Radiology

Optimizing Analysis, Visualization, and Navigation of Large Image Data Sets: One 5000-Section CT Scan Can Ruin Your Whole Day[1]

Katherine P. Andriole, PhD
Jeremy M. Wolfe, PhD
Ramin Khorasani, MD, MPH
S. Ted Treves, MD
David J. Getty, PhD
Francine L. Jacobson, MD, MPH
Michael L. Steigner, MD
John J. Pan, MD
Arkadiusz Sitek, PhD
Steven E. Seltzer, MD

The technology revolution in image acquisition, instrumentation, and methods has resulted in vast data sets that far outstrip the human observers' ability to view, digest, and interpret modern medical images by using traditional methods. This may require a paradigm shift in the radiologic interpretation process. As human observers, radiologists must search for, detect, and interpret targets. Potential interventions should be based on an understanding of human perceptual and attentional abilities and limitations. New technologies and tools already in use in other fields can be adapted to the health care environment to improve medical image analysis, visualization, and navigation through large data sets. This historical psychophysical and technical review touches on a broad range of disciplines but focuses mainly on the analysis, visualization, and navigation of image data performed during the interpretive process. Advanced postprocessing, including three-dimensional image display, multimodality image fusion, quantitative measures, and incorporation of innovative human-machine interfaces, will likely be the future. Successful new paradigms will integrate image and nonimage data, incorporate workflow considerations, and be informed by evidence-based practices. This overview is meant to heighten the awareness of the complexities and limitations of how radiologists interact with images, particularly the large image sets generated today. Also addressed is how human-machine interface and informatics technologies could combine to transform the interpretation process in the future to achieve safer and better quality care for patients and a more efficient and effective work environment for radiologists.

Supplemental material: *http://radiology.rsna.org/lookup/suppl/doi:10.1148/radiol.11091276/-/DC1*

---

[1] From the Department of Radiology, Brigham and Women's Hospital, Harvard Medical School, Brigham Circle, 1620 Tremont St, Boston, MA 02120-1613 (K.P.A., R.K., F.L.J., M.L.S., J.J.P., A.S., S.E.S.); Department of Psychology, Massachusetts Institute of Technology, Cambridge, Mass (J.M.W.); Department of Radiology, Boston Children's Hospital, Boston, Mass (S.T.T.); and BBN Technologies, Boston, Mass (D.J.G.). Received August 12, 2009; revision requested September 29; revision received August 16, 2010; accepted October 4; final version accepted October 27. **Address correspondence to** S.E.S. (e-mail: *sseltzer@partners.org*).

Modern medical imaging modalities such as multidetector computed tomography (CT), magnetic resonance (MR) imaging, and positron emission tomography (PET) fused with CT generate large data sets that are difficult and time-consuming to review by using the standard axial section view. Advanced image visualization and data navigation techniques, adapted successfully in other fields, may aid radiologists in their daily tasks. An understanding of radiologists' visual and interpretive behaviors, explored in conjunction with the capabilities of innovative advanced technologies, may provide useful new paradigms for interpreting results from medical imaging examinations.

Because the interpretive process involves multiple complex steps, each cannot be discussed in detail here. What follows is a broad historical, psychophysical, and technical review focused predominately on medical image analysis, visualization, and navigational tasks performed during the interpretive process. Although nonimaging data could alter how visualization tools are adopted, and other elements of the interpretive process will likely fundamentally change, this overview is meant to examine evolving challenges of radiologists in the visualization, navigation, and interpretation of the large complex imaging studies of today in the context of human perception, human-machine interfaces, and advances in informatics technologies.

Essentials

- The technology revolution in image acquisition instrumentation now far outstrips the human observers' ability to view and interpret medical images by using traditional methods, and a paradigm shift may be required.
- As human observers, radiologists must search for, detect, and interpret targets; potential interventions should be based on an understanding of human perceptual and attentional abilities and limitations.
- New technologies and tools, already in use in other fields, can be adapted to the health care environment to improve medical image analysis, visualization, and navigation through large data sets; three-dimensional image display and incorporation of innovative human-machine interfaces will likely be the future.
- Successful new paradigms will integrate image and nonimage data, incorporate workflow considerations, and be informed by evidence-based practices.
- Psychophysics and informatics technologies can combine to achieve safer and better quality care for patients and a more efficient and effective work environment for radiologists.

Historical Overview

Analog Era

In the analog era (up to the mid-1990s) in radiology, we lived in simpler times. Diagnostic imaging studies typically contained a relatively small number of images for review (eg, perhaps 30 cross-sectional images from a single-section shoot-and-scoot CT scanner). The physical properties of images recorded on film were based on the technical factors that were fixed at the time of image acquisition by a combination of the properties of the acquisition device and the characteristics of the film used as the display device. For a given exposure technique, the main variables were contrast, brightness, sharpness, and noise. Although some reprocessing of images could be done (eg, at the scanner), once recorded on film, images were immutable—the only display tools were the use of a hot light to impart a perceived enhancement of contrast to visualize dark areas of the film better and the use of a magnifying glass to visualize fine detail. The film display systems of the time (eg, light boxes) were standardized and easy to deploy and maintain.

On the psychophysical side, improvements in eye tracking technology made it possible to characterize radiologists' viewing and search patterns on these static projection images. On the basis of these data, Kundel, Carmody, Nodine, and their colleagues proposed that radiologists began with a quick gestalt overview, followed by a visual search and detailed inspection of the image (1–3). Eye movement data could also document increases in search efficiency with training and experience (4).

Early Digital Era

In the early digital era (up to the early 2000s), the field witnessed evolutionary changes. Image acquisition devices produced somewhat larger numbers of images per examination (eg, a spiral CT scanner could generate as many as 100 images at a time). Images were often still printed and archived on film—still with contrast, brightness, sharpness, and noise as the main image characteristics. The acquired data sets were inherently digital and thus had a large dynamic range, so several versions of the image set had to be printed with varying mappings of image data to gray levels, corresponding to different contrast and brightness (or window and level) settings. Signal to noise was still a function of technique and a tradeoff between dosage and human safety factors. The spatial resolution was limited largely by what was considered a manageable digital file size, as well as by digital detector capabilities, as it is today.

However, once printed to film, the images were still immutable, and the light box display systems were still simple. When faced with the need to review dozens of static images, which were often spread out over several viewing panels, radiologists needed to modify their reading patterns. However, this does not seem to have been the subject

Radiology 2011; 259:346–362

Abbreviations:
CAD = computer-aided detection
PACS = picture archiving and communication system
3D = three-dimensional

of much eye tracking research to date. Clearly, substantial eye and head movements would be required to cover all of the "real estate." Moreover, any gestalt impression would now need to be based on the concatenation of the axial sections into some internalized three-dimensional (3D) representation.

Current Era

In the current dynamic digital era (from 2005 onward), there have been revolutionary changes in image-viewing paradigms. The radiologist must now view hundreds or thousands of images (eg, advanced multidetector CT of the cardiovascular system produces several thousand images during one examination). It is no longer practical to print images from entire imaging examinations on film (5). The studies are instead viewed on computer workstations by using electronic displays, taking fuller advantage of the inherently digital characteristics of the data. Images are generally still viewed as axial sections, which is an artifact of image acquisition for the cross-sectional modalities. Display formats such as cine or stack mode have become generally preferred over tile format as radiologists begin to move away from the traditional film paradigm (6–9).

Further advances in the technologies of today enable the acquisition of isotropic voxels with equal dimensions in the x, y, and z planes, which when combined with current computing capabilities, can be used to create true 3D volumes of data. Options now exist to produce and view studies as multiplanar reformations, multiplanar slabs, maximum intensity projections, 3D shaded surface and volume renderings, and virtual reality representations—visualizing images with color, motion, and multimodality fusion of anatomic structural and physiologic functional information. Images making use of the large digital dynamic range can now be produced on the fly by using various preset window and level (contrast and brightness) display settings for viewing. The images are no longer immutable; their digital nature makes them amenable to postprocessing and novel displays. There is also great potential to more easily and accurately extract quantitative information from the image data, including morphologic and physiologic metrics to combine with genomic information which is now increasingly available.

The display of radiologic images has therefore evolved from static analog film on a light box to true 3D dynamic color displays that can be manipulated in real time (Fig 1). Some standards currently exist for the hardware and software requirements for producing and viewing processed images (10–14). Electronic display systems have different variables than film-based displays and can be more difficult to characterize, standardize, and maintain.

With the transition from small static analog to large dynamic digital medical imaging sets, radiologists and/or human observers must be radically changing their visual search and image interpretation rituals. While in simpler times even an introductory textbook could suggest optimal visual search paths (15), the radiologist of today is faced with an enormous number of viewing and reading options. We are only now returning to human performance research that can identify the strengths and weaknesses of different viewing paradigms.

In this article, we will attempt to articulate and describe the types of tasks that radiologists perform when interpreting images and communicating results to referring clinicians. We will go back to basics and review what is known about the interaction of human observers with complex data sets. Thereafter, we will attempt to identify promising approaches that use technology to help radiologists perform their increasingly complex jobs more efficiently while maintaining a high quality of care and performance.

Radiologists' Visual and Interpretative Tasks (Back-to-Basic Psychophysics)

Radiologists must perform a wide variety of tasks, each of which may call on different aspects of human visual processing capabilities. Advanced technologies may be useful in facilitating these tasks if their application can be adapted to radiology and health care environments. One attractive approach to organizing the growth, development, testing, and deployment of new assistive technologies in medical imaging would be to understand the radiologist's tasks and to identify technologies and approaches that best fit each task.

Detection and Localization

When interpreting a diagnostic imaging study, the radiologist's first task is the detection and localization of any potential abnormalities. This task typically takes different forms, depending on the imaging modality being used and the conspicuity of any abnormalities. Human performance limitations lead to errors in this task. These errors can take the form of false-negative or false-positive judgments (16), with the relative costs of each depending on the specific situation. Errors arise from several causes. Lesions can be missed if the radiologist's gaze is never directed to the target. Even when the target attracts the viewer's gaze and is fixated visually, the target may not be "strong" enough for the viewer to recognize it as an abnormality, or the viewer may consciously decide not to report the existence of the target as an abnormality (eg, believing it is an artifact or a normal structure) (17). The dramatic increases in the number of images associated with each examination make the radiologist's search job more complex and time-consuming. For a variety of reasons, error rate might be expected to increase with the number of images required to be examined (18,19).

There are several key psychophysical factors that influence radiologists' ability to perform the detect-and-locate task. These include perceptual factors such as target conspicuity and background clutter, as well as attentional factors that arise in the search process. The probability that a target will be "hit" increases as the conspicuity increases. The signal-to-noise ratio is a standard way to quantify the conspicuity of the target. For examinations such as projection radiography and nuclear medicine (noise-limited modalities), the probability of detection is closely related to the signal-to-noise ratio of the target

Figure 1

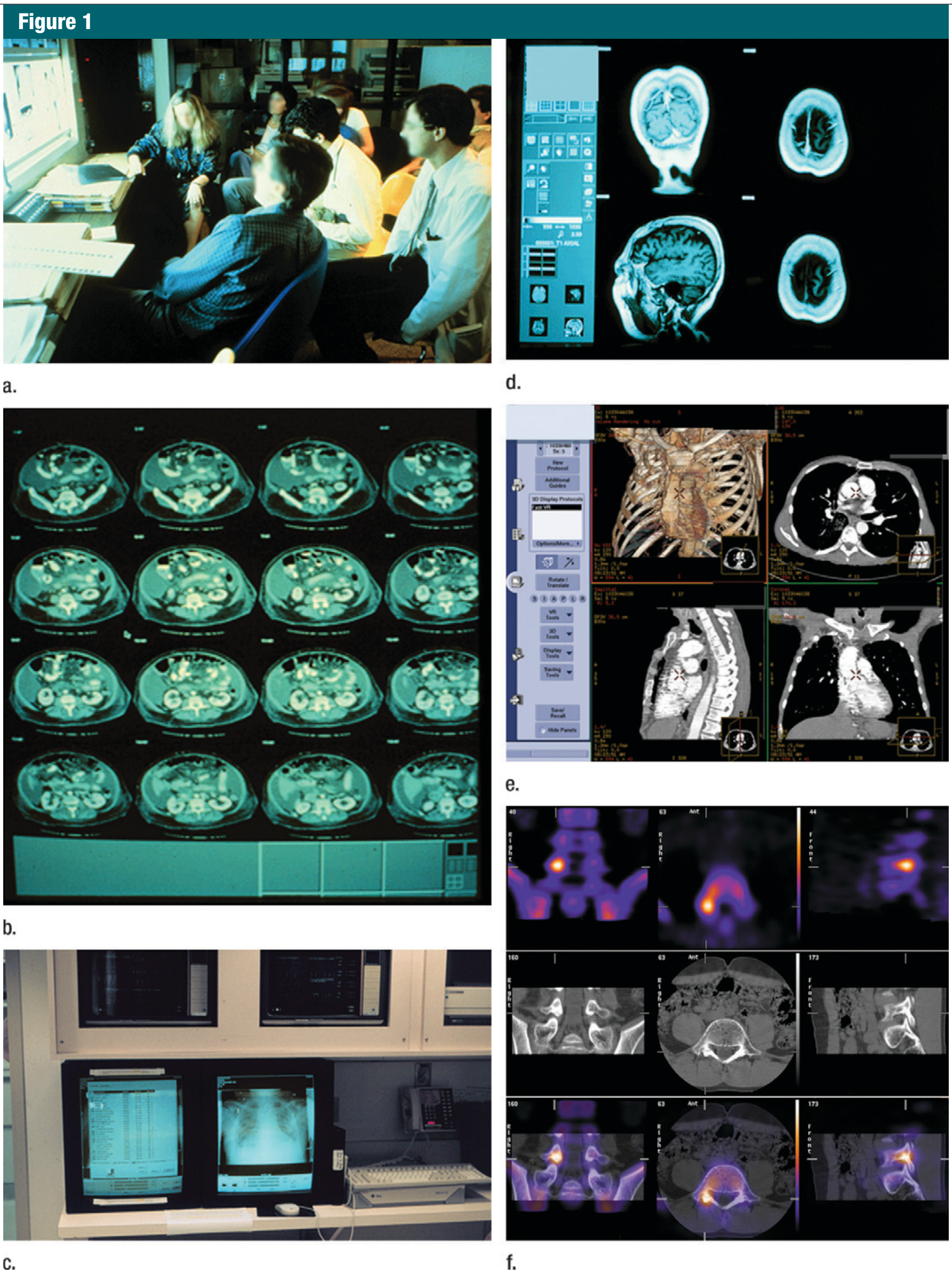


Figure 1: Evolution of radiologic imaging display paradigms. **(a)** Analog light box or alternator. **(b)** Analog view of digital modality (CT) using tile mode with one set window and level. **(c)** Simple picture archiving and communication system (PACS) workstation using digital display but largely static film paradigm. **(d)** Dynamic digital display paradigm with simultaneous stack or cine mode of images from multiple orthogonal MR sequences. **(e)** Advanced postprocessed 3D volume-rendered CT images with color and multiplanar reformations. **(f)** PET, CT, and fused PET/CT, from top row to bottom row, respectively.

and whether this value exceeds a threshold (often cited as the signal being four times stronger than the noise in the surrounding image [20,21]). Interestingly, with cross-sectional images, the signal-to-noise ratio of the target is typically higher than the threshold (for example, the signal strength of a soft-tissue nodule surrounded by air-containing lung

Figure 2

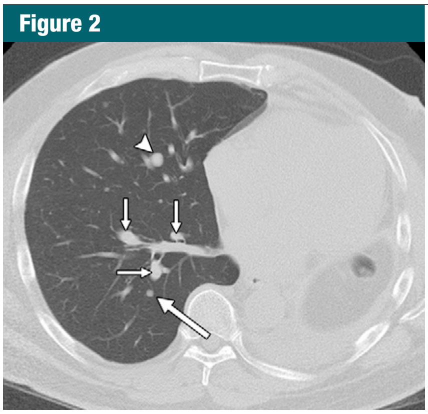


Figure 2: Single axial chest CT image shows it can be difficult to differentiate a lung nodule from a vessel of similar size. The central nodule (arrowhead) in right middle lobe is of the same size as the segmental vessels (small arrows) in right lower lobe. The tiny nodule (large arrow) in the posterobasilar segment of right lower lobe is more readily understood because of the lack of adjacent vessels.

Figure 3

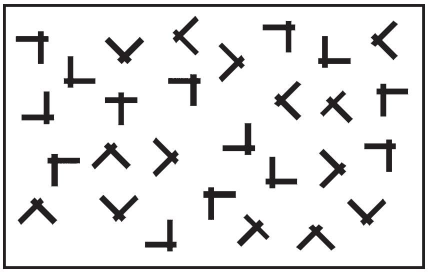


Figure 3: The search component: Find the Ts.

on a CT image is typically far above the threshold needed to see the abnormality).

Interventions that boost the signal-to-noise ratio would be expected to improve performance. For example, with cross-sectional images, a key constraint on a reader's ability to detect and locate targets is often the physical similarity of the lesion with nearby normal structures. In the lung nodule case, a spherical nodule looks similar to a tubular vessel in cross section (Fig 2). Tools are still lacking to quantify such anatomic noise that is generated by distracting or indistinguishable structures on the image. Visualization techniques such as 3D renderings can help the reader separate objects in space and differentiate normal from similarly appearing abnormal structures. Advanced assistive technologies can provide flags to ensure that the radiologist has at least fixated on all parts or all relevant parts of the whole image volume. Several virtual or CT colonographic applications have this capability (V3D; Viatronix, Stony Brook, NY). Other tools such as computer-aided detection (CAD) systems for mammograms (R2 ImageChecker; Hologic, Bedford, Mass) highlight potentially abnormal areas on an image, alerting the radiologist to reexamine them.

Mere visibility is not enough. Although the example search task in Figure 3 is far simpler than one would encounter in medical imaging, it illustrates several concepts. The items in Figure 3 are visible enough, and once readers attend to a specific item, they will have no problem determining if it is a T or an L. However, a reader will have to search to find a T. If a target lesion is not immediately detectable on first glance, the task becomes a visual search task, and the rules governing the deployment of selective attention to different parts of the image are invoked. Work with nonmedical stimuli has uncovered a wide range of factors that govern the efficiency and success of visual search (22). For example, the course of a search is influenced by the specificity with which the shape, orientation, and other basic features of the target can be described. The searcher benefits from knowing a priori the characteristics of the target (23). This is not always possible in a medical image detection task.

Search for an unknown number of targets raises the possibility of satisfaction of search errors (24–26) in which detection of one target makes detection of subsequent targets less likely. Effectively, the readers either give up their search too early or change their decision criterion in a manner that causes them to reject a second target that they might have flagged if they had not found another target. If fewer than three Ts were found in Figure 3, the reader has fallen victim to satisfaction of search. This is a near relative of the larger problem of search termination. It can be difficult for an image reader to decide when to stop the search process and declare an image to be normal. Search processes can also be influenced by the prevalence of targets on the images (27,28), with rare targets being missed more often in laboratory experiments (29). This problem only becomes more difficult as the number of images or the size of the data set increases.

Computer-based aids can search an image set and mark candidate abnormalities for rereview by the radiologist, potentially reducing false-negative rates if used correctly. Such tools are referred to as CAD systems, as opposed to computer-aided diagnosis systems which are designed to help radiologists determine whether or not a lesion is cancerous, for example (30). The predominant existing applications in clinical use today are for nodule detection on mammograms and for chest radiography and CT (31). Numerous studies have shown the effectiveness of CAD systems when used in conjunction with radiologists (32). Even though a reader finds an object on the image, normal structures can be misinterpreted, and artifacts or unfortunate concatenations of findings can generate a false-positive result. Although this is improving, many CAD systems currently have false-positive rates that are high, particularly under conditions in which a lesion is rare (eg, screening). Assumptions of prevalence made by CAD systems (33,34) can affect diagnostic accuracy.

Two key studies have examined the perceptual effects of CAD in the detection of lung nodules on chest radiographs; the first examined the effect of reader skill on the benefits of CAD, the effect of reading pattern (independent, sequential, and concurrent) on the benefits of CAD, the effect of true-positive, false-positive, and false-negative CAD prompts, and the effect of CAD on interpretation time (35). In addition to the aforementioned factors, the second study examined the effect of CAD on radiologists' confidence in their decisions (36). Both studies showed that radiologists did improve their detection of cancerous lung nodules when they used CAD prompts (30). The failure of CAD to mark a cancer (false-negative) slightly lowered the radiologist's confidence in such cases; CAD true-positive prompts tended to increase the radiologist's confidence levels slightly in cases in which CAD confirmed the radiologist's initial correct detections of cancer, and confidence increased greatly in cases in which the radiologist did not originally detect a cancer, but with CAD, did detect it and was highly confident that this detection was correct (36). Investigators of both studies thought the benefits of using CAD outweighed the risk (30). One might imagine that improved image processing, display visualization, and navigational tools could increase the conspicuity of lesions and depict those potentially confusing image features more clearly, thus contributing to a reduced false-positive rate.

Change Assessment

After search, detection, and localization of a lesion, a second visual task for the radiologist may be to establish the pattern of change of an abnormality over the course of time. Typically, this is done with pairwise comparisons of images obtained at different time points. Radiologists can use qualitative or quantitative criteria, or both, to estimate the direction and magnitude of change. This can be a difficult perceptual task, made more difficult if the target lesion is poorly seen, is poorly defined, or exhibits multiple or complex changes over time. Acquisition differences between the images to be compared (eg, changes in the positioning of the patient, reconstruction kernel, or section selection) can make comparison harder. For example, Figure 4a and 4b show the same axial CT section through the liver but processed with different reconstruction kernels. The subtle low-attenuating soft-tissue lesion in the liver is more apparent on Figure 4b because of less image smoothing. Figure 4b and 4c demonstrate the effect a slightly different section location has on the shape and conspicuity of the liver lesion, as well as visibility of a splenic lesion. Performance can deteriorate further if multiple lesions exist, if lesions are of multiple types, and/or if change needs to be traced over many time points. As with the detection tasks, these problems are only made worse by an ever-increasing number of images to be reviewed.

Figure 4

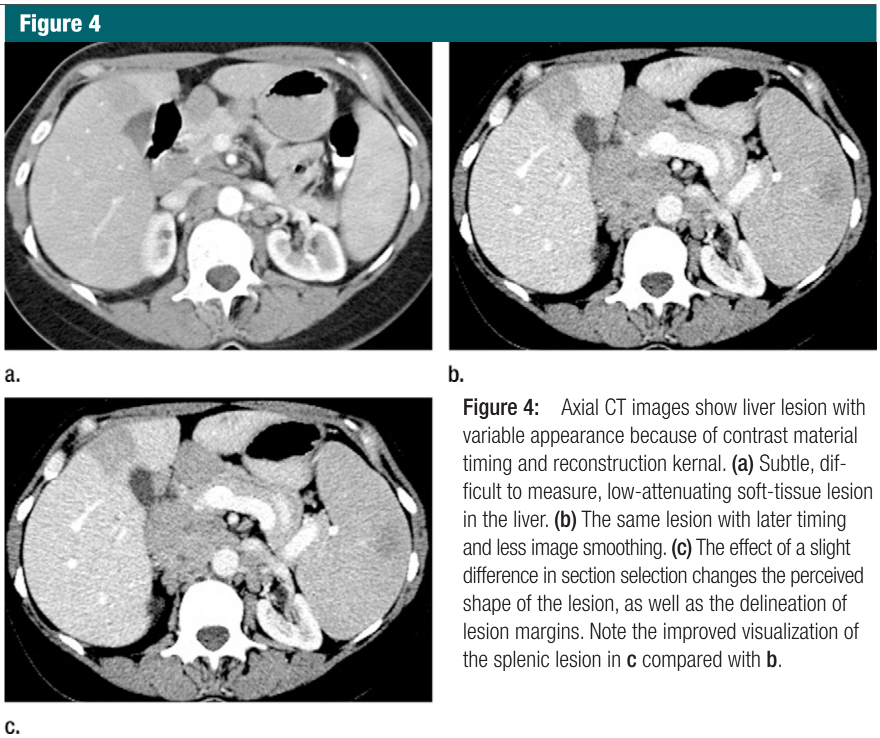


Figure 4: Axial CT images show liver lesion with variable appearance because of contrast material timing and reconstruction kernal. **(a)** Subtle, difficult to measure, low-attenuating soft-tissue lesion in the liver. **(b)** The same lesion with later timing and less image smoothing. **(c)** The effect of a slight difference in section selection changes the perceived shape of the lesion, as well as the delineation of lesion margins. Note the improved visualization of the splenic lesion in **c** compared with **b**.

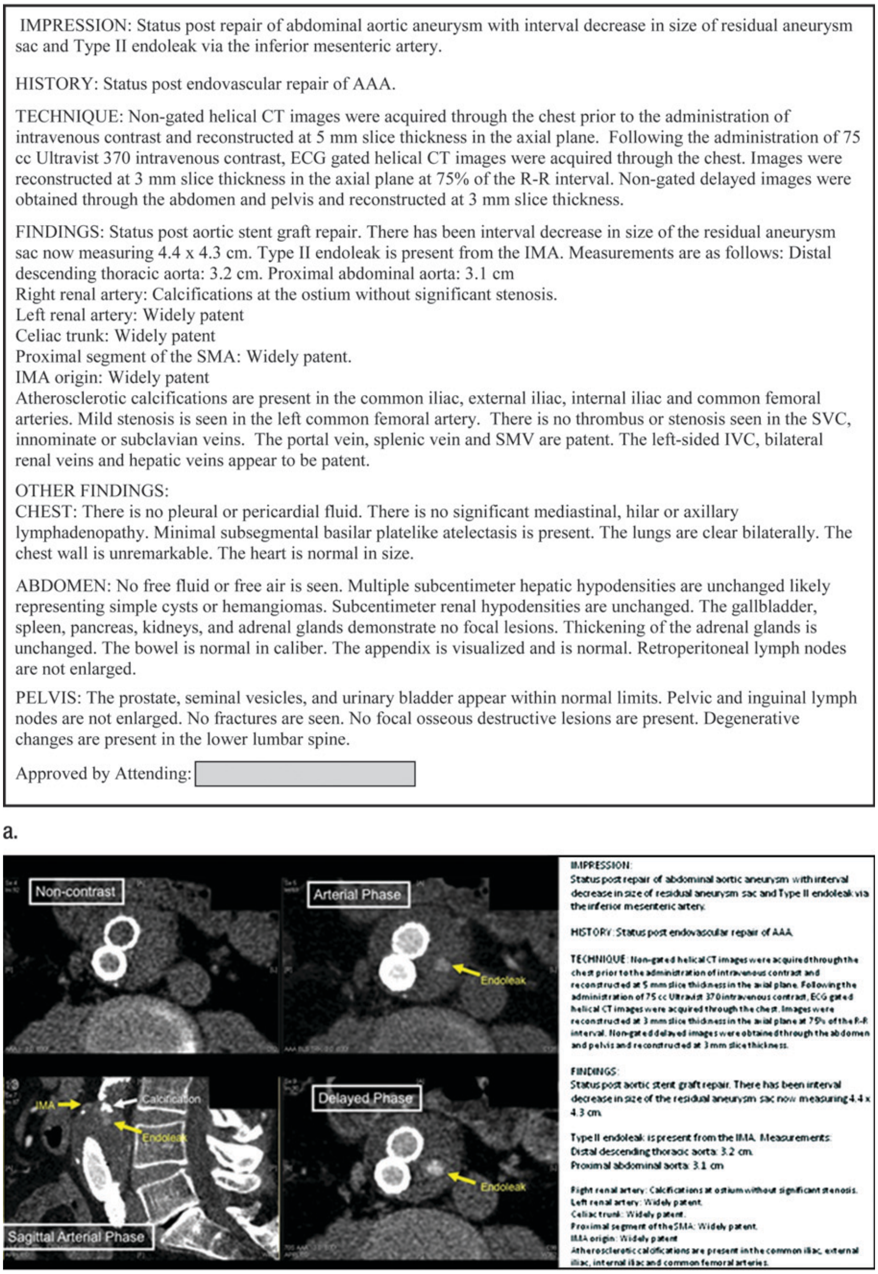
Assistive technologies, such as multimodality image fusion, image subtraction, texture analysis, and the use of motion and color, may be able to help the radiologist make more accurate assessments of lesion change and facilitate analysis of larger data sets. Standardization in methods (eg, mensuration techniques, imaging acquisition protocols, processing algorithms, and error measurements) across researchers and from vendor to vendor is required to enable high precision and scientific evaluation and validation of quantitative measures. Quantitative information in change detection is particularly important in informing clinical management decisions in oncologic cases, for example.

Target Characterization

A third visual task is to characterize the nature of the target lesion. This task calls on visual and cognitive resources to correctly match the appearance of the lesion to a specific pathologic entity. Increasingly, radiologists are also called on to combine information obtained from multiple types of imaging studies performed in the same patient. Combining multispectral information by using techniques such as multimodality image fusion or image registration can clarify the anatomic physical structure and physiologic functional character of a target abnormality (37,38). However, to perform this task well, the radiologist is called on to use perception, memory, and organizational skills to identify the lesion(s) properly at multiple examinations and to have internalized complex algorithms that permit improved lesion classification based on the appearance of the lesion across modalities.

Assistive technologies can make this task easier by embodying and automating delivery of at least some of the knowledge required for the task. Technology could help the radiologist correlate the appearance of the same lesion on multiple studies or provide intelligence through decision aids to assist in differential diagnosis. Electronic teaching files and clinical decision support applications with case examples accessible at the diagnostic workstation and embedded in the clinical radiology workflow could improve this process. Automated matching of the content of the clinical decision support and case examples to reflect the specific lesion in question (sharing the

Figure 5



IMPRESSION: Status post repair of abdominal aortic aneurysm with interval decrease in size of residual aneurysm sac and Type II endoleak via the inferior mesenteric artery.

HISTORY: Status post endovascular repair of AAA.

TECHNIQUE: Non-gated helical CT images were acquired through the chest prior to the administration of intravenous contrast and reconstructed at 5 mm slice thickness in the axial plane. Following the administration of 75 cc Ultravist 370 intravenous contrast, ECG gated helical CT images were acquired through the chest. Images were reconstructed at 3 mm slice thickness in the axial plane at 75% of the R-R interval. Non-gated delayed images were obtained through the abdomen and pelvis and reconstructed at 3 mm slice thickness.

FINDINGS: Status post aortic stent graft repair. There has been interval decrease in size of the residual aneurysm sac now measuring 4.4 x 4.3 cm. Type II endoleak is present from the IMA. Measurements are as follows: Distal descending thoracic aorta: 3.2 cm. Proximal abdominal aorta: 3.1 cm
Right renal artery: Calcifications at the ostium without significant stenosis.
Left renal artery: Widely patent
Celiac trunk: Widely patent
Proximal segment of the SMA: Widely patent.
IMA origin: Widely patent
Atherosclerotic calcifications are present in the common iliac, external iliac, internal iliac and common femoral arteries. Mild stenosis is seen in the left common femoral artery. There is no thrombus or stenosis seen in the SVC, innominate or subclavian veins. The portal vein, splenic vein and SMV are patent. The left-sided IVC, bilateral renal veins and hepatic veins appear to be patent.

OTHER FINDINGS:
CHEST: There is no pleural or pericardial fluid. There is no significant mediastinal, hilar or axillary lymphadenopathy. Minimal subsegmental basilar platelike atelectasis is present. The lungs are clear bilaterally. The chest wall is unremarkable. The heart is normal in size.

ABDOMEN: No free fluid or free air is seen. Multiple subcentimeter hepatic hypodensities are unchanged likely representing simple cysts or hemangiomas. Subcentimeter renal hypodensities are unchanged. The gallbladder, spleen, pancreas, kidneys, and adrenal glands demonstrate no focal lesions. Thickening of the adrenal glands is unchanged. The bowel is normal in caliber. The appendix is visualized and is normal. Retroperitoneal lymph nodes are not enlarged.

PELVIS: The prostate, seminal vesicles, and urinary bladder appear within normal limits. Pelvic and inguinal lymph nodes are not enlarged. No fractures are seen. No focal osseous destructive lesions are present. Degenerative changes are present in the lower lumbar spine.

Approved by Attending:

a.

IMPRESSION:
Status post repair of abdominal aortic aneurysm with interval decrease in size of residual aneurysm sac and Type II endoleak via the inferior mesenteric artery.

HISTORY: Status post endovascular repair of AAA.

TECHNIQUE: Non-gated helical CT images were acquired through the chest prior to the administration of intravenous contrast and reconstructed at 5 mm slice thickness in the axial plane. Following the administration of 75 cc Ultravist 370 intravenous contrast, ECG gated helical CT images were acquired through the chest. Images were reconstructed at 3 mm slice thickness in the axial plane at 75% of the R-R interval. Non-gated delayed images were obtained through the abdomen and pelvis and reconstructed at 3 mm slice thickness.

FINDINGS:
Status post aortic stent graft repair. There has been interval decrease in size of the residual aneurysm sac now measuring 4.4 x 4.3 cm.

Type II endoleak is present from the IMA. Measurements:
Distal descending thoracic aorta: 3.2 cm.
Proximal abdominal aorta: 3.1 cm

Right renal artery: Calcifications at ostium without significant stenosis.
Left renal artery: Widely patent.
Celiac trunk: Widely patent.
Proximal segment of the SMA: Widely patent.
IMA origin: Widely patent
Atherosclerotic calcifications are present in the common iliac, external iliac, internal iliac and common femoral arteries.

b.

Figure 5: Radiology report formats. **(a)** Plain text report. **(b)** Report with text and annotated images.

context of search) should optimize workflow and thus enhance adoption of these assistive technologies.

Communicating Results

Once a lesion is detected, characterized, and followed, a fourth task for the radiologist is to communicate the results of their image interpretation to the referring physician. This traditionally has been done by translating visual observations into a prose description of the finding(s) along with their meaning. This filtering and restatement process involves a tremendous amount of data compression in the radiologist's mind and can introduce errors. Findings in image data sets that may contain hundreds of megabytes of data are assimilated into a prose report that may contain just a few kilobytes of information.

Assistive technology could augment the prose content of the report by adding illustrative and/or annotated images, in the form of multimedia reports (Fig 5). This would permit the radiologist to transmit images with each abnormality annotated. The images could provide graphical information about the change in a lesion over time. Advanced telecommunication devices and high-speed networks could allow radiologists to transmit images and reports to referring physicians and to use handheld devices to engage in a collaborative, real-time discussion, by using markups of the images themselves. Several guidelines for appropriate communication of diagnostic imaging findings exist (39,40), and there have been multiple efforts to improve the quality and clarity of radiology reports by further structuring the content, most notably the Breast Imaging Reporting and Data System lexicon for breast imaging (41) and structured reporting for ultrasonography (42,43) and cardiovascular imaging (44). A large effort has been underway to create and augment a lexicon for uniform indexing and retrieval of radiology information from radiology reports (the ontology RadLex®) (45,46), the adoption of which could additionally improve report quality. It is likely that more radiologic reports will be structured in the future perhaps with embedded clinical management decision support features (47,48).

Methods for communication of radiologic interpretations, in particular communication of critical test results, could benefit from advanced information systems technologies. Traditional methods of communicating results include telephone or hallway conversations and mailed or faxed reports; each has its limitations (40). Best practices for improved patient care and higher quality radiologic services include mechanisms for verifying receipt and understanding of results, audit logs of communication times, and alerts or reminders for follow-up patient treatment activities (49). Automated electronic communications software and hardware technologies could facilitate this process to ensure patient safety, particularly for findings that are nonurgent but may require further diagnostic tests or clinical management decisions needing to be performed in the future. Adoption of newer communications technologies in health care, such as text messaging or social networking tools such as Facebook or Twitter, may fundamentally transform the communication paradigm.

Image-guided Interventions

A fifth task for the radiologist, which is largely beyond the scope of this review, is to use imaging systems to guide the performance of interventional or minimally invasive procedures. In these circumstances, an array of different perceptual, cognitive, and motor skills need to be integrated constructively to ensure that the procedure is performed safely and effectively. Assistive technologies exist that can help train radiologists in procedure performance and sharpen the accuracy of percutaneous procedures, as well as allow real-time monitoring of procedure effectiveness.

Use of Advanced Technologies to Aid Radiologists

The radiologist and/or image interpreter is facing increasing difficulty accomplishing the visual and interpretive tasks of search, detection, localization, change assessment, and target classification as the complexity of image and nonimage data sets grows. It is incumbent on our community to develop new tools or adapt existing technologies to help radiologists, as well as referring clinicians, cope with the overwhelming amount of information contained in modern medical imaging studies.

Several national and professional organizations, including the Society for Imaging Informatics in Medicine, the Radiological Society of North America, the National Institutes of Health (specifically the National Cancer Institute), and others, have made strides to tackle this problem. The Society for Imaging Informatics in Medicine launched an initiative in 2004 termed Transforming the Radiological Interpretation Process to raise awareness of the problem of increasingly large medical image data sets. The initiative brought together physicians and scientists to collaborate on the development of a shared vision for the future of diagnostic radiology image interpretation and to articulate specifications for technical systems that would help realize the vision.

Interestingly, now in 2011, glimpses of potential assistive technologies may be emerging from sources outside of medicine. Specifically, computer-based visualization, navigation, and rendering tools derived from the entertainment and gaming industries, as well as target detection, classification, and change detection tools derived from the aerospace and security industries, may be useful for radiology in the not too distant future, if they can be applied to health care and made practical for adoption in the clinical arena. The remainder of this review describes some of these emerging tools and discusses how they could help in our field of medical imaging.

Visualization Tools That Facilitate Data Reduction

The classic approach taken by a radiologist to detect and locate an abnormality in a small data set, such as frontal and lateral chest images, has been to first create (almost instantly) a holistic or gestalt impression of the image, then to conduct a more organized search (1–4). From experience, although viewing a whole image set in rapid cine mode can provide some gestalt, with the gigantic data sets of the 21st century typically displayed as a series of cross-sectional images, the opportunity to create an overview or holistic look could be lost. Viewing methods, such as a 3D display of the entire cross-sectional imaging data set, may permit the radiologist to recapture the opportunity to develop a comprehensive gestalt survey before digging deeper into the image data.

Stereoscopic displays.—One approach to 3D visualization that is making a comeback is stereoscopic viewing (50,51). Stereo pairs of skull x-ray films were once in widespread clinical use for evaluation of the skull but are no longer used routinely. With the development of high-quality digital radiography, the value of stereo displays is now being rediscovered. Specifically, it has been found that stereoscopic viewing of stereo pairs of mammograms (Fig 6) produced greater true-positive and much fewer false-positive results than conventional viewing methods (52). Investigators reported that the use of stereo gave the reader a clearer overall picture of normal as well as abnormal breast anatomy and freed the reader from the confusion of overlapping shadows encountered at projection radiography.

Several different technologies exist for displaying stereo pairs of acquired images or stereo pairs of projections through volumetric image sets (53), including dual displays utilizing passive cross-polarized glasses (54), frame sequential displays utilizing active shutter glasses (55), and autostereoscopic displays that require no glasses (56). Figure 7 shows a dual-display system. Regardless of the technology used, the requirement is to deliver one image of the pair to one eye only and the other image to the other eye only, with the result that the observer perceives depth as the visual system fuses the two images. This approach could, for example, allow the image reader to take in all, or a movable portion, of a 5000-image data set in a single, holistic view. Then, in a fashion analogous to the classic detection and localization process, the reader could zero in on suspected abnormalities and examine those image regions in greater detail for target classification.

Head tracking.—Another way to achieve a 3D effect for the reader is to use devices that track the position of the reader's head and eyes and adjusts the reader's view accordingly. This approach uses motion parallax to create a similar perceptual effect as stereoscopic viewing. Stereopsis relies on the geometric regularity of the difference between the two retinal images to recover the third dimension from two-dimensional images. Similar geometry applies when even a single eye moves. Given two or more views of the same scene or, better yet, a moving view of

Figure 6

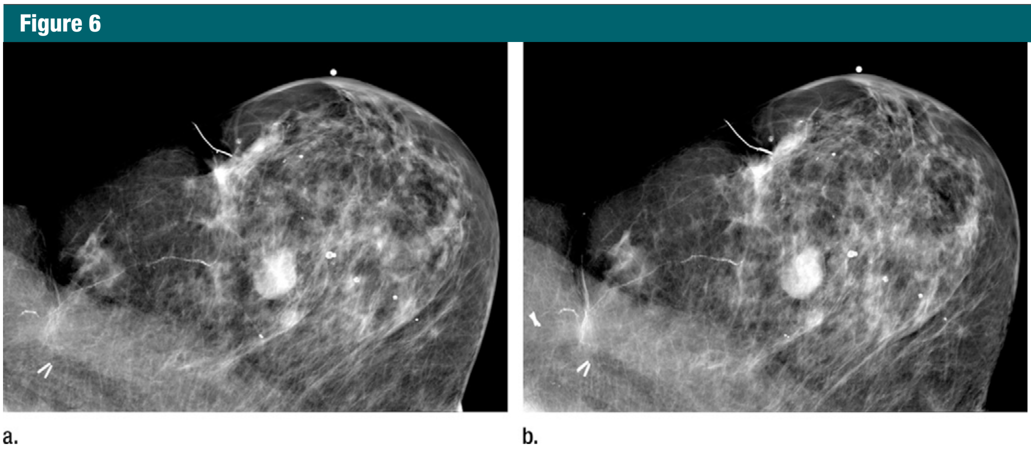


Figure 6: **(a, b)** Mammogram stereo pair. To visualize the stereo affect, readers must cross their eyes slightly to direct the left mammogram to the right eye and vice versa. Visual fusion results in the perceived depth on the mammogram.

Figure 7

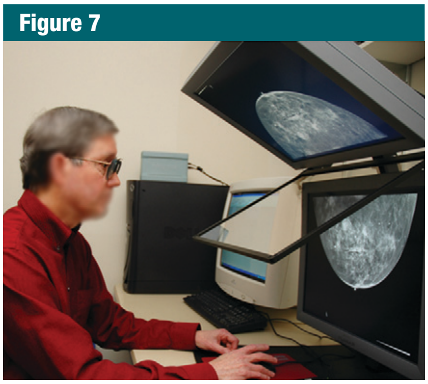


Figure 7: Stereo display workstation for mammography. This dual-display system based on a prototype high-resolution display (StereoMirror; Planar, Beaverton, Ore), utilizes passive cross-polarized glasses.

the scene, the visual system is able to recover 3D. To experience this, close one eye and look at the branches of a tree with the head held still. If you now move your head from side to side, the depth relations of branches and leaves will become far more vivid. Of course, if you move your head in front of a two-dimensional image, nothing of the sort happens. However, with inexpensive technology developed for gaming, such as the infrared sensors in the handheld controller for the Wii video game console (Nintendo, Kyoto, Japan), it is possible to track the observer's head. If the image data are 3D, the image presented to the observer can be transformed in response to head movement to mimic the viewing of a 3D scene. The result is a compelling sensation of depth that allows an observer to move his or her head in a natural and intuitive manner to see more of an object (eg, an imaged organ) and to examine it from different positions, as one might examine a sculpture in a museum. (For a demonstration of Johnny Chung Lee's [Human-Computer Interaction Institute, Carnegie Mellon University] desktop virtual reality version, see *http://www.youtube.com/watch?v=Jd3-eiid-Uw*.) Different immersive displays or virtual caves are a variation on this approach in which rear projection systems are combined with stereo 3D graphics to immerse the viewer in the display environment (57,58).

Volumetric rendering.—A number of different 3D viewing technologies such as those described below have seen dramatic development during the past decade. Coupled with the ability to acquire true isotropic voxel data sets, these 3D renderings produce realistic and useful representations (59). Modern CT and MR imaging systems that generate isotropic voxels facilitate image viewing in the three orthogonal planes (axial, sagittal, and coronal) or in a customized angled or curved format. Some MR imaging pulse sequences result in 3D data primarily. Visualizations of such data in 3D can now be rendered relatively quickly and easily on personal computers, even though the mathematical algorithms used are very computationally intensive.

Once the radiologist has viewed a condensed overall view of the complex image, he or she may want to move on to a second stage of image interrogation that would involve more detailed analyses of cross-sectional images. A remaining challenge facing the sectional phase of image interpretation is the length of time it would take for the reader to scroll through thousands of such images. One approach to speeding and simplifying this task has been to combine several extremely thin sections into a single slab of arbitrary thickness and then to slide this viewing slab through the imaged volume (60). This takes less time than what would be required to view the individual thin sections. Again, if an abnormality were suspected on the sliding slab images, the reader could zoom in and evaluate the individual thin sections that demonstrate the suspected abnormality optimally.

Three-dimensional and pseudo 3D volumetric rendering.—A number of 3D and pseudo 3D visualization techniques currently exist with some becoming more commonly used clinically (60). These methods typically combine planar or curved reformations, projection techniques, shaded surface displays, or volume renderings, with motion or viewer-driven scrolling to create the impression of three dimensionality. Several of these technologies have been used in nuclear medicine for decades and have become fairly common ways of displaying CT and MR imaging vascular studies (61,62). The 3D relationships among structures, when displayed in a rotating frame, can be difficult for an untrained observer to internalize but are increasingly being used by radiologists and image-intensive specialists for task-specific applications (60).

Figure 8

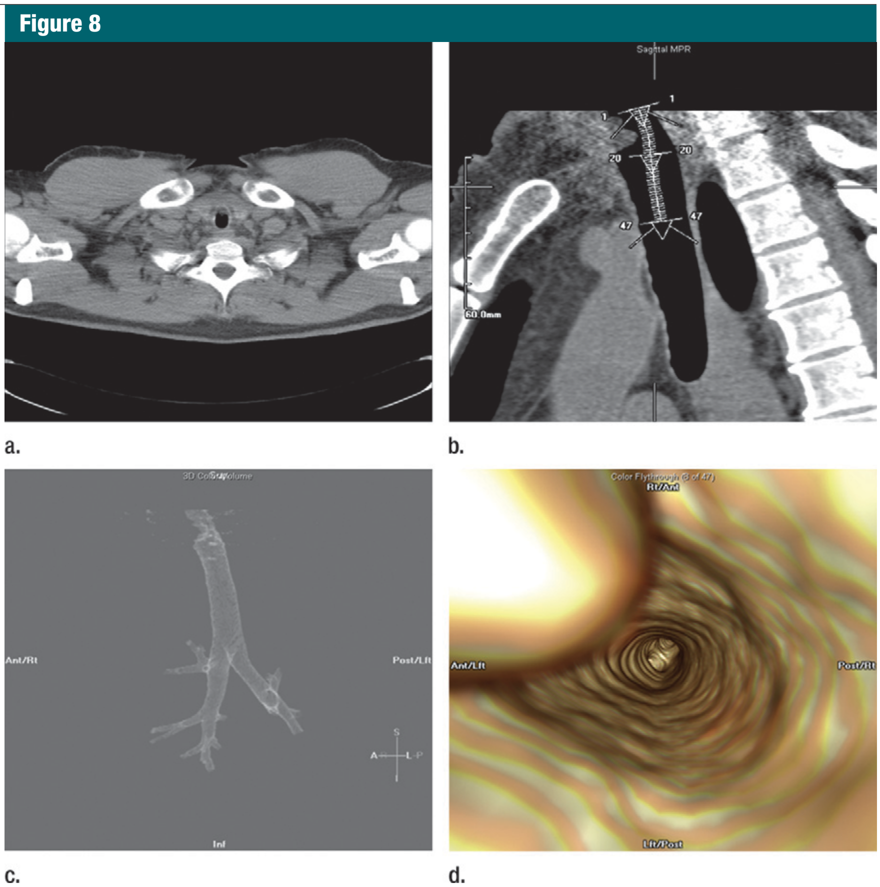


Figure 8: Advanced 3D and pseudo 3D displays of the central airways used in surgical planning. **(a)** Axial CT, **(b)** curved multiplanar reformation, and **(c)** 3D volume-rendered CT images and **(d)** color virtual bronchoscopic fly-through image. (Images courtesy of Ritu Randhawa Gill, MBBS, Brigham and Women's Hospital, Boston, Mass.)

Currently, multiplanar reformations in coronal, sagittal, and oblique planes are used in conjunction with axial sections to eliminate the superposition of voxels lying outside the selected plane (59,60,63). They can be interactively interrogated in cine loops on many postprocessing workstations and some PACS. Curved reformats can be used to visualize structures that do not follow a straight line (eg, vasculature, ureter, intestine) (61,62,64).

Multiplanar slabs use projection techniques, such as maximum intensity projections and minimum intensity projections, to enhance the visualization of specific tissues or diseases. Maximum intensity projections are used to display bony structures, vasculature, and nodules, while minimum intensity projections are used to visualize airways and emphysema (60,65,66).

Shaded surface displays are surface representations of the volumetric data based on a threshold, and although shaded surface displays are increasingly being replaced by volume renderings, shaded surface displays have been used in virtual bronchoscopy (Fig 8, Movies 1–3 [online]) and colonography and are often viewed as fly-through movies. True 3D volume renderings use transparency effects, color, and weighted representations of the data to preserve depth and spatial relationships between structures. Although computationally intensive, these visualizations are fairly easy to create and will likely remain a reference standard for 3D viewing for some time, though volume rendering is now preferable to shaded surface display for most applications (66,67) (Fig 9).

Beyond the third dimension.—Four-dimensional viewing adds temporal information to the 3D volumes where multiple volumes acquired at sequential time points can be viewed in a cine loop to give the appearance of motion (eg, the beating heart, respiration, perfusion, joint motion) (68–70). Five-dimensional display representations typically use functional measures to add another layer of information (eg, myocardial perfusion data at cardiac PET/CT) (71). This additional layer is registered and fused with the underlying data set (Fig 10, Movie 4 [online]).

Multimodality image fusion.—Fusion has been routine for viewing PET/CT data for years (72) (Fig 11). There have been advances in fusion acquisition techniques with novel imaging systems (eg, single photon emission computed tomography [SPECT]/CT and PET/MR imaging) (71,73,74) (Fig 12). Techniques have been developed to register image data acquired at different time points and with different imaging systems to facilitate fusion (eg, PET/CT and MR imaging). These techniques have also been applied to change detection across serial examinations.

Holographic rendering.—Creating a static or dynamic holographic projection of 3D data is attractive because the free-standing appearance of the image makes its interpretation intuitive to the human observer, and in addition, the viewer gains different perspectives on the image through head motion (75). Many advances have been made, including full-color holography. However, to date, the spatial resolution of holographic displays has been insufficient for radiologic image interpretation, although holography has been used in microscopy (76), echocardiography (77,78), guiding invasive medical-surgical procedures (79), measurement of tympanic membranes (80), depicting pelvic fractures (81), and forensics (82).

Advanced Postprocessing Workflow and Hanging Protocols

The creation of multiplanar reformats and 3D representations can be time-consuming, requires additional training,

Figure 9

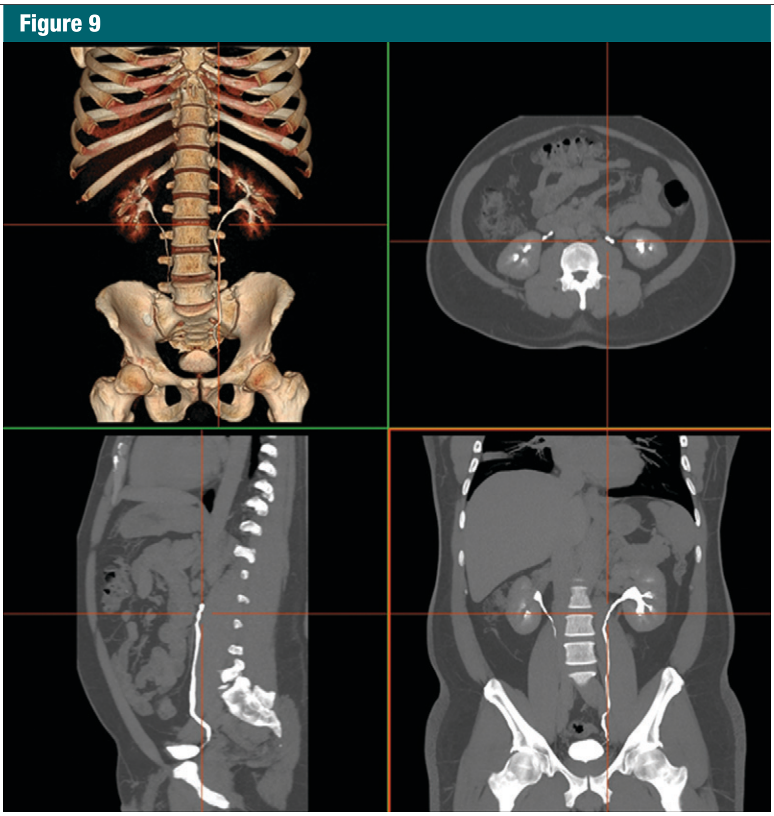


Figure 9: Screenshot of graphical user interface for viewing CT urograms. Top left: 3D volume-rendered image. Top right: Axial multiplanar reformation. Bottom left: Sagittal multiplanar reformation. Bottom right: Coronal multiplanar reformation. (Images courtesy of Luciano M. Prevedello, MD, Brigham and Women's Hospital, Boston, Mass.)

Figure 10

Figure 10: Three-dimensional volume-rendered cardiac PET/CT image from fused rubidium 82 vasodilator stress PET with coronary CT angiography. Coronary CT angiographic component demonstrates high-grade stenosis (arrow) in the second obtuse marginal branch. PET component shows medium-sized, moderate perfusion defect (purple hue) in the corresponding lateral myocardium.

Figure 11

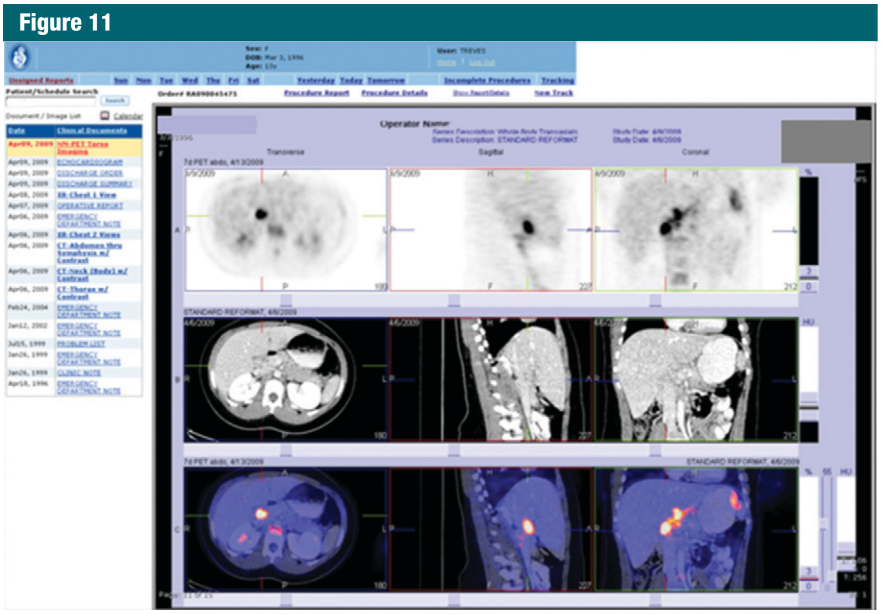


Figure 11: Screenshot of nuclear medicine viewer shows PET (top), CT (middle), and fused PET/CT (bottom) images.

and is often performed on stand-alone workstations in a separate 3D laboratory. Powerful and intuitive software applications now exist (eg, 3D Slicer [Brigham and Women's Hospital, Boston, Mass] and software from multiple vendors) that make it possible to perform advanced postprocessing more easily. However, to optimize their use, it is our belief that these applications must be embedded into clinical workflow through integration into PACS workstations where radiologists perform all of the tasks involved in primary image interpretation (8,83,84). This will enable the real-time advanced visualization and navigation through the image data provided by the specialty applications, with all of the necessary features that a PACS workstation provides (eg, access to all the relevant nonimage data, optimized workflow through real-time virtual work lists coordinating simultaneous use by multiple physicians, automated archiving and prefetching of relevant prior examinations, integrated report generation) that are lacking with the stand-alone systems.

These workflows would allow the reader, armed with the overview developed from the holistic 3D displays, to also use the sectional data to zero in on suspected abnormalities and evaluate them in a thorough and flexible fashion at the interpretation workstation. The ability to automate and easily switch between various display format hanging protocols is essential for adoption and eventual transition to the new visualization paradigms. Advanced visualizations must be available in enterprise-wide image distribution systems as well to enable viewing by referring clinicians at the point of care.

Figure 12

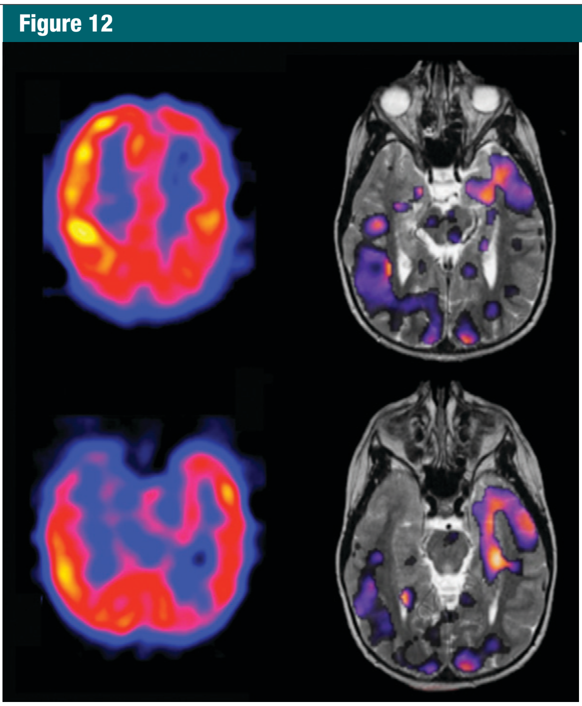


Figure 12: Subtraction ictal SPECT (left) coregistered with MR images (right) are used to localize the region of seizure onset characterized by hyperperfusion for epilepsy surgery planning.

Tools That Facilitate Navigation through Large Numbers of Images

Radiologists currently use keyboard and mouse flywheel or trackball systems almost exclusively for navigation through image sets in a single plane at a time. These hardware interface devices are relatively unsophisticated and provide only fairly coarse controls. Repetitive stress injuries can result from thousands of mouse clicks or flywheel spins in a given day. Optimization of the human-machine user interface must be achieved to facilitate navigation through the increasing number of medical images a radiologist must view and interpret (6,8,9,85). Ergonomic design must be followed to minimize user mouse movement, clicks, and scrolls (86,87).

Newer designs for the traditional computer mouse may provide the radiologist with more flexibility than simply scrolling through stacks of images (88). One such design is a 3D mouse that allows manipulation of the 3D volume so that one hand can control the viewing perspective (eg, rotation, zoom, pan, roll and tilt of the volume), while the other hand is free to use the traditional mouse or other interactive device for other specific tasks, including adjusting brightness and contrast, volume trimming, or other segmentation tools.

Alternative devices for image navigation exist that are more flexible and less cumbersome and have been in use in the gaming setting (and other venues) for many years. The simplest of these devices is the joystick. This controller can be used with one hand (freeing the other to hold dictation report generation recording or speech recognition microphones or to perform other tasks) and could permit navigation through image sets by using a range of tracking speeds and directions (88). The joystick typically is also equipped with push button or trigger controls that could launch specific image analysis or viewing routines. A fairly new handheld device for image navigation in computer games is the previously mentioned infrared controller in the popular Wii system (Nintendo). This device can be held in one hand and offers many degrees of freedom to the observer for perusing image data sets. Figure 13 illustrates a historical array of interface devices.

Efforts to develop even more sophisticated and flexible image navigation systems are beginning to deliver products to the marketplace. For example, contemporary versions of touch-sensitive screens permit the user to manipulate images on the computer screen (89), while simple hand gestures have been used in surgical suites to allow image manipulation while maintaining a sterile environment (90,91). Those familiar with the user interface of the iPhone and iPad (Apple, Cupertino, Calif) or other similar devices have experienced the swishing movements of a finger used to scroll through text and image information, as well as the spreading movements used to enlarge image size. More advanced systems available today allow multiple inputs simultaneously, thereby permitting the user to engage both hands and all 10 fingers at once. The user can manipulate the system by either touching the screen or wearing gloves with infrared emitters to signal hand positions and movements. This concept was fictionalized in the movie *Minority Report*.

Yet another approach to flexible navigation through image sets can be found in products such as Sea Dragon and Photosynth (Microsoft Live Laboratories applications, Seattle, Wash). These tools allow the user to zoom and pan seamlessly through a large library of registered images, permitting visualization of a scene from virtually any perspective and at any degree of magnification or resolution. Voice-activated workstation commands are another potential technology to simplify radiologists' daily routine.

Technology Tools That Speed Image Rendering

For the radiologist to take full advantage of advanced image processing and

Figure 13

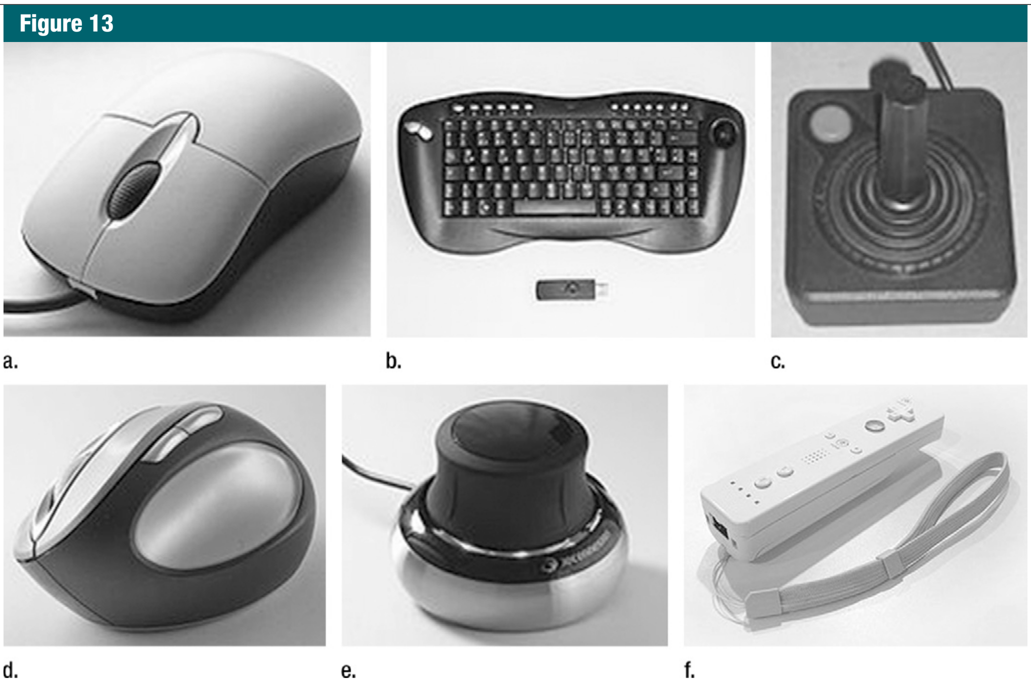


Figure 13: Composite historical array of computer interface devices from the public domain. **(a)** Computer mouse with standard features of two buttons and a scroll wheel. **(b)** Wireless keyboard with trackball. **(c)** Joystick. **(d)** Advanced five-button mouse. **(e)** Three-dimensional motion controller navigation device with six degrees of freedom commonly used in 3D modeling and animation. **(f)** Gaming controller that utilizes motion-sensing optical technology.

navigational tools, electronic displays will need to have the computing speed to render processed images and to display new views virtually instantaneously. While the computational tools are not yet widely available at reasonable cost in medical image displays, they are widely available for personal computers, particularly in use for gaming and in the entertainment industry. A key technical advance is the acceleration provided by expanded processing speeds of video graphics cards (eg, the NVIDIA card [Santa Clara, Calif]).

Tools That Facilitate Distribution of Images and Reports to Referring Physicians

It is important to remember that once the radiologist has completed the task of image interrogation and interpretation, the electronic round trip of information passed from the referring physician to the radiologist and back again is still not complete. Historically, the radiologist's interpretation would be transcribed, edited, and signed, and the report mailed to the referring physician. While initially somewhat controversial, recent years have seen widespread adoption of speech recognition applications that eliminate the need for report transcription. Through integration of PACS with the electronic medical record, imaging studies can be accessible electronically, typically through a Web-based viewing application that is part of a comprehensive virtual electronic medical record in which multivendor applications are well integrated in context to provide the broad clinical functions necessary to deliver high-quality care (92–96) (Fig 14). The availability of these newer approaches has dramatically increased the speed of the distribution of images and reports to ordering clinicians and to their clinics, operating rooms, and other practice settings, potentially leading to faster clinical decision making and ultimately better care (97).

Newer technologic advances derived from the computer and telecommunications industries hold promise to make this information transfer even more rapid and more flexible. Specifically, the evolution of the capabilities of handheld computer and/or telephonic devices and the deployment of faster cellular or wireless networks combine to open a new way for radiologists to communicate the results of imaging studies to referring physicians (98–100). To cite a specific example, the iPhone (Apple) now runs medical image viewing applications that permit image display, navigation, windowing, and mark-up (Fig 15). This and other devices run on 3G and potentially soon 4G wireless networks that improve the speed and bandwidth of telecommunication. Security and data confidentiality challenges will need to be addressed, however.

The availability of these complementary tools opens up exciting new options for rapid communication and consultation. For instance, one can now push selected images from a trauma CT scan from the emergency radiologist to the trauma surgeon's handheld telecommunications device virtually instantaneously. In addition to providing the surgeon with critical image data and the associated report, the radiologist can use the same device to have a telephonic consultation

Figure 14

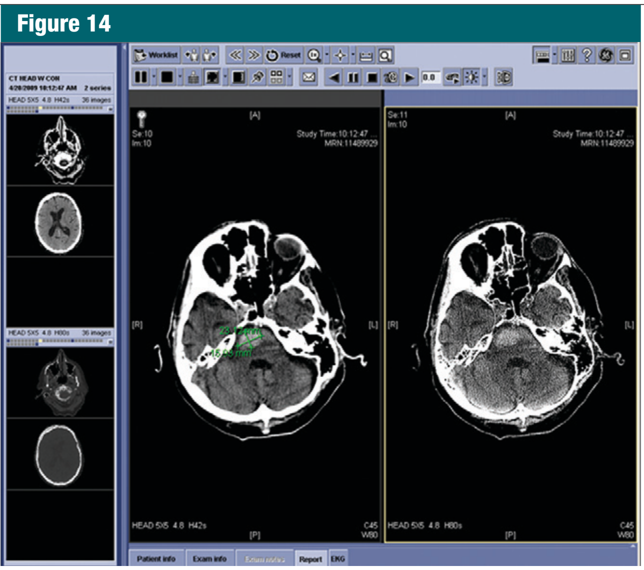


Figure 14: Screenshot of test patient's CT examination results from an enterprise-wide Web-based image viewer that can be launched in context from the electronic medical record. Radiologic reports and electrocardiograms are also available through the application.

Figure 15

HISTORY: Status post endovascular repair of AAA.

IMPRESSION:
Status post repair of abdominal aortic aneurysm with interval decrease in size of residual aneurysm sac and Type II endoleak via the inferior mesenteric artery.

Figure 15: Handheld device with a medical image viewing application that permits image display, navigation, markup, and consultation.

with the surgeon, and both parties can mark up images to provide clarity.

A related advance in medical information network development is the increasing capability of Web-based systems to display information from multiple sources in near real time on a single-display device. Particularly with the advent of the next generation of Web-based systems (eg, Web 2.0), service-oriented architecture versus client-server architecture, and cloud computing (101), referring physicians and radiologists can have secure easy access to both image-based and non–image-based patient information in synchronous sessions on compact, portable display devices. The concurrent availability of multidimensional multimedia medical information should facilitate image interpretation and streamline clinical decision making.

Tools to Transform Modern Image Management

While the technologic developments described are tremendously exciting and open up vast new clinical applications for radiologists and referring physicians alike, it is important to remember that the availability of such advanced image processing, analysis, display, and navigation tools is necessary, but not sufficient, for their widespread clinical adoption. The optimum interpretive environment will require data archival, query, delivery, and integration tools beyond image processing. A relevant synopsis of nonimaging clinical information, including clinical notes, surgical and discharge summaries, pathology or endoscopic reports, and laboratory, genetic, and proteomic data, will need to be integrated context specific to the patient, the clinical problem or disease, and the end-user, to inform the medical imaging interpretive process (102). Even the most contemporary PACS and radiology information systems do not embed these advanced capabilities. Currently, most advanced image processing, display, and communication must be done by using third-party, stand-alone hardware and software. It is our belief that these advanced postprocessing approaches are too costly, time-consuming, and complex to be widely adopted (83,84).

Database ingest speed is something that must improve to make the acquisition of large data sets more practical and efficient so as not to overload clinical systems and their routine performance. It will be necessary to develop and deploy entirely revamped image management systems that combine elements of PACS and radiology information systems, that run on a single platform, and are integrated fully with the electronic medical record and the radiologist's workstation providing one virtual window to all relevant image and nonimage information. This will be necessary for our field to take full advantage of the nascent hardware and software tools that will permit radiologists to take interpretation of a 5000-image CT data set in stride.

Conclusions

The technologic revolution in image acquisition instrumentation now far outstrips the human observers' ability to view and interpret medical images by using traditional methods, and a paradigm shift may be required. Profitable areas for intervention can be identified by examination of radiologists' visual and attentional capabilities and consideration of the specific tasks that must be accomplished. It is also likely that with the aid of sophisticated informatics tools, delivery of a relevant detailed synopsis of nonimaging components of the patient-centric electronic medical record to the radiologist in real time will have a profound effect on every step of the image interpretation process.

New technologies and tools already in use in other fields can be adapted to the health care environment to improve medical image analysis and visualization and navigation through large data sets. Three-dimensional image display and incorporation of innovative human-machine interfaces will likely be the future. New paradigms must include integration of image and nonimage data, as well as workflow considerations, and be informed by evidence-based practices. Academic-industry collaborations could potentially accelerate the delivery of these tools to the clinical arena.

We are approaching a revolution in the role of the imaging specialist in direct patient care. To achieve this, current practice must take full advantage of the technologies of today. This is radiology's challenge and opportunity. Psychophysics and informatics can combine to achieve safer and better quality care for patients and a more efficient and effective work environment for radiologists.

Disclosures of Potential Conflicts of Interest: **K.P.A.** Financial activities related to the present article: author receives travel money as a member of RSNA Radiology Informatics Committee, as program chair for Society for Imaging Informatics in Medicine, and as charter member of NIH/NIBIB Biomedical Computing and Healthcare Informatics Study Section; RSNA Education Exhibits Committee member; associate editor of *Journal of Digital Imaging*. Financial activities not related to the present article: none to disclose. Other relationships: none to disclose. **J.M.W.** Financial activities related to the present article: author and institution receives research funding support from Toshiba. Financial activities not related to the present article: receives payment for lecture and travel from the ASNR and ISMRM. Other relationships: none to disclose. **R.K.** No potential conflicts of interest to disclose. **S.T.T.** No potential conflicts of interest to disclose. **D.J.G.** Financial activities related to the present article: none to disclose. Financial activities not related to the present article: consultant for FujiFilm Medical Systems; employee of BBN Technologies. Other relationships: none to disclose. **F.L.J.** No potential conflicts of interest to disclose. **M.L.S.** No potential conflicts of interest to disclose. **J.J.P.** No potential conflicts of interest to disclose. **A.S.** No potential conflicts of interest to disclose. **S.E.S.** Financial activities related to the present article: institution received research grant from Toshiba; author is principal investigator on the grant but receives no personal support. Financial activities not related to the present article: president of Brigham Radiology Research and Education Foundation; BRREF is an equity holder in Medicalis, but author has no personal equity and receives no financial benefits. Other relationships: none to disclose.

References

1. Kundel HL, Nodine CF, Conant EF, Weinstein SP. Holistic component of image perception in mammogram interpretation: gaze-tracking study. Radiology 2007;242(2):396–402.
2. Carmody DP, Nodine CF, Kundel HL. Finding lung nodules with and without comparative visual scanning. Percept Psychophys 1981;29(6):594–598.
3. Kundel HL, Nodine CF, Krupinski EA, Mello-Thoms C. Using gaze-tracking data and mixture distribution analysis to support a holistic model for the detection of cancers on mammograms. Acad Radiol 2008;15(7):881–886.
4. Kundel HL, La Follette PS Jr. Visual search patterns and experience with radiological images. Radiology 1972;103(3):523–528.
5. Morin RL. Cross-sectional imaging: a technology crisis upon us. J Am Coll Radiol 2006;3(3):218–219.
6. Andriole KP, Morin RL, Arenson RL, et al. Addressing the coming radiology crisis: the Society for Computer Applications in Radiology transforming the radiological interpretation process (TRIP) initiative. J Digit Imaging 2004;17(4):235–243.
7. Jacobson FL, Berlanstein BP, Andriole KP. Paradigms of perception in clinical practice. J Am Coll Radiol 2006;3(6):441–445.
8. Andriole KP, Barish MA, Khorasani R. Advanced image processing in the clinical arena: issues to consider. J Am Coll Radiol 2006;3(4):296–298.
9. Andriole KP, Morin RL. Transforming medical imaging: the first SCAR TRIP conference—a position paper from the SCAR TRIP subcommittee of the SCAR research and development committee. J Digit Imaging 2006;19(1):6–16.
10. American College of Radiology. Practice guideline for digital radiography. Reston, Va: American College of Radiology, 2009.
11. American College of Radiology. Practice guideline for determinants of image quality in digital mammography. Reston, Va: American College of Radiology, 2007.
12. Williams MB, Yaffe MJ, Maidment AD, Martin MC, Seibert JA, Pisano ED. Image quality in digital mammography: image acquisition. J Am Coll Radiol 2006;3(8):589–608.
13. Siegel E, Krupinski EA, Samei E, et al. Digital mammography image quality: image display. J Am Coll Radiol 2006;3(8):615–627.
14. Krupinski EA, Williams MB, Andriole KP, et al. Digital radiography image quality: image processing and display. J Am Coll Radiol 2007;4(6):389–400.
15. Novelline RA. How to study the chest. In: Squire's fundamentals of radiology. Cambridge, Mass: Harvard University Press, 2004; 80–91.
16. Chakraborty DP. ROC curves predicted by a model of visual search. Phys Med Biol 2006;51(14):3463–3482.
17. Krupinski EA, Berger WG, Dallas WJ, Roehrig H. Searching for nodules: what features attract attention and influence detection? Acad Radiol 2003;10(8):861–868.
18. Palmer J. Attention in visual search: distinguishing four causes of a set size effect. Curr Dir Psychol Sci 1995;4(4):118–123.
19. Eckstein MP, Thomas JP, Palmer J, Shimozaki SS. A signal detection model predicts the effects of set size on visual search accuracy for feature, conjunction, triple conjunction, and disjunction displays. Percept Psychophys 2000;62(3):425–451.
20. Judy PF, Swensson RG, Szulc M. Lesion detection and signal-to-noise ratio in CT images. Med Phys 1981;8(1):13–23.
21. Swensson RG, Judy PF. Detection of noisy visual targets: models for the effects of spatial uncertainty and signal-to-noise ratio. Percept Psychophys 1981;29(6):521–534.
22. Wolfe JM, Reynolds JH. Visual search. In: Basbaum AI, Kaneko A, Shepherd GM, Westheimer G, eds. The senses: a comprehensive reference. Vol 2, Vision II. San Diego, Calif: Academic Press, 2008; 275–280.
23. Wolfe JM, Horowitz TS. What attributes guide the deployment of visual attention and how do they do it? Nat Rev Neurosci 2004;5(6):495–501.
24. Berbaum KS, Franken EA Jr, Dorfman DD, et al. Satisfaction of search in diagnostic radiology. Invest Radiol 1990;25(2):133–140.

25. Berbaum KS, Franken EA Jr, Dorfman DD, et al. Time course of satisfaction of search. Invest Radiol 1991;26(7):640–648.

26. Nodine CF, Krupinski EA, Kundel HL, Toto L, Herman GT. Satisfaction of search (SOS). Invest Radiol 1992;27(7):571–573.

27. Gur D, Rockette HE, Armfield DR, et al. Prevalence effect in a laboratory environment. Radiology 2003;228(1):10–14.

28. Gur D, Rockette HE, Warfel T, Lacomis JM, Fuhrman CR. From the laboratory to the clinic: the “prevalence effect.” Acad Radiol 2003;10(11):1324–1326.

29. Wolfe JM, Horowitz TS, Kenner NM. Cognitive psychology: rare items often missed in visual searches. Nature 2005;435(7041): 439–440.

30. Freedman M, Osicka T. Perceptual effect of CAD in reading chest radiographs. In: Samei E, Krupinski E, eds. The handbook of medical image perception and techniques. Cambridge, England: Cambridge University Press, 2010; 290–303.

31. Doi K. Computer-aided diagnosis in medical imaging: historical review, current status and future potential. Comput Med Imaging Graph 2007;31(4-5):198–211.

32. Freedman M. State-of-the-art screening for lung cancer (part 1): the chest radiograph. Thorac Surg Clin 2004;14(1):43–52.

33. Berbaum KS, Caldwell RT, Schartz KM, Thompson BH, Franken EA Jr. Does computer-aided diagnosis for lung tumors change satisfaction of search in chest radiography? Acad Radiol 2007;14(9):1069–1076.

34. Horsch K, Giger ML, Metz CE. Prevalence scaling: applications to an intelligent workstation for the diagnosis of breast cancer. Acad Radiol 2008;15(11):1446–1457.

35. Kobayashi T, Xu XW, MacMahon H, Metz CE, Doi K. Effect of a computer-aided diagnosis scheme on radiologists’ performance in detection of lung nodules on radiographs. Radiology 1996;199(3):843–848.

36. Freedman MT, Osicka T, Lo SC, et al. Methods for identifying changes in radiologists’ behavioral operating point of sensitivity-specificity trade-offs within an ROC study of the use of computer aided detection of lung cancer. In: Proceedings of SPIE: medical imaging 2001—image processing and performance. Vol 4324. Bellingham, Wash: International Society for Optical Engineering, 2001; 1311–1319.

37. Meyer CR, Boes JL, Kim B, et al. Demonstration of accuracy and clinical versatility of mutual information for automatic multimodality image fusion using affine and thin-plate spline warped geometric deformations. Med Image Anal 1997;1(3):195–206.

38. Maintz JBA, Viergever MA. A survey of medical image registration. Med Image Anal 1998;2(1):1–36.

39. American College of Radiology. ACR standard for communication: diagnostic radiology—impact of reporting errors. Reston, Va: American College of Radiology, 1995.

40. American College of Radiology. ACR practice guideline for communication of diagnostic imaging findings. Reston, Va: American College of Radiology, 2005.

41. American College of Radiology. Breast Imaging Reporting and Data System (BI-RADS) atlas. http://www.acr.org/SecondaryMainMenuCategories/ACRStore/FeaturedCategories/QualityandSafety/birads_atlas.aspx. Accessed June 10, 2010.

42. Bell D, Greenes R, Doubilet P. Form-based clinical input from a structured vocabulary: initial application in ultrasound reporting. Proc Annu Symp Comput Appl Med Care 1992:789–790.

43. Bell D, Greenes R. Evaluation of UltraSTAR: performance of a collaborative structured data entry system. Proc Annu Symp Comput Appl Med Care 1994:216–222.

44. Douglas PS, Hendel RC, Cummings JE, et al. ACCF/ACR/AHA/ASE/ASNC/HRS/NASCI/RSNA/SAIP/SCAI/SCCT/SCMR 2008 health policy statement on structured reporting in cardiovascular imaging. J Am Coll Cardiol 2009;53(1):76–90.

45. RadLex. A lexicon for uniform indexing and retrieval of radiology information resources. Radiological Society of North America. http://www.rsna.org/Radlex/. Accessed June 10, 2010.

46. Sistrom CL, Langlotz CP. A framework for improving radiology reporting. J Am Coll Radiol 2005;2(2):159–167.

47. Dunnick NR, Langlotz CP. The radiology report of the future: a summary of the 2007 Intersociety Conference. J Am Coll Radiol 2008;5(5):626–629.

48. Reiner BI, Knight N, Siegel EL. Radiology reporting, past, present, and future: the radiologist’s perspective. J Am Coll Radiol 2007;4(5):313–319.

49. Hanna D, Griswold P, Leape LL, Bates DW. Communicating critical test results: safe practice recommendations. Jt Comm J Qual Patient Saf 2005;31(2):68–80.

50. Getty DJ. Stereoscopic and biplane imaging. In: Samei E, Flynn MJ, eds. 2003 syllabus: categorical course in diagnostic radiology physics—advances in digital mammography. Oak Brook, Ill: Radiological Society of North America, 2003; 199–209.

51. Getty DJ, Green PJ. Clinical medical applications for stereoscopic 3D displays. J Soc Inf Disp 2007;15(6):377–384.

52. Getty DJ, D’Orsi CJ, Pickett RM. Stereoscopic digital mammography: improved accuracy of lesion detection in breast cancer screening. In: Krupinski EA, ed. Proceedings of the International Workshop on Digital Mammography, 2008; 74–79.

53. 3D Forums Stereoscopic Discussion Forums. Active versus passive 3D glasses. http://www.3d-forums.com/active-vs-passive-3d-glasses-t81.html. Accessed June 29, 2010.

54. Planar Stereo Mirror. http://www.planar3d.com/. Beaverton, Ore. Accessed June 29, 2010.

55. NVIDIA Corporation 3D Vision. http://www.nvidia.com/object/product_geforce_3D_VisionKit_us.html. Santa Clara, Calif. Accessed June 29, 2010.

56. 3D Forums Stereoscopic Discussion Forums. Autostereoscopic displays. http://www.3d-forums.com/autostereoscopic-displays-t1.html. Accessed June 29, 2010.

57. Visbox. VisCube-SX Multiscreen Immersive 3D Display. http://www.visbox.com/viscube-SX.html. Champaign, Ill. Accessed June 10, 2010.

58. Zhang S, Demiralp C, Keefe DF, et al. An immersive virtual environment for DT-MRI volume visualization applications: a case study. In: IEEE Visualization, San Diego, Calif: IEEE Computer Society, 2001; 437–584.

59. Rubin GD, Napel S, Leung AN. Volumetric analysis of volumetric data: achieving a paradigm shift. Radiology 1996;200(2): 312–317.

60. Dalrymple NC, Prasad SR, Freckleton MW, Chintapalli KN. Informatics in radiology (infoRAD): introduction to the language of three-dimensional imaging with multidetector CT. RadioGraphics 2005;25(5):1409–1428.

61. Rankin SC. Spiral CT: vascular applications. Eur J Radiol 1998;28(1):18–29.

62. Rubin GD. 3-D imaging with MDCT. Eur J Radiol 2003;45(suppl 1):S37–S41.

63. Rubin GD. Multislice imaging for three-dimensional examinations. In: Silverman PM, ed. Multislice helical tomography: a practical approach to clinical protocols. Philadelphia, Pa: Lippincott Williams & Wilkins, 2002; 317–324.

64. Raman R, Napel S, Beaulieu CF, Bain ES, Jeffrey RB Jr, Rubin GD. Automated generation of curved planar reformations from

volume data: method and evaluation. Radiology 2002;223(1):275–280.

65. Napel S, Rubin GD, Jeffrey RB Jr. STS-MIP: a new reconstruction technique for CT of the chest. J Comput Assist Tomogr 1993; 17(5):832–838.

66. Ravenel JG, McAdams HP. Multiplanar and three-dimensional imaging of the thorax. Radiol Clin North Am 2003;41(3):475–489.

67. Kuszyk BS, Heath DG, Bliss DF, Fishman EK. Skeletal 3-D CT: advantages of volume rendering over surface rendering. Skeletal Radiol 1996;25(3):207–214.

68. van Dam IE, van Sörnsen de Koste JR, Hanna GG, Muirhead R, Slotman BJ, Senan S. Improving target delineation on 4-dimensional CT scans in stage I NSCLC using a deformable registration tool. Radiother Oncol 2010;96(1):67–72.

69. Barfett JJ, Fierstra J, Willems PW, Mikulis DJ, Krings T. Intravascular functional maps of common neurovascular lesions derived from volumetric 4D CT data. Invest Radiol 2010;45(7):370–377.

70. Badea CT, Johnston SM, Subashi E, Qi Y, Hedlund LW, Johnson GA. Lung perfusion imaging in small animals using 4D micro-CT at heartbeat temporal resolution. Med Phys 2010;37(1):54–62.

71. Li G, Citrin D, Camphausen K, et al. Advances in 4D medical imaging and 4D radiation therapy. Technol Cancer Res Treat 2008;7(1):67–81.

72. Brunetti J, Caggiano A, Rosenbluth B, Vialotti C. Technical aspects of positron emission tomography/computed tomography fusion planning. Semin Nucl Med 2008;38(2): 129–136.

73. Schillaci O, Filippi L, Manni C, Santoni R. Single-photon emission computed tomography/computed tomography in brain tumors. Semin Nucl Med 2007;37(1):34–47.

74. Schillaci O, Filippi L, Danieli R, Simonetti G. Single-photon emission computed tomography/computed tomography in abdominal diseases. Semin Nucl Med 2007;37(1):48–61.

75. Bjelkhagen HI, Mirlis E. Color holography to produce highly realistic three-dimensional images. Appl Opt 2008;47(4):A123–A133.

76. Langehanenberg P, Ivanova L, Bernhardt I, et al. Automated three-dimensional tracking of living cells by digital holographic microscopy. J Biomed Opt 2009;14(1):014018.

77. Vannan MA, Cao QL, Pandian NG, Sugeng L, Schwartz SL, Dalton MN. Volumetric multiplexed transmission holography of the heart with echocardiographic data. J Am Soc Echocardiogr 1995;8(5 pt 1):567–575.

78. Pinto FJ, Veiga F, Lopes MG, de Pádua F. Dynamic three-dimensional echocardiography: a new era in ultrasound technology. Rev Port Cardiol 1997;16(10):787–795; 745–746.

79. Galeotti JM, Siegel M, Stetten G. Real-time tomographic holography for augmented reality. Opt Lett 2010;35(14):2352–2354.

80. Del Socorro Hernández-Montes M, Furlong C, Rosowski JJ, et al. Optoelectronic holographic otoscope for measurement of nano-displacements in tympanic membranes. J Biomed Opt 2009;14(3):034023.

81. Robertson DD, Sutherland CJ, Chan BW, Hodge JC, Scott WW, Fishman EK. Depiction of pelvic fractures using 3D volumetric holography: comparison of plain X-ray and CT. J Comput Assist Tomogr 1995;19(6):967–974.

82. Biwasaka H, Saigusa K, Aoki Y. The applicability of holography in forensic identification: a fusion of the traditional optical technique and digital technique. J Forensic Sci 2005;50(2):393–399.

83. Prevedello LM, Andriole KP, Gill R, Oliva IB, Khorasani R. Post-processing tools for radiologists: understanding the principles, obstacles and utility of embedding advanced processing into the routine workflow in thoracic radiology [abstr]. In: Radiological Society of North America scientific assembly and annual meeting program. Oak Brook, Ill: Radiological Society of North America, 2007; 840.

84. Prevedello LM, Andriole KP, Khorasani R. Advanced processing tools in radiology: what do we know, what should we know, and how can we utilize them in an evidence-based approach? [abstr]. In: Radiological Society of North America scientific assembly and annual meeting program. Oak Brook, Ill: Radiological Society of North America, 2008; 911.

85. Lidén M, Andersson T, Geijer H. Alternative user interface devices for improved navigation of CT datasets. J Digit Imaging doi:10.1007/s10278-009-9252-2. Published online December 1, 2009.

86. Goyal N, Jain N, Rachapalli V. Ergonomics in radiology. Clin Radiol 2009;64(2):119–126.

87. Prabhu SP, Gandhi S, Goddard PR. Ergonomics of digital imaging. Br J Radiol 2005;78(931):582–586.

88. Weiss DL, Siddiqui KM, Scopelliti J. Radiologist assessment of PACS user interface devices. J Am Coll Radiol 2006;3(4):265–273.

89. Greene JR. Design and development of a new facility for teaching and research in clinical anatomy. Anat Sci Educ 2009;2(1):34–40.

90. Wachs JP, Stern HI, Edan Y, Gillam M, Handler J, Feied C, Smith M. A hand gesture sterile tool for browsing MRI images in the OR. J Am Med Inform Assoc 2008 Feb 28. [Epub ahead of print]

91. Wachs JP, Stern HI, Edan Y, et al. A gesture-based tool for sterile browsing of radiology images. J Am Med Inform Assoc 2008; 15(3):321–323. [Published correction appears in J Am Med Inform Assoc 2009; 16(3):284.]

92. Fernàndez-Bayó J, Barbero O, Rubies C, Sentís M, Donoso L. Distributing medical images with internet technologies: a DICOM web server and a DICOM java viewer. RadioGraphics 2000;20(2):581–590.

93. Arenson RL, Andriole KP, Avrin DE, Gould RG. Computers in imaging and health care: now and in the future. J Digit Imaging 2000;13(4):145–156.

94. Zhang J, Sun J, Stahl JN. PACS and Web-based image distribution and display. Comput Med Imaging Graph 2003;27(2-3):197–206.

95. Tellis WM, Andriole KP. Integrating multiple clinical information systems using the Java message service framework to enable the delivery of urgent exam results at the point of care. J Digit Imaging 2005;18(4):316–325.

96. Bandon D, Lovis C, Geissbühler A, Vallée JP. Enterprise-wide PACS: beyond radiology, an architecture to manage all medical images. Acad Radiol 2005;12(8):1000–1009.

97. Andriole KP, Prevedello LM, Dufault A, et al. Augmenting the impact of technology adoption with financial incentive to improve radiology report signature times. J Am Coll Radiol 2010;7(3):198–204.

98. Flanders AE, Wiggins RH 3rd, Gozum ME. Handheld computers in radiology. RadioGraphics 2003;23(4):1035–1047.

99. Raman B, Raman R, Raman L, Beaulieu CF. Radiology on handheld devices: image display, manipulation, and PACS integration issues. RadioGraphics 2004;24(1):299–310.

100. Nakata N, Kandatsu S, Suzuki N, Fukuda K. Informatics in Radiology (infoRAD): mobile wireless DICOM server system and PDA with high-resolution display—feasibility of group work for radiologists. RadioGraphics 2005;25(1):273–283.

101. Andriole KP, Khorasani R. Cloud computing: what is it and could it be useful? J Am Coll Radiol 2010;7(4):252–254.

102. Lin A, Harris M, Zalis M. Initial observations of electronic medical record usage during CT and MRI interpretation: frequency of use and impact on workflow. AJR Am J Roentgenol 2010;195(1):188–193.