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A Perspective on the New Millennium[1]

The future of diagnostic imaging will rely, in large part, on the digital revolution that is currently affecting all technology-driven disciplines. Superimposed on the digital substrate, however, are a variety of wide-ranging developments that are modality-specific advancements in image receptor technology and modality-specific image data reduction. Diagnostic imaging is classically divided into the general areas of radiography and fluoroscopy, computed tomography (CT), magnetic resonance (MR) imaging, nuclear medicine, and ultrasonography (US). The following comments are divided along the same lines and were specifically contributed by individuals specializing in each of those imaging disciplines.

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Radiography

Screen-film technology has been gradually improving in certain respects, but the well-known problems associated with the limited dynamic range and contrast capabilities of the screen-film combination still persist. Stimulable phosphor technology, which was introduced in the early 1980s, provided a convenient alternative for direct digital image acquisition. The present stimulable phosphor technology provides a practical solution, but, as with other technologies including film, it can be further optimized with respect to spatial resolution and dose efficiency (1).

The new technologies that are generating considerable enthusiasm, and are likely to revolutionize x-ray imaging, use either amorphous silicon detectors with a scintillator or amorphous selenium with an amorphous silicon electronic panel readout. The former technology uses a scintillator as the primary detector, which converts x rays to light and then to electrons (indirect detection), while the latter uses a direct conversion approach from x rays to electrons in the selenium detector (direct detection). It is currently premature to draw conclusions about which technology offers the most advantages, and this may depend on the particular imaging application. Research on the indirect detection approach with flat-panel amorphous silicon is currently in progress by Antonuk et al (2,3) and Siewerdsen et al (4,5) in collaboration with the Xerox Corporation. In a separate effort, GE Medical Systems has also manufactured experimental feasibility prototypes of flat panels by using an indirect conversion amorphous silicon design with a high x-ray absorption cesium iodine (thallium) scintillator. These panels have been made from a single piece of 50 × 50-cm glass substrate with an active area of 41 × 41 cm and a pixel size of 200 μm. The image matrix consists of about 2,000 × 2,000 pixels. Smaller prototypes based on the same technology and with 100-μm pixel size are currently under clinical evaluation for mammography. A wealth of information in the direct-detection approach with amorphous selenium can be found in recent literature (6–8). In a separate effort, Sterling Diagnostic Imaging has adopted the direct-detection approach by using a layer of amorphous selenium detector in conjunction with an amorphous silicon flat panel. A detection area of about 35 × 43 cm (14 × 17 inches) is achieved by joining two panels, thus forming a matrix of 2,560 × 3,072 pixels with a pixel size of 139 μm. Other types of flat-panel detector technologies such as cadmium zinc telluride are currently under consideration, and we are also likely to see improved versions of stimulable phosphor technology that will compete with flat-panel approaches in certain imaging tasks.

Fluoroscopy

The introduction of image-intensifier tube technology in the early 1950s was an important milestone in x-ray imaging. This technology has been further improved with substantially better tube technology in conjunction with low-noise, tube-based video cameras and, more recently, with solid-state charge-coupled devices. However, the well-known limitations in subtle contrast discrimination, spatial resolution, and geometric distortions still persist and there is a need for improved consistency of image quality and dose efficiency in fluoroscopy. The proliferation of new interventional techniques that require prolonged fluoroscopic time have prompted the reexamination of equipment and techniques to minimize the radiation dose to the patient (9,10). To this end, flat-panel technology will eliminate geometric distortions and has the potential to improve contrast at a reduced dose. The flat-panel

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detector technology that is intended to replace image intensifiers is based on the same direct- or indirect-detection approaches mentioned previously. Although the spatial-resolution requirements of fluoroscopy are modest, the transition from image intensifiers to flat-panel detectors will require a considerable investment in resources to resolve many technical issues such as electronic noise, image lag, variable resolution, and dose efficiency.

Future Directions in Digital Radiography and Fluoroscopy

All these direct digital acquisition technologies will be able to circumvent many of the well-known problems associated with screen-film cassettes and image intensifiers. These detectors have greater dynamic range than film and offer the potential for higher x-ray detection efficiency and improved overall detective quantum efficiency. The ability to acquire a digital image directly, without digitizing film, will not only preserve image quality but also will make implementation of the totally digital radiology department closer to reality. The new generation of flat-panel direct digital detectors will enable further evaluation of powerful image acquisition techniques such as digital tomosynthesis and dual-energy imaging, which were impractical with screen-film techniques.

Currently, the pixel size of these detectors is on the order of 100 µm, and while this may be adequate for several radiographic applications, it is not yet clear whether it will suffice for applications requiring high spatial resolution such as mammography and skeletal imaging. Results in preliminary experience suggest that these detectors exhibit excellent spatial-resolution characteristics at low to middle spatial frequencies and appear to produce excellent images, even in applications where one would expect that a pixel smaller than 100 µm would be required. The transition from the current state of the art to a smaller pixel size would require a major investment in time and resources. It is therefore extremely important that research in the near future be aimed at evaluating the minimum pixel size that will be required for different radiographic applications to avoid costly development of flat-panel detectors with very high resolution, which may not be essential.

Despite recent encouraging developments, the technology of flat-panel detectors for digital radiography and fluoroscopy is still in its infancy. At the beginning of the new millennium, we will see many new developments in detector technologies and acquisition techniques. Digital detector technologies are likely to be available in the form of fixed sensors for fluoroscopy and for a dedicated chest imaging room or in the form of a plug-in removable cassette for radiographic or even mammographic applications (11). We have already witnessed proof of principle for some of these approaches, but further research and development will be required to harvest the full potential of digital detectors for radiographic and fluoroscopic applications. The National Cancer Institute has been one of the major funding agencies that have recognized the potential of these technologies in the diagnosis and treatment of disease. Continued commitment from the various funding agencies, universities, and corporations will be necessary to bring this technology into widespread use.

CT Scanning

The development of CT is widely considered the most important advance in x-ray imaging since the discovery of x rays. In the 1970s and 1980s, CT enabled radiologists to visualize internal anatomy within seconds of beginning the examination, often reducing the need for exploratory surgery. Recent developments in hardware and software have enabled subsecond spiral section acquisition for dynamic imaging with increased contrast detectability and spatial resolution (12,13). Three-dimensional reconstruction of internal anatomy for diagnostic purposes and for surgical or radiation therapy treatment planning is now practical and has become routine at many institutions. Dynamic CT and CT angiography are common clinical procedures. CT angiography is emerging as a powerful diagnostic tool that can be substituted for more invasive and time-consuming angiographic studies in certain situations. Three-dimensional CT angiography has become routine for head, chest, and abdomen with spiral CT technology. Electron-beam CT is a unique scanning technique that eliminates mechanical motion (14) and has very short exposure times that allow noninvasive imaging of coronary arteries (15).

Future research in CT technology should continue on the evolution of solid-state detectors, signal acquisition electronics, reconstruction-software artifact suppression, and three-dimensional reconstruction workstations. Isotropic spatial resolution may not be essential for all studies, but it would be very desirable for certain applications that require high spatial resolution. More efficient volumetric detection schemes involving simultaneous multiple-section acquisition, or faster spiral scanning, are also worthy of further exploration, especially in pediatric applications where motion is a problem (16). The efficient utilization of the technology and the formulation of effective scanning protocols for CT scanning must be carefully planned by the user. As in the past, the efficacy of the new capabilities of CT should be validated in well-designed experimental studies. Particular attention should be given to the refining of pediatric imaging protocols for optimization of image quality at low radiation dose.

MR Imaging

A current trend in clinical MR imaging has been a move to more "open" magnet designs. Open systems have the advantage of cost, ease of use, and niche applications. Among these applications are trauma, orthopedics, and interventional (17). Open systems are also more accommodating to claustrophobic and obese patients. Since truly open systems will probably continue to be relatively low-field-strength systems, an image quality issue may persist. The situation at the high-field-strength segment of the MR imaging market, which seems likely to continue, is the steady introduction of new enhancements. Current examples are high-performance gradient systems, phased-array radio-frequency coils, segmented acquisitions, and short bore magnets. The more expensive systems are also being offered with a continued stream of new application packages such as functional MR imaging, diffusion-perfusion imaging (18), and contrast material–enhanced MR angiography. Echo-planar techniques offer promise for imaging flow in the coronary arteries. Interventional and intraoperative MR imaging will likely be pursued aggressively by several leading equipment vendors. Considerable progress has been made in imaging-guided biopsies, MR imaging–guided interventions, and intraoperative MR imaging (19). The optimistic outlook for this method is rooted in the belief that the exquisite contrast of MR images, when coupled with recent advances in bioengineering methods that allow minimally invasive therapies, has a potential to revolutionize treatment of a variety of pathologic conditions. Functional imaging may also become aleading application (20,21). Functional MR imaging will likely offer images of the entire brain in real time, noninvasively, and at modest cost. The method, even in its present early stage, evokes great interest among neurologists, psychologists, and psychiatrists. Cardiac MR imaging holds promise as the "one-stop shopping" modality for evaluation of cardiac function (22). Diffusion imaging has already evolved into an important tool with promising applications in stroke assessment and management. MR angiography in the brain has made spectacular progress in the past. Contrast-enhanced MR angiography is likely to rival conventional x-ray angiography in peripheral vascular applications (23). Many new applications rely on faster and stronger gradient systems and increased computer power. However, this technology faces problems of patient safety and patient acceptance. If the gradient performance characteristics are boosted further, patients undergoing MR imaging studies may experience peripheral nerve stimulation and potentially may have a painful experience. The issue may once again be the assessment of risk versus benefits associated with the procedures.

MR contrast agent technology continues steady advancement. New and very promising agents are emerging almost daily, offering many new applications. Examples include high-dose bolus tracking in MR angiography and improved image contrast with organ-targeted agents. These are all in addition to a potentially new generation of agents that are tumor specific. MR spectroscopy is, after much early enthusiasm, becoming routine for several clinical assessments.

Nuclear Medicine

Camera design has been steadily improving through the incorporation of advances in mechanical design, computer science, and materials science. Current designs bear only a superficial resemblance to what was available a few years ago. In addition, advances in materials science are already making inroads into the monopoly that sodium iodide crystals have had over nuclear medicine since its inception. Future advances in materials science are expected to greatly accelerate this trend in the 5- to 10-year time frame. While multiple-head, single photon emission computed tomography (SPECT) gamma cameras have been with us for 10 years or more, the introduction of gantries, stands, and packing arrangements that permit the detectors to be placed at 90° orientation (variable angle configuration and L-shaped detectors) with respect to each other has had an effect on the quality of cardiac scanning. In many cases, these arrangements do not compromise whole-body, torso, or brain applications. Perhaps the most exciting advances have been made possible with fast digital electronics and pulse processing techniques that permit sodium iodide detectors to be used in coincidence mode for the imaging of positron emission tomography (PET) isotopes, most notably 2-[fluorine-18]-fluoro-2-deoxy-D-glucose, or FDG. This is done without compromising performance at lower energies. Before the introduction of this new technology, these PET isotopes had to be imaged by using expensive dedicated PET scanners. These all-digital camera designs have also improved SPECT performance by providing exquisite energy and linearity corrections to reach the theoretic limits of spatial resolution with sodium iodide detectors (24).

Faster computers and faster algorithms are allowing the use of iterative reconstruction algorithms to process not only PET data but also the data from more conventional acquisitions. This has made possible the introduction of hardware and software to permit the collection of transmission data that are used to provide attenuation-corrected SPECT images, a technique applied mainly to cardiac scans. Whereas clinical results have been mixed so far, the introduction of further corrections for scatter and resolution is expected to improve quantitative accuracy if not clinical accuracy (25).

Finally, this discussion would not be complete without mentioning the recent introduction of a commercial semiconductor camera based on cadmium zinc telluride. This small camera should have applications in cardiac and general nuclear medicine. Within the next 5–10 years, new scintillators will appear that will strongly challenge the performance of sodium iodide (thallium) in the area of combined SPECT and PET cameras. These new scintillators, lutetium orthosilicate and ytterbium orthosilicate, may permit a hybrid camera to far surpass the limited (but improving) count rate properties for sodium iodide that limit its ultimate utility as a PET detector.

US Scanning

US is in the early stages of a new series of advances. Findings in recent research will further improve and extend the utility of US in medical imaging. A few of the many areas of progress in imaging applications are reviewed in this section. One area under rapid development provides advances in transducer array technology. Specifically, new piezoelectric materials are resulting in higher operating frequencies, improved sensitivity, and broader bandwidth (26,27). In addition, multidimensional arrays are becoming commercially available. Standard linear- and phased-array probes have a large number of transducer elements arranged in a one-dimensional array. This configuration allows the acoustic beam to be focused and steered in the image plane. The focal properties in the elevation direction (section thickness, perpendicular to the image plane) are fixed geometrically. A new linear-array design (28) incorporates the same large number of transducer elements in the image-plane direction with a small number (approximately five) of elements in the elevation direction. This configuration, a so-called 1.5-dimensional array, allows the acoustic beam to be focused and steered in the image plane, as with a one-dimensional array, and also allows focusing in the elevation direction. The advantage is a more uniform section thickness, reduced partial volume effects, and better small object detectability. Phantoms that demonstrate this improved detectability have been developed (29). An extension of transducer design that incorporates a large number of transducer elements in both directions (two-dimensional arrays) has also been developed. A two-dimensional array allows the beam to be focused and steered in both the image plane and in elevation. Applications of two-dimensional arrays include imaging in arbitrary planes (relative to the transducer face) and in real-time volumetric imaging (30). In the future, we expect to see further increases in the number of US system channels needed to address the increased number of array elements, and the system bandwidth of each of these channels will increase to support the high frequency and broader bandwidth of the new transducer materials.

One exciting application of the latest broadband array systems is the use of harmonic imaging (31). With this technology, a relatively low-frequency pulse is transmitted (3.5 mHz, for example) and the echo signals for a higher harmonic (the second harmonic, 7.0 mHz, in this example) are received and processed for image formation. The advantages are improved spatial resolution and lower sidelobe amplitudes (higher image contrast) compared with standard B-mode images at the fundamental frequency (3.5 mHz in this example). This technique is being applied to imaging with contrast agents (32–34) and imaging without contrast agents (see the websites of most major US equipment manufacturers for sample images).

Finally, a relatively new area of research involving US is actually the development of a fundamentally new imaging modality called elastography. Elastography can be thought of as a "high-tech" form of palpation. In elastography, sonograms acquired before and after a small amount (about 1%) of axial displacement are compared, by means of techniques such as cross correlation, to detect displacement of the tissue. Soft tissues are deformed more than stiff tissues, and these differences are quantified in images of tissue strain (fractional displacement). No other imaging modality is sensitive to tissue stiffness. Independent laboratory measurements of tissue stiffness suggest that the physical elastographic contrast of many cancers is 10 times greater than that for any other imaging modality. Elastography research is progressing rapidly in laboratories worldwide. Findings in the limited clinical work performed to date (35) have been very encouraging. The new generation of US systems is designed to be highly adaptable. As a result, manufacturers can quickly implement new technologies as they become available. The utility of US is likely to improve at a rate even faster than we have already seen.

References

1. Seibert JA. Computed radiography: technology and quality assurance. In: Frey GD, Sprawls PS, eds. The expanding role of medical physics in diagnostic imaging. Madison, Wis: Advanced Medical Publishing for the American Association of Physicists in Medicine, 1997.
2. Antonuk LE, Yorkston J, Huang W, et al. A real-time, flat-panel, amorphous silicon, digital x-ray imager. RadioGraphics 1995; 15:993–1000.
3. Antonuk LE, el-Mohri Y, Siewerdsen JH, et al. Empirical investigation of the signal performance of a high-resolution, indirect detection, active matrix flat-panel imager (AMFPI) for fluoroscopic and radiographic operation. Med Phys 1997; 24:51–70.
4. Siewerdsen JH, Antonuk LE, el-Mohri Y, et al. Empirical and theoretical investigation of the noise performance of indirect detection, active matrix flat-panel imagers (AMFPIs) for diagnostic radiology. Med Phys 1997; 24:71–89.
5. Siewerdsen JH, Antonuk LE, El-Mohri Y, Yorkston J, Huang W, Cunningham IA. Signal, noise power spectrum, and detective quantum efficiency of indirect-detection flat-panel imagers for diagnostic radiology. Med Phys 1998; 25:614–628.
6. Zhao W, Rowlands JA. X-ray imaging using amorphous selenium: feasibility of a flat panel self-scanned detector for digital radiology. Med Phys 1995; 22:1595–1604.
7. Zhao W, Rowlands JA. Digital radiology using active matrix readout of amorphous selenium: theoretical analysis of detective quantum efficiency. Med Phys 1997; 24: 1819–1833.
8. Que W, Rowlands JA. X-ray imaging using amorphous selenium: inherent spatial resolution. Med Phys 1995; 22:365–374.
9. Wagner LK, Elfel PJ, Geise RA. Potential biological effects following high x-ray dose interventional procedures. JVIR 1994; 5:71–84.
10. Shope TB. Radiation-induced skin injuries from fluoroscopy. RadioGraphics 1996; 16:1195–1199.
11. Levis I, Sechopoulos I, Karellas A. Physical characteristics of a very large CCD for high resolution digital mammography (abstr). Radiology 1997; 205(P):302.
12. Kalender WA. Technical foundations of spiral CT. Semin Ultrasound CT MR 1994; 15:81–89.
13. Hsieh J. A general approach to the reconstruction of x-ray helical computed tomography. Med Phys 1996; 23:221–229.
14. McCollough CH, Morin RL. The technical design and performance of ultrafast computed tomography. Radiol Clin North Am 1994; 32:521–536.
15. Achenbach S, Moshage W, Ropers D, Nossen J, Bachmann K. Noninvasive, three-dimensional visualization of coronary artery bypass grafts by electron beam tomography. Am J Cardiol 1997; 79:856–886.
16. Frush DP, Siegel MJ, Bisset GS III. Challenges of pediatric spiral CT. RadioGraphics 1997; 17:939–959.
17. Jolesz FA. Genesis of interventional MRI: a general overview of the field. JMRI 1998; 8:3–7.
18. Detre JA, Leigh JS, Williams DS, Koretzky AP. Perfusion imaging. Magn Reson Med 1992; 23:37–45.
19. Hinks RS, Bronskill MJ, Kucharczyk W, Bernstein M, Collock BD, Henkelman RM. MR systems for image-guided therapy. JMRI 1998; 8:19–25.
20. Belliveau JW, Kennedy DN, McKinstry RC, et al. Functional mapping of the human visual cortex by MRI. Science 1991; 254:716–719.
21. Ogawa S, Lee TM, Kay AR, Tank DW. Brain MRI with contrast dependence on blood oxygenation. Proc Natl Acad Sci USA 1990; 87:9868–9872.
22. Atkinson DJ, Edelman RR. Cineradiography of the heart in a single breath hold with segmented turbo FLASH sequence. Radiology 1991; 178:357–360.
23. Manning WJ, Atkinson DJ, Grossman W, Paulin S, Edelman RR. First-pass NMR imaging studies using Gd-DTPA in patient with coronary artery disease. J Am Coll Cardiol 1991; 18:959–965.
24. Coleman RE. Camera-based PET: the best is to come (editorial). J Nucl Med 1997; 38:1796–1798.
25. Heller EN, DeMan P, Liu Y, et al. Extracardiac activity complicates quantitative cardiac SPECT imaging using a simultaneous transmission-emission approach. J Nucl Med 1997; 38:1882–1890.
26. Goldberg RL, Smith SW. Multi-layer PZT transducer arrays for improved sensitivity. Proc IEEE Ultrason Symp 1992; 551–554.
27. Zhang Q, Lewin PA, Bloomfield PE. PVDF transducers: a performance comparison of single-layer and multi-layer structures. Ultrason Ferroelec Freq Contr 1997; 44: 1148–1156.
28. Wildes DG, Chiao RY, Daft CMW, Rigby KW, Smith LS, Thomenius KE. Elevation performance of 1.25D and 1.5D transducer arrays. Ultrason Ferroelec Freq Contr 1997; 44:1027–1037.
29. Rownd JJ, Madsen EL, Zagzebski JA, Frank GR, Dong F. Phantoms and automated system for testing the resolution of ultrasound scanners. Ultrasound Med Biol 1997; 23:245–260.
30. Davidsen RE, Jensen JA, Smith SW. Two-dimensional random arrays for real time volumetric imaging. Ultrason Imaging 1994; 16:143–163.
31. Ward B, Baker AC, Humphrey VF. Nonlinear propogation applied to the improvement of resolution in diagnostic medical ultrasound. J Acoust Soc Am 1997; 101: 143–154.
32. Correas JM, Helenon O, Pourcelot L, Moreau JF. Ultrasound contrast agents: examples of blood pool agents. Acta Radiol Suppl 1997; 412:101–112.
33. Firschke C, Lindner JR, Wei K, Goodman NC, Skyba DM, Kaul S. Myocardial perfusion imaging in the setting of coronary artery stenosis and acute myocardial infarction using venous injection of a second-generation echocardiographic contrast agent. Circulation 1997; 96:959–967.
34. Burns P. Overview of echo-enhanced vascular ultrasound imaging for clinical diagnosis in neurosonology. J Neuroimaging 1997; 7(suppl 1):S2–S14.
35. Garra BS, Cespedes I, Ophir J, et al. Elastography of the breast: initial clinical results. Radiology 1997; 202:79–86.