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Digital Radiographic Image Presentation and Display[1]

The paradigm shift from film-based to filmless imaging has redefined the practice of radiology. All medical practitioners are affected by this transition, including technologists, radiologists, and referring clinicians. They face new challenges and opportunities, along with hopes for improved productivity, operational efficiency, image quality, and interpretation accuracy.

In this chapter, we will evaluate how image display is affected by the transition from film-based to filmless operation, specifically as it pertains to digital radiography (DR), which encompasses computed radiography (CR) and other DR technologies. Questions addressed will include the following: *(a)* What constitutes good image display? *(b)* What are the essential components in optimizing image display? *(c)* What role does the end user (ie, radiologist) play in optimizing image display?

To answer these questions, we must evaluate a number of environmental, technical, and perceptual issues. In a digital imaging environment, radiologists play a key role in optimizing image display. This is contrary to their role in film-based operation, where image display is a relatively fixed and static process. Images are acquired by a technologist, reviewed for quality assurance, transferred to the file room, and hung on a view box or film alternator for interpretation. The components of image display are simply the film and the view box, with little to no opportunity for the radiologist to alter how the image is displayed for final interpretation. The "tools" of the radiologist in the interpretation process are crude at best and limited to the hot light, magnifying glass, and minifying lens. Most image display and interpretation occur within the confines of the radiology department and are often performed in a large open room, filled with ambient noise and light. Radiographic studies are often displayed in a single-image format, with the hope of identifying all pertinent anatomic regions and types of pathologic conditions. This process is fraught with limitations and often results in technically flawed studies with equivocal results. The radiologist is largely a sophisticated "reader" of images, with little to no role in image presentation and optimization.

With the transition to DR and picture archiving and communication systems (PACS), image display becomes a dynamic and flexible process. Although specific technologies play an important role in how images are displayed, the radiologist can now become a proactive participant in the processes of image display, presentation, and processing. This participation creates opportunities for the radiologist, including customized image display presentation, incorporation of decision support tools, selective use of

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image-processing algorithms, and manipulation of the digital images with a variety of electronic tools. Although environmental and technical factors are not deemed particularly important for image display in a film-based department, these factors take on great importance in filmless operation and will be discussed in more detail. The most important point is that radiologists largely control digital image display. If they take full advantage of the opportunities and technologies available, their overall performance can be enhanced. If, however, they choose a passive approach, then they will realize no gains in productivity or interpretation accuracy. DR is, to a certain extent, a double-edged sword. The ultimate success or failure is largely predicated on the willingness of the end user to become intimately involved in the processes of image presentation, processing, and perception.

EFFECT OF COMPUTER HARDWARE ON IMAGE DISPLAY

A number of important decisions must be made in the transition to filmless operation with either CR or DR. The view box will effectively be replaced with a computer workstation, which is the primary vehicle for image display. Selection of the computer workstation is critical and will have a dramatic effect on radiologist performance. Various display workstation parameters must be considered, including the type and number of monitors, resolution, brightness, and quality control utilities.

The two principal types of commercial monitors available for soft-copy image display are liquid crystal display (LCD) and cathode-ray tube (CRT) monitors. LCD monitors have a number of theoretical advantages when compared with CRT monitors, including higher luminance, longer lifetime, less drift over time, smaller effective pixel size, reduced reflection and glare, and reduced sensitivity to ambient light.

The major disadvantage inherent in LCD monitors is the "angle of regard" phenomenon, which occurs when the image is reviewed off axis. Although LCD monitors offer the viewer excellent luminance and image uniformity when the image is viewed on axis, image detail and overall observer performance are compromised when images are reviewed to the side or up/down, because of a dramatic decrease in luminance (1). This increases the importance of ergonomics and reading room design.

In a recent study performed at the Baltimore Veterans Affairs Medical Center (BVAMC), investigators compared observer performance by using dual CRT and LCD monitors in the interpretation of digital chest radiographic images (2). The investigators compared the clinical performance of 5-megapixel CRT and 3-megapixel LCD monitors, which are comparably priced. Tested performance measures included radiologist interpretation time, interpretation accuracy, confidence in diagnosis, and perceived image quality. No statistically significant differences were observed between LCD and CRT monitors for any measured parameters, even though monitor resolution and brightness were optimized for CRT. Additional studies are currently underway at BVAMC to compare the clinical performance of dual 5-megapixel CRT and LCD monitors, along with large single-screen 9-megapixel LCD monitors.

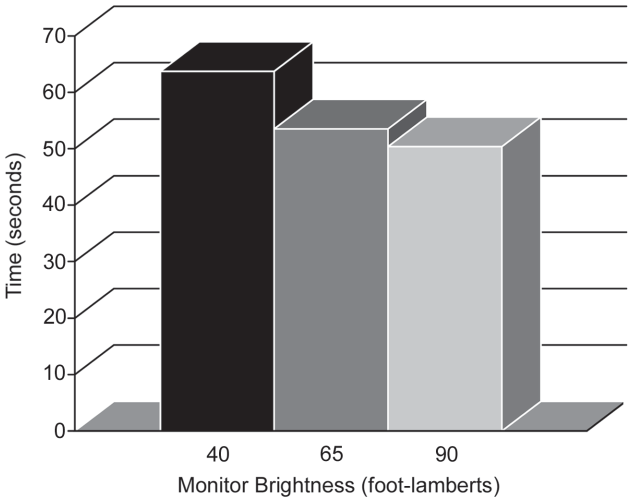

Figure 1. Effect of CRT monitor brightness on reading times for general radiographic studies. Increased monitor brightness is associated with an interval decrease in interpretation times.

One interesting observation to come out of the study of LCDs and CRTs was the importance of window level optimization on radiologist productivity in interpreting soft-copy DR images. Interpretation times increased by more than 70% when window level adjustment was manually performed by radiologists, compared with interpretation times for images not requiring window level adjustment. This phenomenon has been observed in other studies performed by the authors and illustrates the importance of window level adjustment and the lookup table in optimizing digital image display and radiologist productivity in a soft-copy reading environment.

With regard to the number of monitors, PACS adopters are becoming more likely to choose two-monitor rather than four-monitor workstations. This change largely reflects improved functionality with current software programs, as well as advances in image display. In the first generation of PACS, most radiologists elected to reproduce the same reading environment and pattern experienced with film. A horizontal four-monitor configuration allowed side-by-side comparisons between current and historical images, in a manner similar to display presentation with a multipanel view box or film alternator. A two-view chest radiographic examination therefore was presented with the current study displayed on the central

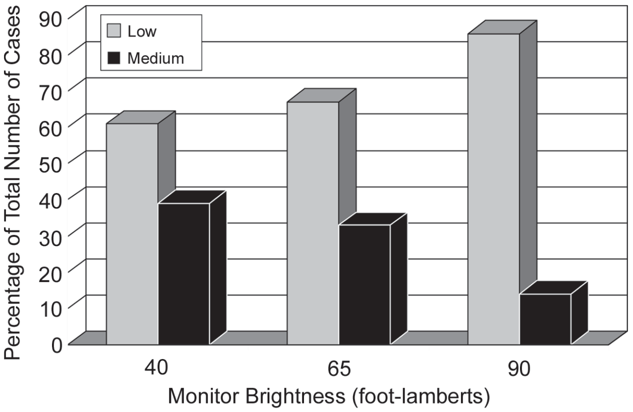

Figure 2. Effect of CRT monitor brightness on self-reported fatigue (low or medium) in the interpretation of general radiographic examinations. Increased monitor brightness is associated with decreasing levels of fatigue.

monitors and the historical comparison images on the peripheral monitors. Each monitor was used to display a single image in full format, much akin to hard-copy display.

As experienced users began to appreciate the advanced functionality afforded with PACS, preferences shifted toward two-monitor configurations. This shift was driven by a number of factors, including the capacity for split-screen functionality, user-specific hanging protocols, and vertical "stacking" of images on a single monitor. Newer large-screen LCD monitors offer split-screen functionality with a large display (22.2 inches) and high (9-megapixel) resolution that effectively offers the equivalent of two 4.5-megapixel 11-inch monitors on a single screen. As previously stated, additional studies are currently underway to compare user performance with conventional two-monitor and single large-screen configurations. As monitor technology and functionality continue to improve, this trend toward using fewer monitors is likely to continue.

The subject of monitor resolution remains somewhat controversial, with conflicting data reported in the radiology literature. Although cross-sectional images such as those from computed tomography (CT) and magnetic resonance imaging can be viewed at full fidelity with lower-resolution 1K monitors, DR requires 2K monitors for full fidelity. Some authors have advocated use of the zoom-and-scroll tool, which allows for use of a 1K monitor in lieu of a 2K monitor, with similar diagnostic accuracy but at greatly reduced cost. However, this strategy comes at a considerable price, in terms of decreased radiologist productivity, by prolonging reading times and increasing operator fatigue (3). Fortunately, the industry trend in declining hardware costs is also being realized for workstation monitors. With the continued decline in monitor prices, the cost differential between 1K and 2K monitors will become less of an issue to new PACS adopters.

Two of the most overlooked factors contributing to observer performance and perceived image quality are monitor brightness and quality control. Radiologists tend to ignore equipment calibration and operational standards. Even though an improperly calibrated monitor can impair performance, most radiologists view monitor optimization as an exercise for the physicist and/or the PACS administrator. This thinking is ironic, considering the fact that the ultimate liability for misdiagnosis of medical images lies with the radiologist.

Monitor luminance is a critical component in maximizing contrast resolution and the perceived gray scale. The results of previous work have shown that both objective and subjective measures of radiologist performance are improved with optimized levels of monitor brightness (4). For CRT monitors, monitor brightness levels of 90–100 foot-lamberts are recommended and have been shown to improve interpretation accuracy, reduce interpretation time, and reduce subjective levels of fatigue (Figs 1, 2). Theoretical disadvantages of increased monitor brightness include focal spot "blooming" (resulting in deceased spatial resolution) and decreased monitor tube life expectancy. These limitations are minimized with LCD monitors, which operate at higher luminance levels, have a longer lifetime, and have smaller effective pixel size. It is important to note that higher levels of monitor brightness have been associated with reduced use of workstation tools (ie, window level adjustment), which largely accounts for the reduced interpretation times. This emphasizes the previous point that image display optimization and radiologist productivity go hand in hand. Any sacrifice in image display quality will be balanced by a decrease in radiologist performance, whether measured in terms of productivity or diagnostic accuracy.

However, not all end users are equally affected by limitations in image display. Soft-copy experience, subspecialty expertise, and level of training all appear to influence how much observer performance is affected. This was observed in a recent study performed at the BVAMC that evaluated the clinical consequences of degraded monitor performance in the soft-copy interpretation of chest CR images (5). The results of an earlier study had demonstrated a higher rate of monitor replacement (41% annually) and shorter monitor life expectancy (2.4 years) than initially anticipated (6).

When the effect of monitor quality on interpretation time was assessed, a small incremental time savings was observed with increasing monitor quality. Interestingly, this time savings was observed only for abnormal cases. In cases interpreted as "normal," interpretation time was unrelated to monitor quality.

The relationship between interpretation accuracy and monitor quality was far more interesting and complex. For the combined group of readers tested, there were no appreciable differences in sensitivity related to monitor quality. A small (statistically significant) incremental improvement in specificity and overall accuracy was observed when the highest level of monitor quality was compared with all other levels. This observed relationship between improved specificity and overall accuracy and the monitor quality was observed only for the subset of general radiologists participating in the study. The subset of subspecialty-trained thoracic radiologists was less influenced by monitor quality and consistently maintained higher levels of interpretation accuracy than general radiologists for all levels of monitor quality. When the misinterpretations among general radiologists were analyzed, most false-positive interpretations were found to occur with poorer-quality monitors. This finding suggests that such monitors, in the hands of less-experienced less-specialized readers, can potentially lead to increased ordering of added imaging studies, additional consultations, and increased overall cost of patient care. This finding underscores the need for rigorous quality control within the filmless imaging department, through the use of mandatory computerized quality assurance or quality control programs (Figs 3, 4).

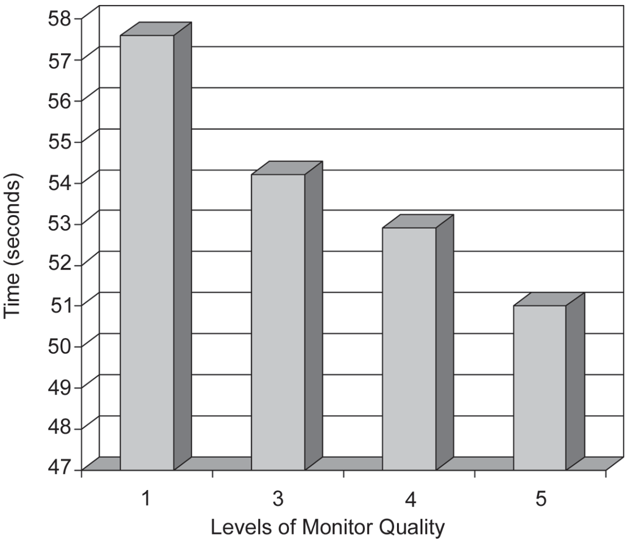

Figure 3. Effect of monitor quality (rated 1–5) on interpretation time for general radiographic studies. Increases in objective measures of CRT monitor quality are associated with decreases in interpretation time. Numbers on the horizontal axis represent CRT monitor quality, with higher numbers indicating better quality (1 = poor, 5 = good [no monitors rated as 2]).

Display calibration is a frequently overlooked area of monitor quality control that has a profound effect on image display. Optimum perceptual performance is achieved with a perceptually linearized display function, which is designed to match the projected image with the perceptual capabilities of the human visual system. In one study, monitors calibrated to the Digital Imaging and Communications in Medicine (DICOM) gray-scale standard display function were compared with monitors calibrated with a nonperceptually linearized display (eg, a Society for Motion Picture and Television Engineers [SMPTE] pattern); several clinically important differences were observed (7). Perceptually linearized display was associated with improvement in many measures of radiologist performance time, including image search, dwell, and decision times.

EFFECT OF COMPUTER SOFTWARE ON IMAGE PRESENTATION, DISPLAY, AND INTERPRETATION

Among the factors to be considered in assessing radiologist performance, the two most important are interpretation accuracy and productivity. Although optimizing accuracy remains the ultimate goal, radiologists must continue to be productive in their everyday work to meet increasing demands. This fact is reinforced by the crisis in radiologist staffing, which occurs at a time when both the volume and the complexity of medical imaging examinations are increasing. In 1998, according to the American College of Radiology's Professional Bureau, there were 1.3 job listings per job seeker (8). By 2000, this ratio had increased to 3.8 (9), reflecting the existing crisis in the radiologist workforce. In a recent article, Bhargavan et al (9) postulated that if the growth in demand for imaging services continues to increase at its current rate and if radiologists do not become more productive, this radiologist shortage could increase further by 250%.

The single most important strategy to increase radiologist productivity is work-flow optimization software, which is specifically designed to improve work flow in a soft-copy reading environment. Software tools currently available allow for automatic retrieval of historical examinations and reports ("prefetch"), as well as user-specific customized image display presentation (hanging protocols), which can be linked to the electronic password of the user. One problem, however, is that electronic hanging protocols are somewhat cumbersome to set up, are not intuitive, and have limited flexibility in selection. As a result, most users tend to choose vendor-selected hanging protocols, which detract from the user specificity and work-flow potential. In addition, existing protocols do not differentiate unique views of a single examination or anatomic region, such as apical lordotic or decubitus views of the chest.

As new CR and DR applications evolve, such as dual-energy subtraction and tomosynthesis, these challenges will become accentuated. It is therefore important for work-flow optimization software to keep pace with developing technologies and applications while allowing for improved customization by the end user. One way to enhance this iterative process is to create an intuitive graphic interface, which allows the user to point and drag various images in an interactive fashion. If inherent intelligence can be built

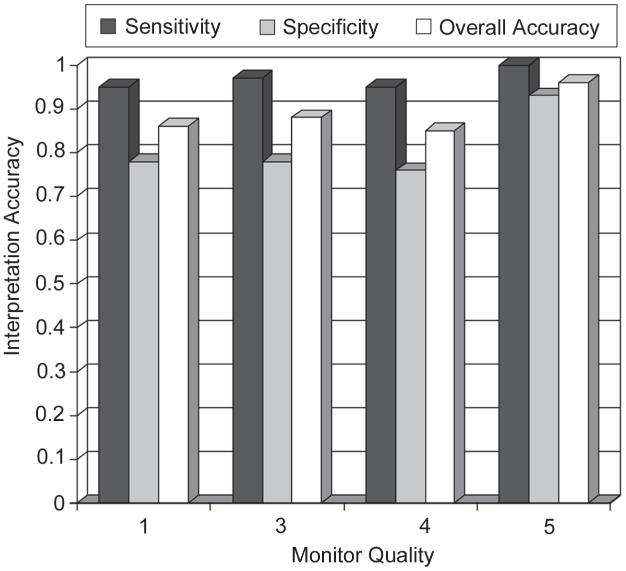

Figure 4. Effect of CRT monitor quality (rated 1–5) on interpretation accuracy for general radiographic examinations. Interpretation accuracy was proportional to objective measures of CRT monitor quality. All three measures of interpretation accuracy (sensitivity, specificity, and overall accuracy) were maximized with the highest levels of monitor quality ($P < .0001$). Numbers on the horizontal axis represent CRT monitor quality, with higher numbers indicating better quality (1 = poor, 5 = good [no monitors rated as 2]).

into the interface, a functional wizard could incorporate the reading patterns of each user into customized display protocols, without the added anxiety and the time-consuming steps currently required.

These software tools automate the steps of image retrieval and display but do not address the process of visual perception and interpretation. For these important functions, a number of developments are underway that assist in diagnostic and decision support. These developments include advanced CR and DR image-processing algorithms (which can be disease specific), computer-aided detection (CAD) software, and other decision support tools (eg, neural networks) that attempt to mix artificial and human intelligence.

IMAGE PROCESSING IN DR

Throughout the lifetime of screen-film radiography, most technical advancements were focused on image acquisition. Radiologists had few, if any, options available to enhance the image once acquisition was complete. With the introduction of CR, vendors realized that the wider dynamic range and exposure latitude offered the opportunity to improve perceived image quality beyond that of static screen-film images. A number of CR image-processing parameters were introduced, along with presentation of an image in a dual format. This feature was offered as a way to accentuate specific features within the image but was largely rejected by radiologists, who preferred a "single best image."

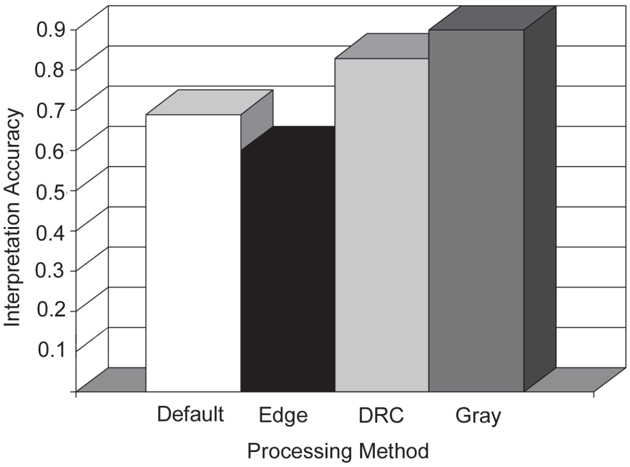

Figure 5. Effect of specialized CR image-processing algorithms in the detection of pulmonary nodules. For the soft-copy interpretation of pulmonary nodules (with CR), both dynamic range control *(DRC)* and gray-scale inversion *(Gray)* had higher measures of interpretation accuracy than did standard default processing. *Edge* = edge enhancement.

With the introduction of PACS and soft-copy interpretation of DR images, a new era of opportunity was introduced, offering the ability to extract information not readily apparent to the human eye. Although screen-film images were "static," soft-copy CR and DR images are now "dynamic," allowing the user to apply a number of image enhancement techniques to highlight certain anatomic or pathologic features. Digital image enhancement generally involves three techniques: luminance enhancement, frequency enhancement, and pattern enhancement (10).

In preliminary research, Reiner et al (2,5) studied advanced image-processing algorithms in the soft-copy interpretation of CR images, algorithms with the potential to improve interpretation accuracy and radiologist productivity in specific disease states. In the detection of pulmonary nodules, the use of dynamic range control was found to improve perceived image quality and diagnostic accuracy (Fig 5), compared with standard CR image processing (11). In the soft-copy evaluation of pneumothoraces, another specialized image-processing technique, edge enhancement, was shown to improve diagnostic accuracy and reduce radiologist interpretation time (2). Additional work is currently underway to evaluate the efficacy of advanced image-processing algorithms in the musculoskeletal system, specifically in the detection of nondisplaced fractures. The goal is to reduce the time radiologists spend actively manipulating the soft-copy image (to improve productivity), while maintaining or improving diagnostic accuracy.

A number of options are available for incorporating image-processing algorithms into the soft-copy reading process, depending on the specific preferences of the radiologist. These processed images can be displayed as thumbnail images on the workstation monitor or can be vertically “stacked.” The radiologist can elect to page through the stacked images or click on selected thumbnail images for full resolution.

An alternative image display strategy incorporates processing algorithms directly onto the keyboard as presets. This strategy is frequently used in soft-copy interpretation of CT examinations (for different window level settings based on different anatomic regions) and allows rapid application of the processing algorithms as directed by the radiologist. The application of processing algorithms can also be driven by clinical information conveyed in the examination requisition or the patient’s electronic file (via the hospital information system or electronic medical record). An example would be a patient who has undergone recent placement of a central venous catheter and has a requisition order stating, “rule out pneumothorax.” The computer would automatically display the image by using the pneumothorax algorithm (edge enhancement), in addition to the standard default processing. The conventional single-best-image presentation could eventually be supplanted by multiple image presentation.

DECISION SUPPORT SOFTWARE

The concept of CAD for improving the diagnostic accuracy of radiographic images arose as a result of numerous studies that showed substantial error rates in screening for lung and breast cancers (12–15). The results of later studies demonstrated that the use of radiologist “double reading” produced increased sensitivity compared with interpretation by one radiologist alone (16,17). The downside of this strategy was the increased radiologist time and diminished productivity that resulted from these double readings. However, if computers could be trained to provide this second reading, they could theoretically improve sensitivity without diminishing radiologist productivity.

From a technical perspective, CAD quantifies specific visual features of the radiographic image and provides metrics for the geometric, topologic, and other characteristics by which medical images are evaluated (18). For the detection of breast cancer, segmentation (the process of separating an image into regions of similar attributes) is used to determine the boundaries of suspected masses. Once a lesion has been segmented, the computer algorithm uses specialized image-processing techniques to measure pertinent features, such as the borders of the suspected lesion. After multiple features of the suspected lesion have been analyzed, artificial intelligence is used to make a comprehensive decision as to the clinical importance of the imaging finding. The artificial intelligence techniques include rule-based codes, decision trees, linear to higher-order classifiers, and neural networks (19). A neural network is a computer code that assists in clinical decision making on the basis of certain features within the image. It is important to realize that the quality of this computer decision making depends on the features chosen by the programmer. These artificial intelligence and image-processing techniques have been used within the military for decades, to evaluate satellite reconnaissance photographs and to track objects on battlefields.

As the volume of screening studies (mammography, chest radiography) continues to increase, what strategies can we adopt to handle the increasing demands without sacrificing diagnostic accuracy? The answer may lie in CAD, which offers the radiologist an intelligent screening of the image. The radiologist is ultimately responsible for image review and interpretation, but CAD offers an efficient means to maintain productivity without sacrificing accuracy. At the same time, findings from studies have shown that CAD as a second reader can increase both sensitivity and specificity for the detection of breast and lung cancers in screening populations (17,20). The final three chapters in this syllabus discuss CAD more thoroughly.

CAD and PACS technologies offer a new approach to image interpretation. Radiologists are no longer constrained by single-best-image presentation state or image quality. Instead, radiologists will be limited only by the psychophysical and ergonomic boundaries inherent in human perceptual processes.

IMAGE PERCEPTION

In its most basic form, the interpretation of a medical image involves looking at the image (visual processing) and determining whether it is normal or abnormal (decision making). Although this process may appear simple and straightforward, it is actually complex and not well understood (21). Misdiagnosis is frequently the result of observer factors, with at least half of the errors made in clinical practice believed to be perceptual (22). Most malpractice suits are brought because of alleged mistakes attributed to errors in perception (23,24) and judgment (25). Understanding the perceptual and cognitive processes involved in image display and interpretation will theoretically improve diagnostic performance, reduce interpretation errors, and decrease medical malpractice. One study that used perceptual feedback (identifying areas of extended dwell time) to improve observer performance found improvements on the order of 16% (26).

The results of studies performed to date estimate 20%–30% false-negative and 2%–15% false-positive rates for radiologist interpretation errors (12,27,28). False-positive readings are largely the result of summation artifacts, caused by overlying anatomic structures that mimic disease. On a chest radiographic image, such errors can be caused by a vessel *en face* or a nipple mimicking a pathologic lung nodule. False-negative readings, on the other hand, are more difficult to understand and are classified into three categories on the basis of how long the findings are fixated or dwelt on (29). These categories include search errors, recognition errors, and decision errors. Search errors involve lesions missed because they are never seen. Recognition errors involve lesions that are seen for short periods but not long enough for the reader to recognize suspicious features. Decision errors involve lesions that are seen and looked at for extended periods but still missed.

Most research on image perception and its effect on diagnostic performance has involved hard-copy image display. Although this remains important for our understanding of the mathematical relationship between the physical properties of images and the human visual system, it does not take into account the inherent differences in digital image displays on computer workstations. The first research on medical image perception in 1947 was a study evaluating screening chest radiographs for the detection of tuberculosis (30). Until then, it was generally thought that all radiologists' interpretations were in agreement. This study and several subsequent studies demonstrated high inter- and intraobserver variability, on the order of 30% (30–33). With the realization that radiologist interpretation was often inconsistent, a new area of research was born. Medical image perception research attempted to explain how and why radiologists differed in their diagnostic decisions and what could be done to improve the consistency and accuracy of their interpretations.

A number of basic perceptual issues must be taken into account in the soft-copy interpretation process, including spatial resolution, contrast resolution, and luminance. Other display considerations include the optimal number of images displayed on a single monitor, the number of monitors, the user interface, navigational strategies, the use of electronic workstation tools, and the specific monitor type. The results of recent studies have illustrated the importance of monitor optimization for radiologist performance. These results have shown improvements in performance with higher levels of luminance (34), perceptually linearized display (35), and simplification of the user interface (36). Krupinski and Lund (36) showed that radiologists spent 20% of their search time looking at the menu (ie, image-processing icons and management tools), rather than at the radiographic image. This shows the effect of workstation design on observer performance and suggests that the most efficient interfaces are simple uncluttered ones (37).

As medical imaging undergoes the transition from hard-copy to soft-copy viewing, the specific characteristics of the digital display must be understood if diagnostic performance is to be optimized. To do this, we must match the physical performance of digital displays to the psychophysical and information-processing capabilities of the human visual system. Until computers can accurately detect and classify every lesion in every image without errors, radiologists will continue to serve as the primary interpreters of medical images (assuming self-referral is not part of the equation). There are certain lesions that computers can detect and humans cannot, and there are others that human observers can detect and computers cannot (38).

Radiologists approach the tasks of image perception and cognition with a certain degree of flexibility and common sense not possessed by a computer. Computers, on the other hand, can perform rigorous and reproducible analyses of narrowly defined problems better than most radiologists. The ideal strategy for medical image interpretation would be to combine the best of both worlds in a logical and methodical fashion. Computers can assist radiologists by deconstructing the complex processes in image perception and diagnostic reasoning into a series of well-defined tasks (10). Radiologists can use this information not for direct diagnosis but as an adjunct to their own analyses.

NEW DR APPLICATIONS

A number of new commercially available applications for CR and DR images have the potential to enhance diagnostic accuracy by demonstrating pathologic conditions in "hard-to-see" areas and demonstrating subtle interval change over time on serial examinations. Dual-energy subtraction radiography can be performed with a single- or dual-exposure technique and exploits the fact that calcium-containing structures (ie, bone) selectively attenuate lower-energy photons. When osseous elements are subtracted from the radiographic image, densities of soft-tissue attenuation (ie, lung nodules) can become more conspicuous against the background of aerated lung. The resultant images consist of "soft tissue," "bone," and "combined" images (Figs 6–8), which can be displayed individually on a computer workstation, either in stack mode or as multiple thumbnail images that can be enlarged to full size.

Historical comparison images can be automatically retrieved from the electronic archive by means of prefetch algorithms and can be displayed side by side with the corresponding current images. Radiologists can customize the image display presentation to suit their individual preferences and to maximize work flow. Dual-energy subtraction has been shown to improve detection of calcified (20) and noncalcified pulmonary nodules (39,40). This improved diagnostic accuracy was independent of observer training and experience (41).

A fundamental objective in image interpretation is the identification of subtle interval change, when one has the benefit of a historical comparison study.

Figure 6. Application of dual-energy subtraction for a DR chest image. This image represents the standard unsubtracted radiographic image, which is customarily displayed for conventional DR imaging of the chest.

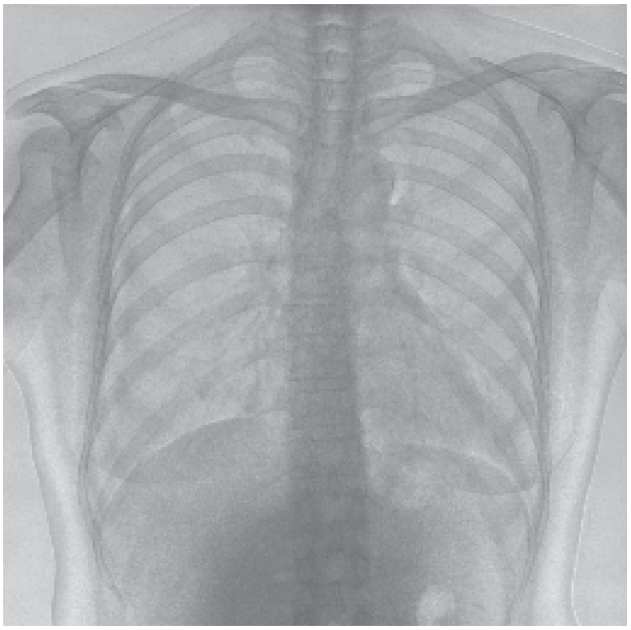

Figure 7. Application of dual-energy subtraction for a DR chest image. This image represents the bone detail image obtained by using dual-energy subtraction to subtract the chest soft tissues. The resultant image highlights bone structures of the chest wall and other calcium-containing structures.

The temporal subtraction technique involves automated two-dimensional warping and registration of prior and current radiographic images to produce a subtraction image. Temporal subtraction in the chest offers increased sensitivity to interval change in a variety of pathologic conditions, including nodules, airspace and pleural disease, and perfusion abnormalities (20). Difazio et al (42) showed that the use of temporal subtraction in chest radiography improved detection of pulmonary nodules and reduced radiologist interpretation times by 19%. This highlights the ultimate goal of radiologist decision support tools, which is to simultaneously improve diagnostic accuracy and productivity. Because temporal subtraction enhances any type of pathologic change, its diagnostic benefits complement those of other CAD techniques.

Another new DR application for improved diagnostic accuracy is tomosynthesis. Tomosynthesis provides an interesting and less expensive alternative to CT and involves the acquisition, during a single breath hold, of multiple images obtained at slightly different angles to one another. The digital images acquired are reconstructed into multiple tomographic planar images by using computers. This in effect provides the observer with high-resolution three-dimensional images from a two-dimensional data set. This is particularly useful in eliminating structural overlap or summation artifact, a problem inherent in two-dimensional radiographic images.

As previously stated, most false-positive interpretation errors are caused by overlying anatomic structures mimicking pathologic conditions. Such overlying structures are especially problematic for chest and mammographic images, in which blood vessels and fibroglandular elements mimic pathologic nodules and mass lesions. Tomosynthesis offers a less expensive alternative to CT with lower radiation exposure. Its application is especially well suited to large-scale screening studies, and tomosynthesis can be coupled with other image enhancement or diagnostic techniques, such as image processing and CAD, to further enhance diagnostic accuracy.

EVOLUTION IN IMAGE DISPLAY

Radiologist work flow in the interpretation of radiographic examinations has also undergone important changes, with several different display strategies employed. The first interpretation stage with screen-film images was that of single image presentation, with individual images typically displayed on a view box or film alternator.

With the transition to filmless imaging by using PACS, the second stage was realized. Early PACS adopters, trained and experienced with film-based interpretation, replicated the same image display format, simply replacing the analog view box with the computer workstation for electronic image display. The radiologist could now display comparison studies quickly and efficiently by using automated hanging protocols, could review historical reports directly (from the interface between the PACS and the radiology information system), and could adjust image brightness electronically.

Figure 8. Application of dual-energy subtraction for a DR chest image. This image represents the soft-tissue image obtained by using dual-energy subtraction to subtract bone from the chest image. The result is an image that optimally displays soft tissues. Note the increased conspicuity of the left upper lobe pulmonary nodule on this soft-tissue image, compared with the unsubtracted image in Figure 6.

Additional workstation tools allow radiologists to magnify images electronically and to perform linear measurements along with electronic annotations. Even though this strategy was an improvement compared with conventional film display, it lacked many of the current advances in workstation functionality.

The third stage in the image display paradigm shifted from single- to multiple-image display, in which individual radiographic images could be vertically stacked on a single computer monitor, allowing the radiologist to quickly move between images by using an electronic trackball or the page-down key on the keyboard. Early on, stacking was typically used for comparing historical images and was particularly useful in patients with numerous comparison examinations, for example, critically ill patients in intensive care with daily chest radiographs. The radiologist could scroll quickly through vertically stacked images, looking for temporal change.

The fourth stage in the display paradigm will be realized not far in the future. As previously mentioned, new applications under development (eg, tomosynthesis) allow DR images to be acquired and displayed in a three-dimensional format. As these technologies are advanced, these three-dimensional data sets will be able to be displayed as holographic images, which in turn will require a whole new suite of software tools for display and interpretation. In the end, we must realize that the only constant in technology is change, which is what drives future advances in medical imaging.

ADVANCES IN DISPLAY TECHNOLOGIES

The need to simultaneously improve the accuracy and productivity of radiologists has spurred a good deal of research into improving human-machine interfaces, for both primary and secondary interpretation of medical images. Two fundamental areas of research are improvements in *(a)* monitor design and *(b)* radiologist input or navigation.

The first generation of PACS workstations used a relatively basic human-machine interface that worked in a manner similar to Adobe Photoshop, with a pull-down menu or icons used to bring up individual examinations. Second-generation PACS workstations continued to use an electronic keyboard or mouse for navigation but incorporated work-flow-enhancing software, such as automated hanging protocols and more intelligent navigation. The enhanced performance and intelligence in computer workstations have led to a progressive reduction in the number of monitors per workstation and an increasing use of color rather than monochrome displays, with a single multipurpose monitor as the ultimate goal.

To date, virtually all strategies for primary interpretation of DR images have been limited to embedded technologies. This has largely limited the radiologist to the confines of the imaging department, which was practical for film-based imaging because that was where images were stored. With the transition to filmless imaging, images have become ubiquitous throughout the health care enterprise, and the historic practice of confining radiologists to the imaging department is being reconsidered. Reiner et al (43) found a dramatic decrease in clinical consultations after implementation of an enterprise-wide PACS, which was believed to be due to digital accessibility to images throughout the medical enterprise and the resultant implication that clinicians no longer had to travel to the radiology department to view images.

If this experience is universal, then radiologists must rethink their practice patterns to maintain relevance to their clinical colleagues. One way to accomplish this might be to become mobile with regard to the location of physical image interpretation and to travel to high-volume areas, such as the emergency room, intensive care unit, and busy outpatient clinics. This change will require a shift from embedded to portable display technologies.

In spite of recent innovations in portable wireless technologies, a number of shortcomings still limit their use for radiology applications. Issues include display quality, screen resolution, battery life, transmission speed and bandwidth, memory, form factor, security, durability, and processor speed. Many of these technical limitations are already being addressed with the development of wireless portable devices containing computer chips running at 900 MHz and having memory capacity of 2 GB. Security concerns will also be addressed as these portable devices incorporate encryption support and begin to use the many security technologies available on other types of computer workstations. Functionality will continue to evolve as speech-recognition technologies become increasingly sophisticated and are incorporated into portable devices. The performance of the next generation of wireless handheld computers, small enough to fit in a coat pocket, will eventually exceed that currently available with networked desktop computers. This change will free radiologists (and other clinicians) from the confines imposed by today's embedded computer workstation. As all medical data become integrated into an electronic patient record, these wireless alternative display devices will play a greater role in the timely access, interpretation, and reporting of medical imaging data.

In addition to handheld portable computers, a number of other alternative display technologies are being developed for use in radiology. These include a number of face-mounted systems, such as goggles, glasses, and stereotactic navigation devices (currently in use for neurosurgery). To date, most technology development in this area has been driven by the entertainment and gaming industry, which has used goggles for display in virtual reality games.

The movie industry has also provided us with a futuristic view of idealized image display devices and functionality. In the movie *Minority Report*, Tom Cruise played the role of a detective who investigated crimes before they were actually committed. The mental images from a clairvoyant were transformed into visual images, which in turn were displayed on a single large flat screen and manipulated by the user with a glove, similar to that currently used in virtual reality games. A radiologist of the future could, in effect, function in a similar fashion, displaying multiple images from a variety of imaging modalities and devices onto a single large screen and navigate by using a combination of hand gestures, eye movements, and speech commands. The data from these acquisition devices could be displayed, processed, and manipulated according to a complex set of rules customized to the preferences of the user. These display and manipulation profiles could be constantly updated by the computer-based changes in the user practice patterns over time, with an electronic wizard recommending new display, perception, and interpretation strategies on the basis of stored data from a master database.

In a recent technical exhibit (44), commercial-grade goggles were combined with video game controllers as an alternative display technology for the review of medical images. Although these off-the-shelf technologies were not specifically designed for use in medical image display, they were found to be an adequate alternative for certain teleradiology applications. As resolution, integration, and image navigation tools improve, wearable displays (perhaps as lightweight as sunglasses) could become a practical alternative for primary interpretation.

New technologies for projecting medical images will also become available and will take different forms, including retinal projection (recently displayed at the annual Comdex meeting) and three-dimensional displays, either wearable or configured as a more conventional monitor, customized to the preferences and applications of each user. The dream of remote review of medical images available any time will undoubtedly be transformed into practical reality within the next few years.

In conclusion, a new era in DR image display and presentation has arrived with the widespread implementation of digital imaging modalities and PACS. Radiologists must understand a number of technical and practical issues if they expect to reap gains in productivity and accuracy with these technologies. Advances in computer hardware and software will be realized only if radiologists are proactive in image optimization and display and are open to the idea of new applications not previously encountered in film-based operation. Technologic advancements will continue as new display technologies and decision support tools are developed to refine the display interpretation processes. These technical innovations will help radiologists to make the transition from an embedded role within the imaging department to a ubiquitous one. The ultimate goal is to make the image interpretation process more accurate and efficient, while allowing radiologists to maintain their position in the medical community as imaging information and technology experts.

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