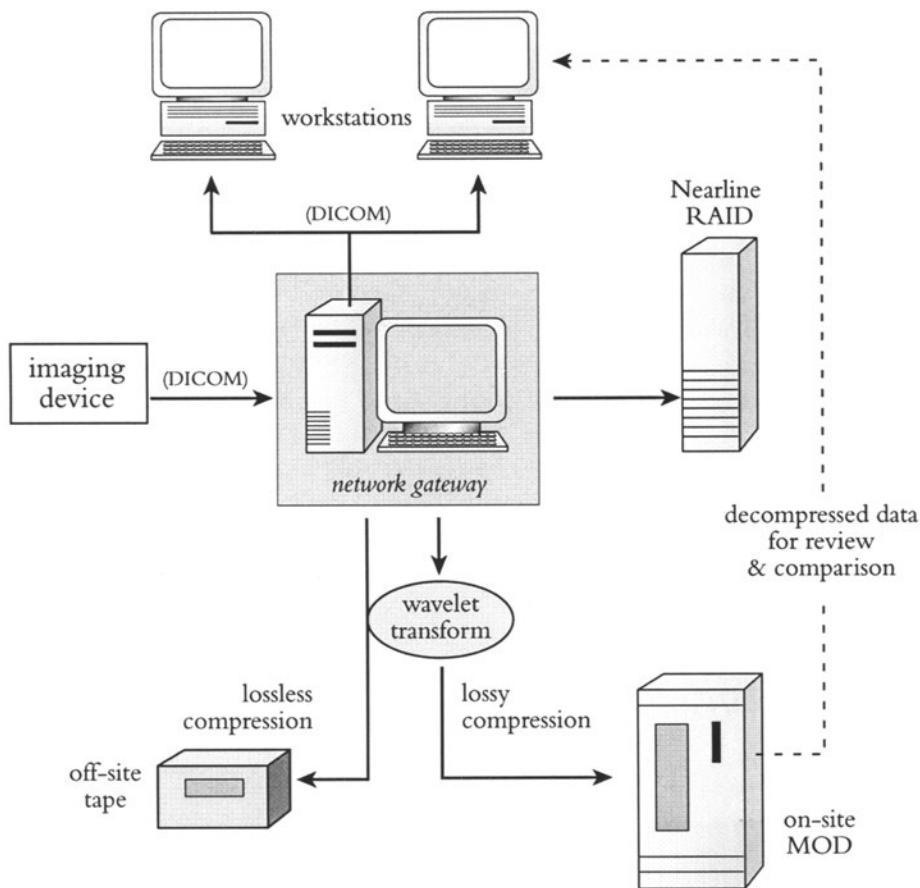


Figure 8-8. Hierarchical Storage Management (HSM) scheme. Image data are viewed at its original content for primary diagnosis, losslessly compressed for the off-site legal record on tape, and wavelet lossy compressed for the on-site near-line storage on MOD for review and historic comparison.

gies. Thus, perhaps the intelligent use of the hardware and software technologies currently available through data migration schema is a sound strategy.

Networked-Attached Storage (NAS). Networked-Attached Storage involves automated storage on a direct-access but separate local drive. NAS utilizes the existing local area network (LAN) to connect storage devices and the systems requiring data. A NAS server is optimized to perform file-sharing functions without the application processing overhead of typical network file servers. This enables files to be served rapidly to clients. Performance is affected by the LAN capabilities and system configuration.

Storage Access Networks (SAN). Storage Access Networks are dedicated networks that link storage devices and servers, creating an independent directly accessible pool of storage. SANs typically utilize fiber channel technology for high-speed serial interconnections, usually over optical fiber. This network type can provide simultaneous access from one or many servers to one or many storage devices, and eliminates potential loading on the LAN.

Content-Addressed Storage (CAS). In Content-Addressed Storage systems data are stored and retrieved based on unique content ID keys. Since medical image data is “fixed content” in that its information needs to be stored but cannot (typically) be altered in any way, CAS may prove useful. CAS associates a digital fingerprint, ID, or logical address to a stored element of data providing content security and integrity. The object-oriented nature of CAS could be exploited to improve database searchability.

Application Service Provider (ASP). An Application Service Provider approach to medical data archival may be practical for some small entities. This strategy, in which an outside vendor provides services for storage using their hardware and software has been around for several years. The advantages include less capitol requirements for on-site hardware, technology obsolescence protection, maintenance and migration shifted to the ASP vendor, and off-site data backup. Disadvantages include potential vulnerability in performance and long-term viability of the ASP vendor, security issues, and potential high cost of service, particularly for large volume sites.

8.2.4 Computer Networking

Computer networks enable communication of information between two or more physically distinct devices. They provide a path by which end user radiologists and clinicians sitting at one geographic location, for example, can access radiological images and diagnostic reports from a computer at another location. A private, locally owned and controlled

network (i.e., within a building or hospital) is called a *local area network (LAN)*, while a network used outside of a local area is known as a *wide area network* or WAN. A WAN utilizes an external service provider and usually has lower bandwidth services than do LANs. *Intranet* communication refers to communication across a private limited-access LAN. *Internet* communication is across public shared-access WANs. Signals are transmitted via either bound media such as over cables or unbound broadcast media.

Analog communications systems encode information into a continuous wave form of voltage signals, while digital systems encode the data into two discrete states or bits—either “0” or “1.” The bits are packaged to form bytes, words, packets, blocks, and files based on a specified communication protocol. These communications standards give detailed specifications of the media, the physical connections between devices, the signal levels and timings, the packaging of the signals, and the software needed for the transport of data (Huang 2004).

Serial data transmission sends digital signals one bit at a time over a single wire; the single bit stream is reassembled at the receiving end of transmission into meaningful byte-word-packet-block-file data (Huang 2004). Parallel data transmission uses multiple wires to transmit bits simultaneously and as such provides increased transmission speeds. Synchronous communication is used in applications that require maximum speed, and is carried out between two nodes that share a common clock. Asynchronous communication relies on start and stop signals to identify the beginning and end of data packets (Huang 2004). An example of this technology is *asynchronous transfer mode (ATM)* technology.

Hardware

Important networking infrastructure considerations include *bandwidth*, a measure of how much data can be transferred per period of time; *latency*, or how long the trip takes; *topology* or *network segmentation*, which describes the path data takes; and reliability and *redundancy*.

Table 8–3 lists different types of network bandwidths available, or speeds in bits per second (bps), along with example transmission times for a single 10-MB CR digital projection radiograph. Over a telephone modem it would take approximately 24 minutes at best to transmit a single 10-MB image, while over Fast Ethernet it would be only a fraction of a second. LANs can consist of low-speed Ethernet, medium-speed Fast Ethernet, or fast-speed Gigabit infrastructure. WANs can consist of a range of digital service speeds from slow telephone modem to medium-speed T1 lines to fast ATM. Transmission cost tracks with speed.

The most common network topologies used in PACS include bus, ring, and star configurations. These are diagrammed in Figure 8–9. *Bus* topologies commonly use Ethernet and have the advantages of network simplicity, but

Table 8-3. Network bandwidths and example image transmission times.

	Maximum Bandwidth	MTT* for 10MB CR
Modem	56 kbps	24 min
T1 Line	1.54 Mbps	52 sec
Ethernet	10 Mbps	8 sec
Fast Ethernet	100 Mbps	0.8 sec
ATM	155 Mbps	0.5 sec

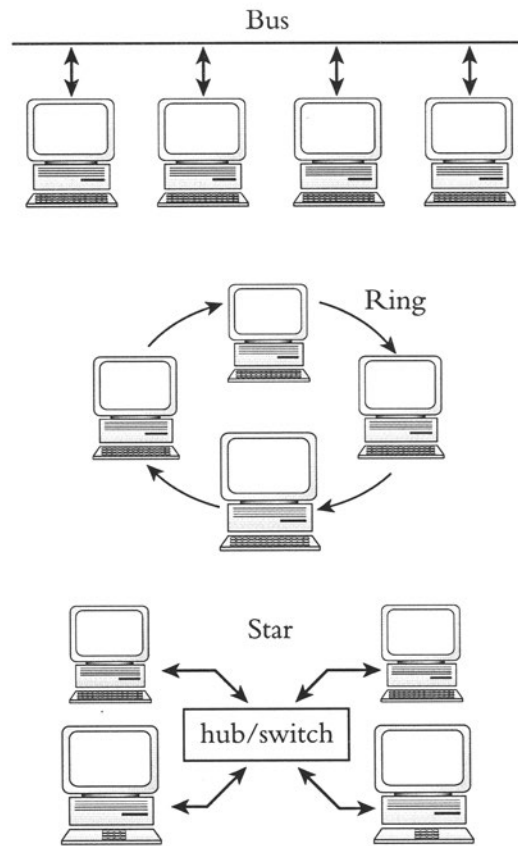
*Minimum Transmission Time

the disadvantage of upper level bottlenecking and difficult to identify channel failure. The *ring* topology uses fiber distributed data interface (FDDI) or high-speed ATM SONET (synchronous optical NETWORK) ring technology. Ring topologies offer simplicity and no bottleneck but in a single ring, if the channel between two nodes fails, then the network is down. The *star* or *hub* topology uses high-speed Ethernet or ATM switching and offers network simplicity but a bottleneck as well as a single point of failure at the hub or switch.

The physical media or cabling that makes up PACS networks varies from telephone wires to unshielded twisted pair (UTP) copper cabling, also referred to as CAT5 or CAT3 depending on the quality of the wiring, to coax cable (also known as *thinnet* or 10Base5) and fiber optic cabling. Fiber optic cabling can transmit more data over longer distances than conventional cabling by using light or lasers instead of electrical signals, but are of relatively high cost. The *network interface card (NIC)* connects a computer to the physical media or cabling of the network. A unique address, the Media Access Control (MAC) address is derived from the NIC. This address is used to identify each individual computer on a network.

A hub or multiport repeater connects multiple computers on a network. A *bridge* isolates network traffic and connects two or more networks together. The bridge listens to all network traffic and keeps track of where individual computers are. A properly located bridge can take a large congested network segment and reduce the number of data collisions, improving performance.

A switch or router can scale a small bandwidth network to a large bandwidth. Switches tend to be protocol independent while routers are protocol dependent. *Routers* or *relays* are used in large networks because they can limit the broadcasts necessary to find devices and can more efficiently use the bandwidth. Routers sometimes referred to as *gateways*, while beneficial in large complicated environments, can unfortunately slow traffic down because they have to examine data packets in order to make routing decisions. Bridges work much more quickly because they have fewer decisions to make.

**Figure 8-9.** Network topologies typically used in PACS: Bus, Ring, Star.

Switches have revolutionized the networking industry. They look at only as much of the data packet as bridges look at and are in a sense bridges with many interfaces. Switching incorporated with routing helps make network bottlenecks easier to remove. Some switches are used in the core of a network while others are used to replace hubs.

Networking software

The *International Standards Organization (ISO)* developed the *Open Systems Interconnect (OSI)* model as a framework to facilitate interoperation of computer networks from the application layer (i.e., the image viewer) all the way down to the physical layer (i.e., the wires). The ISO/OSI communication protocol stack consists of seven layers (Figure 8-10) (Huang 2004). Each layer in the stack is interested only in the exchange of information between the layer directly above or directly below, and each layer has different and well-defined tasks.

The top, or seventh, layer of the ISO/OSI stack is the Application Layer, which provides services to users. The Application Layer knows the data it wants to transmit and which machine it wants to communicate with. The sixth layer is the Presentation Layer, which takes care of data transformation such as encryption, compression, or reformatting.

Layer five is the Session Layer, which controls applications running on different workstations. This is followed by the fourth or Transport Layer; transfer of data between end points is handled here with error recovery. Layer three is the Network Layer that establishes, maintains, and terminates network connections. The second layer in the stack is the Data Link Layer, which handles network access, collision detection, token passing, etc., and network control of logical links, such as sending and receiving data messages or packets. The bottom layer or layer one, is the Physical Layer, corresponding to the hardware layer or the cable itself.

Also diagrammed in Figure 8–10 are the corresponding stacks for TCP/IP (Transmission Control Protocol/Internet Protocol), widely used in the Internet and PACS applications. TCP/IP is commonly viewed as having four layers but is shown here as five, with the lowest level split into two, for the network access and physical layers. The top is called the Process Layer, and it corresponds to the Application and Presentation Layers in the ISO/OSI model; such an application in the PACS world might be the DICOM communications protocol application. The layer below is the Host-to-Host or Transport Layer. This is followed by the Internet Layer and then the Network Access Layer, which encompasses Ethernet, token ring, for example, and the Physical or media Layer.

To determine if two devices in a PACS network are communicating, the physical connection is tested. Using the unique IP address of the devices, a “ping” command will validate whether the one computer can reach the other over some network path. The TCP/IP hostname of the computer relates the unique IP address of the device to its DICOM AE (application entity) title so that computers can communicate using this protocol.

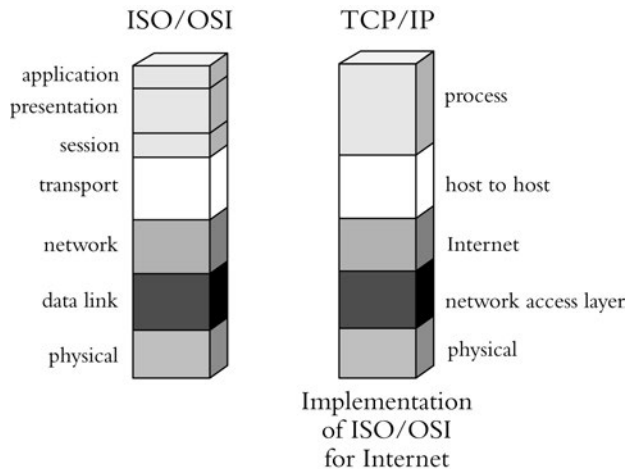


Figure 8–10. Communication Protocol Stacks for (a) ISO/OSI, and (b) TCP/IP.

Figure 8–11 demonstrates the path that a message takes from one subnet, through a router, to another subnet. The process starts at the top of the stack in host A where a DICOM port is opened. The information travels down the stack through the TCP Host-to-Host Layer to the Internet (IP) Layer and out the Network Access Layer across the Physical Layer. Messages pass through the router to the Physical Layer and up the stack of the second device to the Network Access Layer, then the Internet Layer, to the Host-to-Host or Transport Layer, and finally a port is opened in the top Process Application Layer.

Security and redundancy

Advances in networking and communications devices have greatly facilitated the transfer of information between computers all over the world. For the secure transmission of private information such as clinical images and patient data, additional technologies are put into place to make the Internet a safe medium.

Firewalls are protocol-dependent devices often used to secure a network by filtering traffic based on rules and policies. *Intrusion detection systems (IDS)* are another form of security device which uses policy-based monitoring, event logging, and alarms and alerting messaging to protect a network. *Virtual Private Networks (VPN)* protect data by encrypting the information at the source device and decrypting it at the destination device. VPN clients are often used to securely access a hospital network from a location outside its LAN. A path can be created through the firewall or directly to a specific server enabling transmission of data.

PACS networks have become mission-critical devices in the transmission of digital medical images in and among healthcare enterprises. As such, the networks must be highly available and have fault-tolerance mechanisms built in. Requirements for high availability networks include having redundant technology with automatic failover to backup

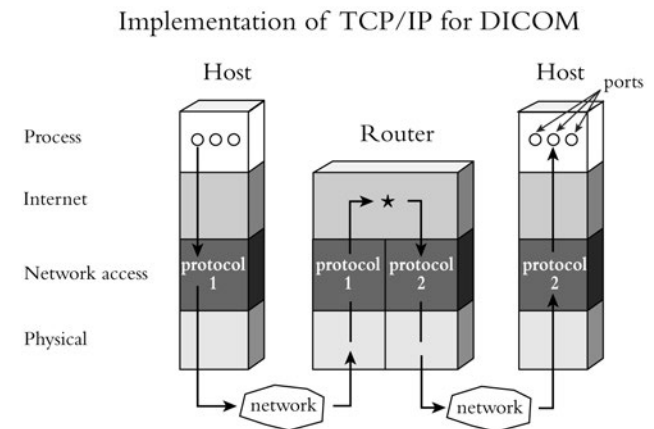


Figure 8–11. Connecting subnets via a router and DICOM.

devices when systems go down. There should be redundant media and multiple paths for the same information to get from one place to another. Redundant power for the devices involved is generally considered routine, as is proactive monitoring and problem mitigation with automated fault detection processes in place.

8.2.5 Medical Image Display

Monitor hardware

The choice of diagnostic display monitors was relatively straightforward for early adopters of PACS. Hardware was of a single type—cathode ray tube (CRT) technology, and was usually oriented in portrait mode emulating the shape of film. Monitors had high brightness, typically 60 to 100 foot lamberts (FL), relative to other computer and television monitors, and high refresh rates of greater than 72 Hz to reduce flicker. The devices themselves were physically large, heavy, and expensive. They generated noticeable quantities of heat while consuming relatively high amounts of power, and their display quality degraded quickly in time, requiring frequent monitor replacement.

Early medical-grade monitors were available in two spatial resolutions (high and low) reflecting their pixel matrix sizes: 2048 (2K) columns by 2500 rows, and 1024 (1K) columns by 1280 columns, respectively. Medium-resolution 1.5K×1.5K monitors were later added to the mix. Because of the exponentially higher cost of 2K monitors as compared with 1K monitors, radiology departments typically had a combination of a few strategically placed high-resolution displays and many low- or medium-resolution displays. The ACR recommended that 2K monitors be used for primary diagnosis of digital projection radiographs because a single image could be displayed per monitor in its full inherent acquired spatial resolution. The cross-sectional modalities with slice matrix sizes of 512×512 for CT and 256×256 for MRI were considered adequately displayed on 1K monitors. As display application software and *graphical user interfaces (GUI)* improved, many radiologists became comfortable reading from 1K monitors even for projection radiography, as long as the images were acquired at their full spatial and contrast resolutions and the GUI allowed for easy manipulation, magnification, and comparison of images.

Today, in addition to the maturation of software, a richer array of hardware technologies exist for the purposes of displaying digital medical images. Unfortunately, there are currently no formally defined standards or specification guidelines to clarify choices of monitors for users, so the different display devices available today, and the specifications to consider when purchasing monitors for use in radiological imaging, are described here. An explanation of the monitor types including CRTs, active-matrix liquid crystal displays (AM-LCDs), and plasma technologies is given, along with a discussion of spatial resolution capabilities and requirements,

contrast resolution and monitor luminance, the orientation or shape and number of displays necessary, and a comparison of color versus monochrome or gray-scale monitors. Device calibration and quality assurance practices are also addressed.

Two types of hardware displays are currently used in medical imaging: the half-century-old, mature CRTs, and what the popular literature refers to as flat-panel technology, of which there are several types (Badano 2003). Of the two broad categories of flat-panel displays, one filters reflected light or light from a source behind the filter, while the second creates light by exciting a phosphor. The term “flat-panel” is not meant to refer to the face of the monitor, as some CRTs have a flat face (Leachtenauer 2004). Rather it refers to the thin-film transistor array panel that addresses each pixel.

CRTs produce light by exciting a phosphor-luminescent coating with a focused electron beam. Light is generated in an emissive structure, where it diffuses in a controlled manner forming the displayed image. The highest spatial resolution CRT monitors available have a display area of 2048×2560 or roughly 5 million pixels (Mpixels). They come in low- and high-bright versions of 50 to 60 FL and 100 FL or greater, respectively. High- and low-resolution (2K and 1K) monitors typically come in the portrait mode with a 9:16 or 3:4 aspect ratio emulating the shape of film. Most medium-resolution CRTs (1.5K) are square or in the landscape mode with an aspect ratio of 16:9 or 4:3. Choice of portrait versus landscape monitor shape is a function of personal user preference, with no technical issues bearing on the issue.

The *flat-panel display* type predominantly used in medical imaging is the *active-matrix liquid crystal display (AM-LCD)*. LCDs use a transistor-driven matrix of organic liquid crystals that filter reflected light. They operate by way of a light-modulating (as opposed to a light-emitting) mechanism for creating the display image. Polarization filtration controls the light intensity such that intensity is maximum when viewed perpendicular to the LCD panel. Consequently, this technology suffers from marked variations in luminance and contrast depending on viewing angle (Badano 2003). This is the *off-axis viewing* or *angle-of-regard* problem in which images can appear quite different if viewed from different angles or heights above and below the center axes of the screen. Newer LCD designs have a more uniform luminance and contrast profile within a larger viewing angle cone (some as high as 170°). Users should inquire about the horizontal and vertical viewing angle capabilities and better yet, ask the vendor for a demonstration monitor for clinician testing. LCDs typically have the capability to display in both portrait and landscape modes.

Plasma display panels (PDPs) are currently being developed largely for high-definition television (HDTV) viewing with 37 inch or larger screens. A current passes between pixel-size electrodes etched on the interior surfaces of a pair of glass layers, causing local excitation and ionization of the

Ne-Xe (neon-xenon) gas between them; this leads to the immediate emission of ultraviolet light, which excites visible light-emitting phosphors to produce the display image. PDPs have roughly the same number of addressable pixels as 17-inch LCDs, can be hung on a wall and have a wide viewing angle with no loss of quality, and have high brightness but relatively slow response time (Leachtenauer 2004). They are not used currently in medical imaging because of their high cost, slow refresh rates, ghosting artifacts, and contrast limitations.

Other types of displays such as *field-emission display (FED)* and *organic light-emitting diodes (OLEDs)* are undergoing heavy developmental efforts but are not yet viable for medical imaging display purposes (Leachtenauer 2004).

Although the spatial resolution terminology used for both CRTs and LCDs is based on the device pixel matrix dimensions—1K to 2K for CRTs and 3, 5, 9 Mpixels for LCDs—not all monitors are created equal. For example, 1K and 2K CRT monitors tend to have standard diagonal lengths, so that the larger pixel matrix size connotes smaller pixel size, hence better spatial resolution capabilities. Also, all 1K monitors have had equivalent spatial resolution, as did all 2K monitors. This is not the case for LCD displays. For example, 3 Mpixel monitors come with different-sized diagonals, such that a physically bigger monitor actually has larger pixel size, hence poorer spatial resolution. Users need to understand what the pixel or spot size is, since this directly reflects spatial resolution and perception of fine detail, and not necessarily choose the physically largest screen.

Pixel size can be determined from the physical screen size, typically given as a display area diagonal in inches and total pixel count or horizontal and vertical matrix resolution. Often vendors give the device pixel density or pixel pitch spacing and, to confuse the issue, this is often given in millimeters. As for comparison between CRT and LCD monitors, the 1K CRTs at 1024×1280 correspond to 1 Mpixel monitors, 1500×1500 correspond to 2 Mpixel monitors, and 1760×1760 correspond to 3 Mpixel displays. The 2K or 2048×2500 CRTs correspond to the 5 Mpixel LCD. The recently introduced 9 Mpixel LCD display has 200 pixels per inch on a 22-inch diagonal screen.

The brightness (luminance) of a monitor affects perceived contrast, or the number of discernable gray levels, and studies have shown that diagnostic accuracy increases with monitor luminance. The typical lightbox or alternator used to display film is on the order of 400 to 600 FL while the standard PC color monitor is roughly 20 to 40 FL. An LCD color monitor has 65 to 75 FL monitor luminance while the low-bright medical grade CRT monitors have 50 to 60 FL and the high-bright CRTs have 100 FL or greater monitor luminance. Among the device specifications reflecting monitor brightness and affecting contrast resolution are the monitor and display card *bit depth* (typically 8 bits for 256 potential gray values), and the monitor *dynamic range* or *contrast ratio*,

which relates the maximum discernable luminance to the minimum, with typical values of 600:1 or greater.

In comparing CRT versus LCD display technologies, the advantages of LCD over CRT monitors include better stability for longer device lifetime. The change in brightness of standard LCD monitors has been measured at less than 0.5% per month (Badano 2003). LCDs are not prone to the geometric distortion typical of CRTs, they tend to consume less power, and have reduced sensitivity and reflection artifacts from ambient room lighting. Disadvantages of LCD monitors include the aforementioned off-axis viewing or angle-of-regard distortion, backlight instabilities, liquid crystal fluctuations with temperature, and manufacturing defects creating dead or nonresponsive pixel areas.

Receiver Operating Characteristic (ROC) studies are currently the best methodology available to compare monitor quality and associate it with reader performance; that is, diagnostic accuracy, sensitivity and specificity. Numerous clinical studies have been done, most showing no significant difference between diagnostic performance on CRTs and LCDs. Recent studies representative of CRT versus LCD comparison for radiological diagnosis include one which examined brain CTs for identifying early infarction (Partan et al. 2003) and the other looked at CRs of the chest for the evaluation of interstitial lung disease (Langer et al. 2004). The CT ROC study showed no statistically significant differences in diagnostic performance between a 21-inch monochrome CRT monitor with a 1280×1600 pixel matrix and a brightness of 175 FL versus an 18-inch color LCD monitor with a 1024×1280 pixel matrix and a luminance of 55 FL, when ten radiologists were asked to rate the presence or absence of disease on a 5-point scale. Similarly, an ROC study comparing the efficacy of a 5-Mpixel CRT display versus a 3-Mpixel LCD for the evaluation of interstitial lung disease in digital chest radiography showed no statistically significant change in observer performance sensitivity between the two types of monitors. This finding of essentially no difference between CRT and LCD observer performance can be a significant factor, of course, in the purchase of monitors.

Several studies have compared color versus monochrome (technically achromatic) or gray-scale monitors, and there does not seem to be a clear consensus. This is an important issue because color monitors tend to have decreased luminance, contrast, and spatial resolution capabilities than monochrome monitors, and the human visual system has decreased spatial resolution perception in the color channels, but greater dynamic range (500 just-noticeable-differences (JND) versus 60 to 90 JNDs in gray scale). On the other hand, high-performance monochrome monitors are expensive and have a relatively short lifetime of approximately 3 years, and color is becoming increasingly useful with the emergence of 3-D renderings. While a study comparing

monochromatic versus color CRT monitors found no statistically significant differences in display of CR chest images for the detection of subtle pulmonary disease, they did find higher sensitivity rates for specialty chest radiologists on the monochromatic monitor, perhaps due to the lower maximum luminance levels of the color displays (Iwano et al. 2001). Another study comparing pulmonary nodule detection with P45 [a monochrome phosphor with relatively smaller grain size and higher signal-to-noise ratio (SNR), hence better sensitivity and specificity] versus P104 monochrome and color 1600×1200 pixel monitors found significantly greater false-positive and false-negative responses with the color monitors, as well as longer search times (Krupinski and Roehrig 2002). So for primary diagnosis of projection radiographs in particular, monochrome monitors may still be the way to go. Note however that users prefer color LCDs when compared to color CRTs. This may be related to the Gaussian spot pixel and emissive structure of CRTs and the use of black matrix (shadow mask or aperture grille) which separates the red, green, and blue phosphor dots that form an arrangement of color dots or stripes for luminance and chromatic contrast (Badano 2003). Grille misalignment can degrade color purity and contrast.

Early PACS adopters equipped their radiology reading rooms with the highest-quality display monitors, some 2K, others 1K but all high brightness. The software applications were more complex than those targeted for the nonradiologist enterprise user. It was common to provide an intermediate application for use by image-intensive specialists such as orthopedists, neurosurgeons, and radiation oncologists as well as in image-intensive areas such as emergency departments and intensive care units. Lesser-quality monitors with stripped down software capabilities were used by enterprise image users. As display hardware and software continue to evolve, display application software is melding into one flexible, easily configurable GUI and one monitor type may in time meet most needs.

Monitor calibration and quality assurance (QA) practices are important to maintaining high-performing medical displays. The DICOM 14 *Gray-scale Standard Display Function (GSDF)* and Task Group 18 of the American Association of Physicists in Medicine (AAPM) recommend that monitors be calibrated to a perceptually linearized display function, as this is matched to the perceptual capabilities of the human visual system. Monitors forced to follow these standards produce more-uniform images with optimum contrast. CRTs are less stable than LCD monitors, requiring luminance calibration and matching to be done monthly, physically measuring light levels with a photometer. Many LCD displays have embedded luminance meters for automated QA measurements. Some studies have also recommended doing the manual external luminance measures, but less frequently than required without the automated QA.

LCDs must still be manually inspected for nonresponsive pixels. Routine manual viewing of test patterns such as the SMPTE (Society of Motion Picture and Television Engineers) test pattern are usually sufficient for evaluating overall monitor performance, low contrast, and fine detail detection.

A collaborative guideline on digital image quality, specifically for digital mammography, is being developed under the auspices of the ACR with participants from the AAPM, the RSNA, and the Society for Computer Applications in Radiology (SCAR). It will include recommendations regarding display devices and is due for release in 2006.

Software functionality

How many individual monitors does a user need per display workstation—1, 2, 4, 8? Many feel that for primary diagnosis dual-headed configurations are most efficient for comparison of current and prior relevant studies, particularly for projection radiographs. A good GUI design can reduce the need for multiple monitors. The ability to page through and move images around the screen, to instantaneously switch between tile and stack or ciné modes of display, and to view multiple studies on one monitor as well as side-by-side comparison of studies are critical to reducing the amount of hardware and physical display space required. In most cases the two-monitor setup is sufficient for primary diagnosis and image-intensive use, with perhaps a third (color) monitor for worklist creation and access to other relevant medical data. The most common configuration for enterprise users is the single-headed or one-monitor display.

First and foremost, a software GUI must be intuitive and easy to use. The software application must be responsive, robust, and reliable. Most display workstations have GUIs to perform two basic functions. The first is to deliver a patient list or worklist of imaging examinations to be read, for example, today's unread emergency department CTs. The worklist environment allows users to interrogate the entire PACS database for a subset of cases with which they wish to work. Typically, the database can be searched for by a specific patient name or other identifier, for individual imaging modalities, over specified time frames, by imaging or patient location within the hospital or healthcare enterprise, etc. The second basic function workstations perform is study display and image manipulation.

Automated hanging protocols based on examination type, the existence of prior historical examinations, etc., can greatly enhance radiology interpretation workflow. For example, if the current imaging study requiring interpretation is a two-view chest projection radiograph, then the default display might be to place the posterior-anterior (PA) view on the left monitor and the lateral view on the right. If the patient has had a prior chest x-ray, then the current PA should be placed on the left monitor with the lateral view behind and the prior PA on the right monitor, with its corre-

sponding lateral view waiting behind. If the current study is an MRI of the brain, then it might be desirable to automatically hang each sequence as a separate stack and place multiple (i.e., four-on-one) stacks per monitor so that they can be cinéd through simultaneously.

Basic display manipulation tools include the ability to change the window and level (contrast and brightness) of the displayed image dynamically, to magnify a portion of the image or zoom and pan through the entire image, and to change monitor configuration and image navigation tools such as paging, ciné, and linked stack modes rapidly. Image mensuration capabilities including linear, angle, and region-of-interest measurements are also typical. Some advanced tools include the ability to track on a corresponding perpendicular slice, in MR studies for example, where the cursor is on the perpendicular view for 3-D referencing.

Well-designed PACS are tightly integrated with other information systems such as the RIS and HIS. This enables access to other relevant data about the patient or imaging examination from within the display application. Sometimes diagnostic radiology report-generation systems such as speech recognition are embedded in the diagnostic workstation.

It is anticipated that the number of specialty display applications available on display stations will continue to increase as more features are added. Some systems also provide algorithms for image processing, such as image sharpening or edge enhancement and image smoothing. Maximum intensity projection (MIP) displays and multiplanar reformats (MPR) are also appearing on PACS workstations, as is real-time 3-D reconstruction of image data at the PACS display. Multimodality image data fusion such as CT and PET images to depict the functional maps overlaid on the anatomical data will also likely be viewable.

8.2.6 Implementation Strategies

There are several strategies for implementing an all-digital or filmless diagnostic imaging department or healthcare enterprise. One is the incremental or phased implementation, such as replacing analog US devices with digital devices or installing a nuclear medicine mini-PACS. If designing a new area, the specifications could call for only or predominantly digital capabilities such that the facility can open filmless all at once. A second strategy might be to stop printing film for all the inherently digital cross-sectional modalities such as CT and MRI, since radiologists are often somewhat familiar with reading these images soft copy. Yet another approach might be to convert all projection radiographs to digital by investing in digital acquisition devices such as CR and DR, for example, if the radiology department is having difficulty providing services to remote intensive care units.

If the PACS is to serve several constituencies, an important decision is the order in which they are to be converted to filmless—within the radiology department first, or

high image-volume areas or the critical care areas, such as the emergency department, intensive care units, and operating rooms where many image-intensive specialists function, or throughout the healthcare enterprise giving access to referring clinicians first. Regardless, the strategy chosen should be based upon the problem(s) a site is trying to solve by implementing a PACS.

There are a number of common problems that radiology departments face in the analog film-based world that can be improved by implementing a PACS. These include lost films and the inability to access prior imaging examinations for comparison. Large departments may have unread studies and hence lost revenue. Facilities may have a need for contemporaneous interpretation of urgent emergency department or intensive care unit exams. A private practice may need to cover multiple and distant locations, one or more of which may be low-volume sites, making it difficult to justify a full-time radiologist at each location. Implementing PACS could enable the practice to balance workloads across all coverage areas by transmitting images electronically from high-volume sites to low-volume locations for reading. A radiology department may be able to justify a PACS implementation simply to improve imaging services to their referring physicians, or to provide better on-call, night, and weekend coverage, to make up for film library inefficiencies, or to reduce the costs involved with film-based medical imaging.

Whatever the reason behind acquiring a PACS, the first step in doing so is to assemble a multidisciplinary team to plan the process. This team should include representatives from all the constituencies touched by the introduction of the new PACS or information systems technologies. Such members include the radiology departmental administrator, information systems or PACS specialists, a medical physicist, radiological technologist, radiologist, and referring clinicians.

The departmental administrator is tasked with overseeing budget and contracts, space requirements and staffing, workflow issues, and connection of the PACS to other systems. The information systems or PACS specialist is involved with all technical aspects for computers, interfacing devices and systems, networking issues, and management of the servers and system databases. The medical physicist is responsible for all image-quality issues, system capacities, workflow issues, acceptance testing of devices, and quality assurance procedures. Clinical personnel should be involved with radiologist and technologist workflow design, image quality issues, relationships with referring clinicians, and the enterprisewide impact of the implementation of PACS technologies. It is often very helpful to have a PACS champion—a leader of the team who coordinates all activities at a high level, advocates for all parties involved, and generates the enthusiasm necessary for successfully implementing technology change. Overall PACS “PR” (public relations) is often half the battle.

Vendor relationships are an extremely important component in the process of implementing a PACS. Once deciding upon the need to move to a PACS, facilities generally put out a *request for proposals (RFP)*. The RFP should unambiguously stipulate the system specifications (including DICOM compliance and RIS–HIS integration) that must be met by any vendor responding to the proposal. For example, the RFP could state “upon selecting a patient study from a worklist, images should display in 3 seconds or less.” Requirements need not necessarily include how a technology should accomplish a task but more importantly detail the expected result.

PACS team members should educate themselves about PACS. Several organizations including the RSNA, SCAR, and some private institutions sponsor educational conferences and workshops on both technical and practical aspects of PACS. One can also participate in on-line user groups and pose expert hotline queries. Armed with some basic knowledge of PACS, it is often useful to visit a clinically functioning PACS site for a given vendor being considered for purchase. PACS team members should be able to see a system working and test drive it before solidifying the business relationship.

Maintenance, service availability and costs, and system software and hardware upgrades should be addressed in the business contract. Backup, scheduled and unscheduled downtime, and support procedures need to be explicitly stated. Training of users provided by the vendor, or training of in house trainers for a “train-the-trainer” model, should also be included in the contract. It is often beneficial to designate a member of the PACS team to function as the clinical-technical interface and to have a point of contact within the organization for addressing business issues with the vendor, another for addressing technical problems, and perhaps yet another for support issues. This could be a single individual within a facility who then farms out to the appropriate in-house person, or it could be multiple individuals. Stress the team-partnership relationship with the vendor, so that both sides accept ownership of the project.

8.2.7 PACS QA/QC

The current trend for radiology departments and medical imaging within healthcare enterprises is an increasing move toward the all-digital or filmless medical image management system or PACS. This is technologically an enormous shift, and operational concerns with PACS implementations can arise at all stages of the process from the design specifications to installation, training, and acceptance (Honeyman and Staab 1997). Quality control (QC) procedures necessarily become modified in the filmless radiology department, and new processes must be put in place (Honeyman et al. 1997) to better prepare for the total digital clinical department.

During the PACS planning, specifications, and lab testing phases, it can be beneficial to involve anticipated users of the system. User awareness of the goals of a PACS implementation

and its system features prior to clinical installment can affect the overall success of the system. Installation of system components will be most successful when scheduled during low-volume periods and when all affected users are notified well in advance of the install date. Backup contingency plans must be in place prior to going live in the clinical environment.

The QA/QC program

A comprehensive quality assurance/quality control (QA/QC) program is an extremely important component in the implementation of any new technology, including implementing a PACS. While existing procedures may be a good starting point, it is often necessary to develop new procedures better suited to the technology to be implemented.

It may be useful to establish a *continuing quality improvement (CQI)* committee, consisting of medical physicists, radiologists at all levels (resident, fellow, and attending), radiological technologists, film library personnel, end-user clinicians, and PACS team members, to oversee QA. If possible, this committee should be involved at every stage of PACS implementation, from the planning phase, to installation, training, workflow modifications, QA, and clinical acceptance. Regular committee meetings should be set, with more frequent meetings held as necessary during the different phases of the PACS rollout. The CQI committee can assist in workflow re-engineering for the new PACS environment, creation of new management procedures, and system reconfiguration and fine-tuning. It can also provide a means for user feedback and continued education, and ultimately contribute to the overall acceptance of and user satisfaction with the PACS (Andriole et al. 1998).

Routine system monitoring tools can be put in place to perform preventative maintenance and proactive QA. Procedures such as monitoring transmit and receive queues, file system usage, system uptime and load average, and scanning of log files for warnings of larger consequence can be set up to automatically page the responsible personnel before a problem occurs, potentially avoiding system downtime. All databases and system logs should be automatically routinely backed up.

The documentation of any errors or problems should be assessed to determine if they can be categorized as hardware, software, or personnel. Problem descriptions should be solicited and recorded with as much of the following information as possible: When the problem became known, who reported it, or how it was detected, how long it existed, when it was fixed, what corrective action was taken, and who fixed the problem. If the issue has occurred before, what is its frequency, and is it likely to recur? Could the problem have been anticipated or prevented, and how might this have been done? Is the fix that was applied permanent, is there a better fix than the one implemented, and what steps must be taken to put a permanent fix in place? Were the issues able to be resolved in-house, or was the service vendor called in and, if so, did the vendor respond adequately?

Gathering the answers to these questions will assist in developing a good QA program for a new PACS site.

Problems occurring at image acquisition

The imaging modality is the first entry point into the PACS, and any errors in data input here can propagate throughout the system. Thus, interfacing a PACS to the RIS–HIS and, better yet, DICOM Modality Worklist capability at the imaging device are essential. When a PACS is properly interfaced to the RIS–HIS, input data can be verified by comparison of pertinent demographic data (name, date, time, medical record number (MRN), accession number, exam type) at the PACS acquisition gateway with the data recorded in the RIS. Thus, any imaging exam entering the PACS will be RIS-verified prior to archival and distribution, maintaining the data integrity of the system.

Most imaging modalities are now tightly coupled with the RIS, and provide automatic downloading of demographic information from the RIS, sometimes via barcode readers, to the modality, and hence the DICOM header. This eliminates the highly error-prone manual entry of data at acquisition. Unfortunately for manual data entry devices, any errors in data may result in the image data being held in a queue pending manual (human) inspection and resolution. Continuous feedback should be given to technologists making repeated errors in data entry.

The well-designed PACS holds newly acquired studies in a restricted area (fix-queue or “penalty box”) until the demographic data in the header is matched to a pending exam request from the RIS–HIS. If any failure occurs, such as an incorrect MRN or DOB (date of birth), the new exam will not pass automatically into the system to be archived (although it may be displayable) until the discrepancy has been resolved by human intervention. However, the inverse test has not been implemented. Pending exam orders that are held in the RIS–HIS, but that do not relate to any incoming PACS image data within a certain time frame, should be flagged. Full PACS acquisition QA requires this bi-directional process monitor to ensure that data in the PACS are valid and verified with data in the RIS–HIS, and that all data in the RIS–HIS is acquired into the PACS. This may also assist QA procedures in determining, of the studies that have been ordered and completed, which have no associated report and may not have been read.

Some DICOM transfer of imaging exams (i.e., from CT and MR scanners) to the PACS require autosend-networking pathways to be enabled at the scanner. Unfortunately, these features can easily be turned off (frequently by the service manufacturer) resulting in missed real-time transfer to the PACS. Stressing to the imaging technologists, as well as to the manufacturer’s service personnel, the importance of having the *autosend* enabled at the time of the examination can reduce this problem.

Although many digital angiographic/fluorographic systems are DICOM compliant, few have been integrated into a PACS. The large volume of data typically generated by angiographic procedures is one reason for this. One way to reduce the data volume, and perhaps facilitate connection to a PACS might be to store only key images of an angiographic run, much the way they are filmed. Some manufacturers allow operators to create summary series of the examinations, which could then be transmitted to the PACS for viewing on display workstations. A second problem for incorporation of angiographic images into a PACS arises from the inability of most PACS to do subtraction, pixel shifting, and rapid mask selection—features utilized in most angiographic examinations.

Training

Many acute issues occurring with PACS are related to the adequacy of end-user training. It has been found that designating one or more people per shift as “super users” and training them in commonly occurring problems can lead to faster issue resolution. These super-trained users serve as the single point of contact for problem reporting, and as the first line of defense in troubleshooting these complex systems. The super users are on-site and can investigate any issue and try to resolve it. If they cannot fix the problem, they call the PACS on-call support team, who in turn call the vendor service team, if they cannot resolve the issue themselves. People who function well in this role are those familiar with the clinical environment such as x-ray technologists, film librarians, nurses in a unit, fellows in a section, or other personnel constant in an area.

Training of all the affected end-users would be optimal, but is impractical in a fully functioning clinical environment. Often facilities plan formal training on a new PACS prior to, during, and immediately following display station rollout, for example. But most successful training takes place when the system is clinically operational and radiologists are working with real clinical cases. Because of this, it is often best to train users with a brief introduction to the system initially, and to provide them with just enough information to get their work done. Advanced training on the system can then be given at some later date, after the user has had some experience working with the system for clinical purposes in the normal workflow. Having the more-highly trained super users in the clinical environment can provide support to new users and add to their comfort level with the new technology.

8.3 Electronic Medical Records (EMR)

The information technologies most familiar to radiology departments are PACS and RIS. Often separate image management systems exist for primary interpretation in the radiology

department and for use enterprisewide by nonradiologist clinicians.

While implementation of either one or both of these systems can improve workflow and reduce operating costs, the elimination of film and paper from the practice of radiology is not easily realized without integrating the functions performed by several other information technologies. These systems include HIS, Computerized Physician Order Entry (CPOE) systems, report generation systems, decision support systems, and case-based teaching files, and include features such as single sign-on, electronic master patient index, and context sensitivity. Together these make up the electronic medical record (EMR).

Several of these systems are more widely known to the healthcare enterprise outside of diagnostic imaging departments. They nonetheless contain data essential to high-quality, low-cost radiological practice. The value these systems can bring to medical imaging in the clinical enterprise is high but they must be seamlessly integrated. Including several features such as single sign-on, electronic master patient index, and context sensitivity can help make these information systems tools and technologies most useful to radiology.

An effort known as *Integrating the Healthcare Enterprise (IHE)* provides a framework using existing standards such as DICOM and HL7 to facilitate intercommunications among these disparate systems and to optimize information efficiency (Siegel and Channin 2001). The IHE is a joint effort of the RSNA and the Healthcare Information and Management Systems Society (HIMSS) begun in 1998 to define more clearly how existing standards should be used to resolve common information system communication tasks in radiology.

The IHE technical framework defines a common information model and a common vocabulary for systems to use in communicating medical information. It specifies exactly how the DICOM and HL7 standards are to be used by the various information systems to perform a set of well-defined transactions that accomplish a particular task. The original seven tasks facilitated by the IHE include scheduled workflow, patient information reconciliation, consistent presentation of images, presentation of grouped procedures, access to radiology information, key image notes, and simple image and numeric reports—and profiles continue to be added yearly.

8.3.1 Hospital Information Systems (HIS)

The HIS is the patient's first point of entry into the healthcare system. It is traditionally tasked with patient registration, maintaining patient demographic information, and *admission, discharge, and transfer (ADT)* events. A HIS, also known as a clinical information system, often maintains clinical laboratory results, patient history records, and clinical notes. Sometimes ordering of diagnostic tests, examinations and procedures is handled by an HIS, as are medical insurance and billing activities.

8.3.2 Computerized Physician Order Entry (CPOE) Systems

Computerized physician order entry (CPOE) systems are used to electronically order imaging examinations, for example, at the point of care. Electronic ordering can eliminate the need for paper, decreasing inefficiencies and reducing overall operating costs.

Computerized order entry can also unify information capture for completeness and accuracy, often providing details such as the reason for ordering a specific imaging test, that are often not properly communicated from referring clinician to interpreting radiologist.

These systems may also fill orders and allow for scheduling on-line, and may include context-specific decision support features providing feedback to the nonradiologist regarding the best use of medical imaging. Contraindications, allergy warnings, duplicate examination reminders, and the appropriateness of the requested test are provided with suggestions for a better choice.

A high-performance CPOE with a user-friendly GUI (minimal number of mouse clicks and data input required while capturing all the relevant information) can enhance workflow and productivity and can significantly support the clinical management of the patient, and can often provide a means of communicating results from the radiologist rapidly back to the referring physician.

8.3.3 Radiology Information Systems (RIS)

The RIS typically handles the filling of radiological examination orders, scheduling of the resource on which the imaging is to be done, examination status tracking, report archival, and billing for radiology. Though built on standards, radiology information systems tend to be highly customized to meet the specific needs of an individual radiology department or facility. Some of the functionality of a RIS may be handled in an enterprise's HIS or even in the CPOE system.

8.3.4 Report Generation Systems

Report generation systems handle the original dictation, subsequent transcription, and signature finalization of the radiology end-product image interpretation report. There are a variety of systems and facilities may utilize one or a combination of types. Report generation systems can involve traditional dictation into a recording device, followed by typing of the captured audio by a medical transcriptionist and signature by the radiologist author, resulting in reports on paper or reports electronically filed to the RIS. Or they can use some form of speech recognition system to generate the final radiology report.

Computer-aided medical transcription or back-end speech recognition systems have a mixed workflow with traditional dictation, followed by automated computer recognition

of reports which are then passed to medical transcriptionists for editing before signature by the radiologist. Front-end speech recognition systems can eliminate the medical transcriptionist from the equation with near-real-time recognition of the dictated report, radiologist self-editing, and electronic signature.

Many speech recognition systems include some form of structured reporting, template creation, and dictation shortcuts to reduce turnaround time. For example, a template report could be made for the typical normal chest projection radiograph, with all the pertinent negatives listed. Simply by speaking “normal chest,” a properly formatted, complete report will be created instantly, ready for minor modifications if necessary, followed by signature. Shortcuts for imaging protocols that are used frequently and must be stated in the report (i.e., all the detailed imaging sequences performed in an MRI of the head to rule out seizures) can be stored and instantaneously recalled and placed into the radiology report as needed.

8.3.5 Other Electronic Resources

Decision support systems and case-based teaching files including reference libraries and clinical practice guidelines can be useful not only in the clinical arena, but also in the research and teaching environments. Decision support systems can contribute to the reduction of medical errors, provide feedback as to the appropriateness of an examination, clarify and flag abnormal results, and provide reminders and warnings for contraindications. Drug toxicology and disease databases along with on-line reference libraries and access to the medical literature can also aide clinicians in the diagnosis of disease and the management of patients.

In addition to the use of common integration standards and data models such as DICOM, HL7, the IHE profiles, and XML (extensible markup language), several system features are important to the successful implementation, acceptance, and use of the electronic medical record in the clinical arena. One such feature is the ability of users to access all pertinent information systems seamlessly using a single sign-on. Security, authentication, and access to portions or all of an individual patient’s medical record based on privilege and privacy procedures must all be maintained. The ability to search electronically for any portion or all of a patient’s medical history across multiple and separate healthcare enterprises using a master patient index is proving difficult to implement today, but is a very desirable function.

Context sensitivity including the maintenance of user-, patient-, examination-, application-, and tool-sensitivity while utilizing clinical information technologies is beginning to appear in a few of today’s better integrated healthcare environments. Context sensitivity allows users to access multiple information systems from a single user-interface portal, logging in once to identify themselves across all applications.

While seamlessly moving from one application to another, the user and the patient need not be re-identified for each system; rather, the pertinent patient demographic information should be maintained. Details relevant to the specific examination in question should be passed to each application encountered and the tools presented to a user must be appropriate for the data being presented. The Clinical Context Object Workgroup (CCOW) standard is enabling more sophisticated context sensitivity sharing among today’s clinical information applications, providing more elegant systems integration and greater usability and acceptance of these systems.

8.4 Current Trends and Future Prospects

Medical imaging is increasingly a key triage event in a patient’s encounter with the healthcare system. The ability to eliminate the use of film in radiological imaging is a reality today. In addition to the economic advantages of using PACS for digital medical imaging, rapid access to all clinical information on patients, including imaging studies, anytime, anywhere with security, enhances the quality of patient care.

Still there are existing hurdles today. A PACS is not just a radiological tool. Images are required enterprisewide by many different types of clinicians and other healthcare providers. Images are required for viewing in emergency departments, intensive care units, surgical operating rooms, outpatient clinics, and referring physicians’ offices as well as for teaching conferences and at home for viewing by patients and clinical providers. Unless PACS can also deliver images to everyone in the healthcare enterprise who requires them, film cannot be eliminated and facilities will have to operate in a painful mixed environment.

Web-based enterprise PACS applications do exist and continue to improve in their performance. Several requirements in the enterprise environment make transition to the all-digital, totally filmless medical imaging facility more difficult than just within the radiology department. The web-PACS enterprise application GUI must be very intuitive—analogue to the rental car model. Most licensed drivers are able to get into a rental car, orient themselves as to where the lights and windshield wipers are, and then go ahead and drive. They do not need to know how a car works in order to drive it, and the user interface is very standard across most all models. The car works robustly and reliably, and the user does not need to read a manual before they can operate it. Unfortunately, the state-of-the-art in computer GUIs is not quite as intuitive, but much progress has been and continues to be made in this area, making GUIs more self-training and bulletproof. Human-computer interfacing and interaction along with GUI design are currently active areas of research and discovery.

Web-PACS applications are often required to operate in mixed-platform environments to accommodate PC,

Macintosh, and Unix boxes. This is sometimes problematic. Applications must be improved to be able to handle bottlenecks in the system at both the input to the database and the outputs to multiple users accessing the system simultaneously.

In summarizing the key components and essential features for clinical implementation of a PACS, all newly acquired image acquisition devices or imaging modalities should be required to conform to the DICOM standard image format and communications protocol. Devices and PACS in general operate best when well interfaced to other clinical information systems such as the HIS–RIS, report generation systems such as speech recognition applications, CPOE, and decision support systems. The inherently digital imaging modalities should be acquired into a PACS using direct DICOM capture. Film digitizers such as laser scanners can be used to acquire imaging examinations existing only on film into a PACS, if required. Acquisition of digital projection radiographs such as the conventional chest x-ray can be achieved using CR or photostimulable phosphor devices or DR devices that directly convert images to digital at the time of x-ray exposure. CR and DR devices are likely to co-exist for some time.

Archival media and devices will continue to advance, with databases becoming more patient-centric and seamlessly searchable. Computer networking will also improve not only in hardware, but also in the network management software strategies. Display GUIs must continue to become more intuitive and robust, and the monitors themselves will trend toward LCD devices as opposed to CRTs.

Predictors for success of the introduction of new technologies into the clinical arena include ease of integration into the existing workflow and/or change management activities to optimize new workflow with new devices. Systems must be reliable, simple to use, and have optimum performance so that processes can be completed more efficiently than in the analog film-based world. Systems must be flexible and configurable on a per-user basis and they must include fault-tolerance, redundancy, and error-tracking capabilities.

In the future, radiology can help to drive the changes that will greatly impact all of healthcare. Medical image management systems are maturing outside of the radiology department, providing hospital enterprisewide access to clinical images and information via the Internet. The Web will change the way people communicate and perform their duties. Web-based PACS applications will become the norm, offering ubiquitous distribution of and access to clinical data. Computer workstations will become less costly, more reliable, and have more intuitive GUIs. All relevant medical information systems will become more tightly integrated with each other, sharing and maintaining user-, patient-, image-, and application-, context-sensitivity such that multiple distinct applications perform virtually as one.

Future PACS are likely to be supported on the less expensive off-the-shelf PC platforms using industry standards.

PACS display stations are likely to be configured with fewer numbers of monitors—two within radiology and image-intensive specialty areas and one out in the enterprise. Small- and medium-sized community hospitals, private practices, outpatient centers in rural areas, and some indigent care facilities will begin realizing the benefits of PACS and digital medical imaging.

PACS functionality will be incorporated into hand-held devices for some applications and wireless transmission will mature in the clinical arena. Improved integration with other information technologies into the total EMR, including automated speech recognition systems will enable a more efficient filmless environment as well as a paperless workflow.

Advanced image-processing utility and translation from the research environment to clinical applications will increase. Three-dimensional displays, the use of color and video will increase, as will the incorporation of computer-aided detection. Decision support through outcomes research, and evidence-based medicine will become more prevalent. Multimodality functional and molecular imaging will mature clinically and the number and power of value-added applications for specialties outside of diagnostic imaging will increase. Virtual reality imaging presentations and image-guided surgery applications are likely to become more commonly used clinically.

It is likely that the radiological interpretation process will need to transform in order to handle the information and image data overload currently plaguing medical imaging. This image interpretation paradigm shift will be required in order to evaluate, manage, and exploit the massive amounts of data acquired in a more timely, efficient, and accurate manner.

Discovery and development of this new paradigm will require research into technological, environmental, and human factors. Interdisciplinary research into several broad areas will be necessary to make progress and ultimately to improve the quality and safety of patient care with respect to medical imaging. These areas are likely to include studies in human perception; image processing and computer-aided detection; visualization; navigation and usability of devices, databases, and integration; and evaluation and validation of methods and performance. The result of this transformation will affect several key processes in radiology, including image interpretation, communication of imaging results, workflow and efficiency within healthcare enterprises, diagnostic accuracy and a reduction in medical errors, and ultimately the overall quality of patient care (Andriole et al. 2004).

Twentieth-century medical imaging was film-based, where analog images were interpreted on viewboxes, and film was stored as the legal imaging record. Film had to be manually disturbed from one location to another and could be accessed in only one physical location at a time. Twenty-first century medical imaging will be characterized by digital image acquisition, softcopy computer interpretation, digital image archives, and

electronic distribution. It is anticipated that the use of PACS and other information technology tools will enable the filmless, paperless, errorless era of imaging in medicine.

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