A digital prescription for X-ray overload

Already on the horizon are networks for sending diagnostic images between hospital departments or to remote sites, to circumvent present film logjams

ADVANCED TECHNOLOGY

MEDICAL ELECTRONICS

When an accident victim is rushed to the operating room, technicians must shoot a series of X-rays with a portable unit before surgery can be performed. At best, the delay is only about 10 minutes. But in all too many cases, the technicians find the film under- or overexposed and must reshoot the series, possibly three or more times. To interpret the image, the surgeon then must consult with a radiologist over the phone or in the radiology department. Victims in critical condition may trigger a mad scramble as doctors, radiologists, or technicians rush wet X-rays down hallways between the operating room and radiology.

Radiology is vital to the life-saving efforts of surgeons and other physicians, but precious time can be lost generating the images and transferring them to and from the operating room. Furthermore, hospitals are straining under the task of storing and managing the deluge of diagnostic films produced every year. A 300-bed hospital generates about 1 gigabyte (8×10^9 bits) of picture information every day and is legally bound to hold it for three to seven years—30 years in the case of silicosis or black lung disease, illnesses that may have relevance to future lawsuits.

Consequently, hospital warehouses are filling with X-ray film and written reports that are important for analysis of patient histories, for comparison between patients, and for analyzing the progress of disease. Yet only a fraction of the information's potential is being used because access is so complicated. What is more, films are easily lost, erasing valuable medical histories.

The digital promise

As early as the mid-1960s, some visionaries saw the computer as a solution to the hospitals' dilemma. The computer could transport and store the data, as well as route and retrieve it, much more quickly and efficiently than people could, and with less chance of losing it. Diagnostic imagers with a digital output would eliminate wrong exposures and delays due to film developing. Besides digitized images, the system would also handle patient tracking and billing and equipment scheduling in a hospital-wide network. But a quarter of a century ago, computing hardware and software were not yet advanced enough to handle hospital information flow.

By now, although several commercial products are available for tracking and billing patients and for scheduling equipment, research institutions are only just attempting large-scale implemention of picture-archiving and communication systems (PACS)—the technology that would transmit and store diagnostic images. PACS would yield the true jump in hospital efficiency, but a number of challenges must be met and controversies resolved before it becomes a reality.

To date, about a dozen universities in the United States have some portion of a PACS operating routinely in their medical centers, though these are all considered research systems. Almost all these universities have additional systems for pure research. There are about a half-dozen partial PACS in Europe and another half-dozen in Japan.

By definition, PACS accepts pictures or images, with associated text, in digital form and then distributes them over a network. The components of a PACS include control computers and a communication network, interfaces to imaging devices, storage media, display stations, and printers [see p. 36].

One obstacle to introducing large-scale PACS is that conventional X-ray units still produce about 80 percent of the image data in hospitals. Not only does X-ray film take time to develop, but before going onto PACS, it would have to be digitized by any of a variety of devices: video digitizers, linear array scanners, mechanical flatbed and drum scanners, or laser scanners.

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Defining terms

Computed radiography: a diagnostic imaging technique that directs X-rays at the patient as conventional X-ray units do, but develops the image immediately by scanning with a laser beam, a process that also digitizes the image.
Computed tomography: a diagnostic imaging technique (sometimes called a CAT scan) that directs X-rays axially around a patient and computes a two-dimensional image of the body slice that is displayed on a cathode-ray tube (CRT).
Contrast resolution: the number of gray levels at each pixel in a digital image, determined by raising 2 to the power of the number of bits at each pixel.
Digital subtraction angiography: a technique for imaging blood vessels that takes X-ray images both with and without a contrast medium injected in the area of interest and subtracts the two to suppress surrounding details.
Dynamic range: the range of a signal's amplitude compared to the maximum noise level; in the case of a CRT display, determined by the number of gray levels at each pixel.
Flicker: a repetitive variation in luminance in a CRT display.
Magnetic-resonance imaging: a diagnostic imaging technique that detects the variation in density and relaxation times of hydrogen nuclei throughout a patient's body when it is subjected to a strong magnetic field and displays a two-dimensional image on a CRT.
Modulation depth: the difference in brightness between black and white in a CRT display.
Nuclear medical imaging: the first diagnostic imaging technique to produce digital images: the patient is injected with a radioactive tracer element that collects in the tissue to be imaged; its distribution is recorded with a gamma camera.
Persistence: the rate of decay of luminance of a CRT display after the stimulus is removed.
Primary diagnosis: a radiologist's complete assessment of a patient's condition, based on the radiological images and patient history presented.

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More recent imaging devices, such as computed tomography, magnetic-resonance imaging, nuclear medical imaging, and ultrasound imaging, produce pictures digitally and so would be easier to interface to PACS. But only recent models have digital outputs because in the past there was no need to interface to a computer, and manufacturers feared digital data would give competitors proprietary information about the way the images are generated. In most existing models, the digitized images are converted to video signals inside the machine, displayed on a cathode-ray tube (CRT), and photographed onto film, which must then be managed just like conventional X-ray film.

A suitable digital replacement for X-ray film is a prerequisite to introducing a complete PACS. Computed radiography is the most likely candidate, though it has only half the resolution of film and presently costs more. Introduced in the early 1980s, computed radiography uses the same equipment as conventional X-ray units, except the X-rays impinge on an imaging plate, instead of film, and a laser beam scans the plate to develop the image. The photons emitted during the laser scan are converted into an electric signal by a photomultiplier and digitized to produce an image typically containing 1760 by 2240 picture elements (pixels), each 10 bits deep. Besides saving time, the imaging plate tolerates a greater range of exposure, virtually eliminating retakes.

But the units for reading the plates are expensive. Current models are about $400 000, down from $750 000 in the last few years. Consequently, hospitals acquire only a few, increasing the time radiologists waste getting to the units and waiting to use them. A reduction in the readers' cost would be a strong stimulus to PACS. Ideally, direct digital sensors would be built into examination tables so that the image data could be transmitted directly to PACS and displayed on any workstation, obviating the need for transporting cassettes to reading machines.

Displaying the image

Radiologists commonly view diagnostic films in a reading room on lightboxes or alternators. The latter are lighted panels that can store up to 200 films, which are rotated into view by pressing a foot pedal. Only one group at a time can view the images, and there is more risk of their being lost, misfiled, or stolen than with digital images—though errors could be made in operating the computer or entering data in a PACS. The big advantage of the reading rooms is that colleagues can easily view many images at a time and exchange information and opinions.

The standard by which PACS display stations will be judged is the alternator, which displays up to eight images simultaneously, changes a set of images within seconds, and delivers the very high resolution of the film display medium. It even allows rudimentary image processing. To change the image's apparent magnification, the radiologist moves nearer to the film or uses a magnifying glass. To see the details in a dark area of the film, the radiologist holds it in front of an incandescent lamp called a hot light.

To rival the alternator, the digital viewing station must display images of high quality, several at a time, and be able to change them rapidly, as well as provide simple image processing. The basic components are one or more video monitors, video memory, and an interface to the image network. This would suffice for a review console, which would help a referring physician to visualize the radiologist's report—a job requiring only moderate resolution. Analysis consoles, used for primary diagnosis and disease quantification, would be much more sophisticated, including large semiconductor memories, Winchester disk storage, and special image-processing and -analysis hardware.

There is no agreement on just how high the image quality of digital radiology consoles must be. Many factors contribute: spatial resolution, image size and brightness, contrast resolution, noise, flicker, and persistence. Recent studies show that the resolution required depends on examination type and the radiologist doing the reading. Most diagnoses require resolutions of 1000–2000 pixels in each direction, but even more may be required to see certain conditions, such as hairline bone fractures and pneumothoraces (thin pockets of air at the periphery of the lung). The latest monitors have as many as 2560 by 2048 pixels with 60-hertz screen refresh rates. The Medical School of the University of California, Los Angeles (UCLA), is routinely using 1024-by-1024-pixel displays for physician conferences on cases, while for primary diagnosis, its research program is investigating displays with around 2048 by 2048 pixels.

Monitor screens 19 inches on the diagonal are generally large enough. The contrast resolution—the number of gray levels at each pixel—also varies with the type of diagnosis, but the general requirement is 10–16 bits per pixel (a pixel with 10 bits has 1024 gray levels).

While Georgetown University Medical Center in Washington, D.C., and the University of Pennsylvania in Philadelphia have installed commercial workstations from AT&T Co. and Virtual Imaging Inc. in Sunnyvale, Calif., respectively, many are developing workstation hardware tailored to their needs. The University of North Carolina at Chapel Hill recently designed Filmplane 2 around a high-performance Stellar computer; the system can provide images in miniature, to speed sorting through them. Workstations built here at the University of Arizona have 1024-by-1536-pixel resolution and a touch-screen interface. In progress at the University of Washington in Seattle is work on its GSP-3 workstation incorporating a NeXT machine with numerical processing power, graphics, special image processing, and the latest in digital processors from Texas Instruments Inc.

If digital radiology is to replace film, the display station must also have reasonable speed, modularity, and cost. The CRT cannot display as many images at once as the light box can, so it must compensate by displaying a series of images rapidly. Radiologists become impatient if the image writing time is any greater than 2 seconds.

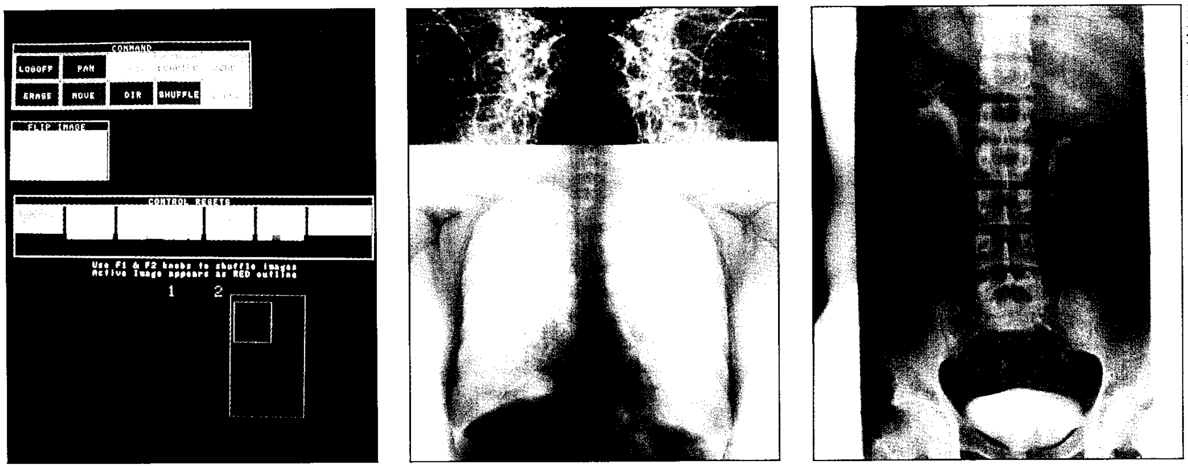
Image processing will selectively enhance aspects of film images in order to adapt them for display on the CRT. The technique being most intensively investigated is adaptive histogram equalization (AHE), developed at the University of North Carolina. AHE automatically compresses the film image's dynamic range—the number of gray levels—for display on a CRT, which has much less dynamic range than film does. Research is also under way at the University of Chicago and other schools on processing software that will aid diagnosis.

The rate of PACS introduction hinges on radiologists' acceptance of processed images. The medical community in general has resisted image processing because it can introduce details not present in the original image. However, processing techniques that introduce minimal artifacts are being developed, and once radiologists gain understanding of the various types of artifacts, they can disregard them.

Image compression, another form of image processing, might encourage acceptance of PACS by reducing its cost. The technique compresses image data, thus reducing the system storage capacity and the transmission bit rate without affecting the diagnostic performance of the system. In general, data can be compressed reversibly or irreversibly. A reversible algorithm will allow exact recovery of the original image from the compressed version; an irreversible algorithm will not, but can attain much higher compression ratios. As a rule of thumb, the highest reversible compression ratio for a medical image is three; in other words, the compressed image will occupy one third the space of the original.

Trouble in storage

For every thousand beds, a large hospital generates about 3 gigabytes of picture data per day. A stack of 360-kilobyte floppy disks containing 3 gigabytes would measure 20 meters, the height of a seven-story building. Storing the five-year aggregate of such a hospital's archived picture-data would require a stack of floppies all of 36 700 meters tall—the height of a 12 000-story building.



University of Arizona

A digital radiology workstation at the University of Arizona has three displays. One shows the menu (left) for managing the storage and retrieval of images. The other two screens display the images (center and right), with somewhat less resolution than X-ray film.

The storage subsystems in a PACS must be able to hold all this data as well as allow convenient and rapid access to them. To keep speed up and cost down, PACS database archive systems will likely be multilevel, hierarchical units containing a mixture of storage technologies. Their structure would conform to the logical organization of current archives, which arrange film into immediate, short-term, and long-term storage categories.

At present, recently made films are mounted on alternators or kept in stacks of envelopes next to light boxes in the reading rooms, and can be accessed within seconds or minutes. Films up to a year old are usually placed in a film library near the reading room, and older films go into basements and distant warehouses. This multilevel storage strategy keeps the average access time low, while the total amount of stored data remains very high. Furthermore, as the storage spaces increase in capacity from alternator through warehouse, they decrease in cost.

The analogous PACS arrangement would be semiconductor memory for immediate, magnetic disks for short-term, and optical discs for long-term storage. Semiconductor memory, which would give PACS an access time in milliseconds, presently costs about $100 per megabyte. Winchester magnetic-disk technology has an access time on the order of seconds and costs around $10 per megabyte. Optical-disc jukeboxes store data for well under $1 per megabyte, but access time rises to minutes. A present-day film library, filling a large room, can be stored in an optical-disc jukebox about a meter on an edge.

Whether all data will have to be duplicated and stored for backup purposes is open to question. Some have proposed backing up only critical data or storing the backup data in highly compressed form suitable only for verification of a diagnosis, but not primary diagnosis. Legal considerations will most likely drive hospitals to completely duplicate the data.

Washington University Medical Center, St. Louis, Mo., has 12.5 gigabytes of magnetic-disk storage for data requiring immediate access and 128 gigabytes on a DEC optical-disc jukebox for long-term storage. Georgetown University's Systek optical-disc jukebox, with 89 platters of 2-gigabyte capacity each, is already half full after one year of storing only a fraction of its hospital's picture information.

UCLA has optical storage systems from Eastman Kodak Co., FileNet Corp., and Hitachi Ltd., and is developing a personal image-filing system, in which each patient's data is stored on one 3- or 5.25-in. optical disc. A similar idea, being investigated by the University of Wisconsin Medical School in Madison for the U.S. Army Biomedical Research and Development Laboratory, would put each patient's imaging data on an optical card about the size of a credit card. With the help of data compression, the card can hold nine images, each having a resolution of 1280 by 1024 eight-bit pixels.

Lifelines

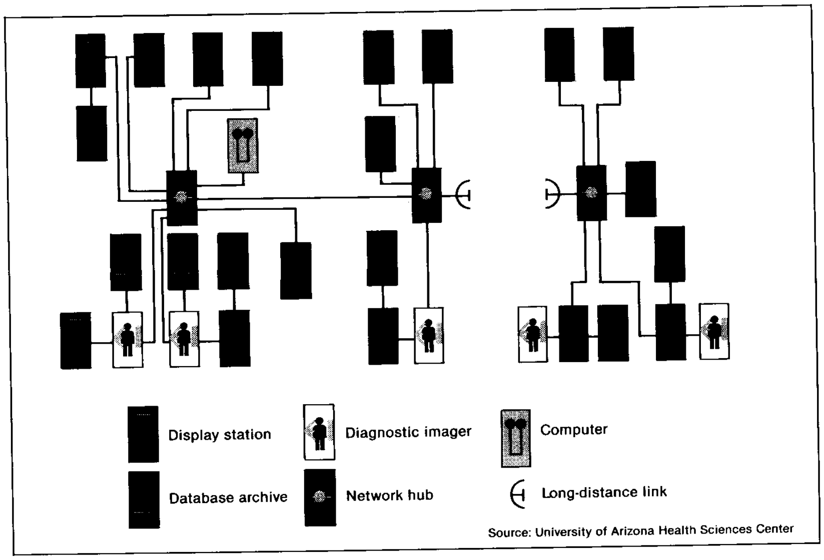
A PACS contains three types of networks. A local-area network (LAN) carries pictures between imaging devices, data storage units, and display stations within one department or clinical section. A wide-area network (WAN) links different LANs within a hospital, and a teleradiology network transmits pictures to other hospitals or remote sites for diagnosis at a distance.

Teleradiology is of growing importance for sparsely populated areas, such as Alaska or the southwestern United States, that may lack a good geographical distribution of radiologists or physicians who can make sophisticated readings to diagnose unusual conditions. It can also minimize duplication of expensive imaging facilities in a medical center spread among a number of sites throughout a region. The University of Arizona is discussing the possibility of using teleradiology to avoid shipping inmates in the Arizona Penal System to external facilities for routine radiological exams.

The University of Washington Medical Center in Seattle communicates at 1.544 megabits per second with the local Veterans Administration Hospital over very high-speed telephone lines. It also has a teleradiology link with Alaska over normal telephone lines, and is in the demonstration phase with a satellite link to Alaska. Communications costs must come down considerably, however, before such systems are economically viable. The University of Arizona's teleradiology link over phone lines to the Veterans Hospital 11 kilometers away resulted in telephone bills of $1200 per month.

Only fiber optics can provide the transmission speeds that will be required for the LANs and WANs. A study at the University of Arizona's hospital found that to match the present flow of picture information on film, a digital network would have to operate at 100 Mb/s, excluding overhead. The overhead can be substantial; Ethernet transmits signals at 10 Mb/s, but a moderately loaded Ethernet can transmit only about 500 kilobits per second.

Washington University Medical Center has had a functioning Ethernet from Digital Equipment Corp. connecting to a cable television network for several years, along with a 10-Mb/s microwave link to interconnect with the main campus. UCLA has several types of networks installed, including Ethernet, broadband, a 100-Mb/s Canstar optical-fiber network, and a fiber-distributed data interface (FDDI), an American National Standards Institute standard that operates at 100 Mb/s. For research purposes only, the University of Arizona has installed a 140-Mb/s optical-



A picture archiving and communication system (PACS) transmits and stores radiological images in local-area and wide-area networks. Medical imaging devices, such as computed-tomography and magnetic-resonance imaging scanners, feed images to the network, which can then display them on any of its workstations. Images are stored in database archives containing semiconductor memory, magnetic disks, or optical discs.

fiber network made by Toshiba Corp.

About 3000 images per day are transmitted from magnetic-resonance imaging, ultrasound, computed-tomography, and X-ray devices across the network at Georgetown University to eight workstations on AT&T's 40-Mb/s optical-fiber network, four workstations on Ethernet, and a number of dial-up workstations. The University of Kansas Medical Center in Kansas City has a HYPERchannel network operating at a speed of 10 Mb/s connecting to computed-tomography and magnetic-resonance-imaging scanners, ultrasound, digital subtraction angiography, digitized fluoroscopy, nuclear medical imaging, and a Digiscan-Siemens computed radiography system.

Washington University recently began an experiment with a modest-bandwidth integrated-services digital network (ISDN) in cooperation with Southwestern Bell, the local telephone company, to serve as a WAN operating at 64 kb/s on a single channel or 128 kb/s on a dual channel.

Standards issues

An obstacle to implementing PACS is the diversity of equipment that must be connected, particularly the various types of imaging devices. It is very difficult to get products from various manufacturers, and even different pieces of equipment from the same manufacturer, to communicate with one another. One solution is a standard developed by the American College of Radiology in conjunction with the National Electrical Manufacturers Association (the ACR/NEMA Standards Publication No. 300-1985, Digital Imaging and Communications).

Organized in layers to break the problem down into more manageable pieces, the standard covers both the hardware—the physical medium layer—and the software, denoted as the physical, data link, and transport/network session, presentation, and application layers. The terminology is the same as for other networks, including the International Standards Organization's Open Systems Interconnection (ISO/OSI) standard protocol, except that the two ISO/OSI transport and network layers have been combined into a single ACR/NEMA layer.

The University of Pennsylvania built the first fully integrated and functioning ACR/NEMA interface in 1986. Shortly thereafter, Matrix Instruments Inc., Orangeburg, N.Y., now a division of AGFA Corp., Ridgefield Park, N.J., became one of the first companies to offer an interface board for sale, which the University of Arizona has connected to its Toshiba network.

In its present form, the ACR/NEMA specification goes into a good deal of detail about the session to physical layers, but lacks specificity for the two upper layers. The standard, first issued in 1985, was originally conceived as providing point-to-point connection between pieces of medical imaging equipment, rather than as a true network. The transfer protocols, in particular, consist of a mixture of attempts to satisfy both goals. The ACR/NEMA committees are trying to correct this problem and others, including the fact the standard was developed for now obsolete 16-bit transfer. The standard has also garnered criticism for not conforming to hardware standards for other LANs, virtually ensuring higher costs for medical LANs because the hardware will have to be manufactured in small quantities.

The fundamental challenge in devising a network for medical images is that it must handle not only multiple types of images with various sizes, number of pixels, and pixel depths, but multiple media—picture, voice, and text. The various media have differing needs that affect efficient network operation. For example, pictures should be transmitted in long data packets, whereas voice is more suited to short packets to minimize the delay between speakers. It is unclear whether all data will travel on one channel or several channels to separate the various media. An optical-fiber network could transmit all data on one physical channel, but separate the media by transmitting them at differing wavelengths of light.

Radiologists' resistance to the digital hospital may be the greatest obstacle to implementing PACS. The new technology will force a change to their routine, requiring a lot of their time initially to learn to use the new image-handling methods. Some even see a wide distribution of diagnostic images as a threat to maintaining the highest-quality patient care since it will help physicians sidestep the radiologist and make their own readings.

The technology for integrating digital information handling systems in hospitals is available, but it is too expensive for immediate introduction. The cost is decreasing and the technology is improving, however, and ultimately, the explosive growth of hospital information will compel the development of digital systems.

To probe further

A basic reference for digital radiology is *Elements of Digital Radiology: A Professional Handbook and Guide* by H.K. Huang, published by Prentice-Hall, Englewood Cliffs, N.J., in 1987.

For up-to-date technical information on PACS, consult the 1989 *Proceedings of the Society of Photo-Optical Instrumentation Engineers Medical Imaging III*, Vol. 1093 PACS, System Design and Evaluation. Contact SPIE at 1000 20th St., Bellingham, Wash. 98225; 206-676-3290.

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