

Current Status of and Future Directions for Digital Mammography

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Screen-film mammography has certain technical limitations which reduce its effectiveness: the film gradient must be balanced against the need for wide latitude, detection of microcalcifications and portrayal of the clarity of the margins of breast masses are reduced due to the presence of film noise in the displayed image, film processing artifacts can degrade the mammographic image, and the day-to-day variability inherent in automated film processors can produce suboptimal image quality.

The principal theoretical advantage of digital mammography comes from decoupling image display from the image receptor. This permits the digital image to be captured, stored electronically, and then manipulated, analyzed, and displayed however, whenever, and wherever it is needed. Numerous practical applications are being developed to take advantage of these intrinsic capabilities of digital mammography. Some of these applications have already gained clinical acceptance; others have not because of current hardware limitations. The following paragraphs describe the several practical applications of full-field digital mammography that can be expected to define its future roles.

Real time image display. This will provide several advantages over conventional film mammography. The waiting time involved in film processing will be greatly reduced, thereby increasing patient throughput and reducing the per capita cost of examination. Day-to-day variability in automated film processors, which now requires careful monitoring including daily sensitometric strips, also will cease to be a problem. Some diagnostic

mammographic work-ups will be performed in a much faster, more interactive fashion, and when truly real-time image display becomes available, mammographic work-ups may be performed in a manner similar to fluoroscopic examinations. This will be most helpful in rapidly and reliably distinguishing summation shadows from true masses and in documenting dermal location of benign skin calcifications. Finally, lesion localization procedures can be facilitated by the ability to visualize localizing needles as they are positioned within or immediately adjacent to suspect lesions (this application, using a 5×5 cm field of view, is already built into several stereotactic-guidance mammography systems).

Post-acquisition image enhancement. Signal processing techniques can be applied to the digitally acquired image to produce overall enhancement or to increase the conspicuity of specific mammographic findings. Window and level controls can be manipulated to portray the entire breast with proper intensity and great contrast, thereby providing an essentially unlimited gray scale to facilitate visualization of important findings that might be obscured by the toe or shoulder of a characteristic film curve. Enlargement and unsharp masking techniques can make more readily visible such tiny structures as breast microcalcifications. Other edge enhancement manipulations can highlight border contours in similar fashion to that produced by xeroradiography. Noise suppression techniques can render low-contrast objects more readily perceptible. Intensity equalization techniques can be applied to clearly portray in a single image structures that usually are difficult

to see, such as the skin and subcutaneous tissues. Digital systems also have the capability to overcome many underexposure and overexposure conditions and display fully interpretable mammograms despite what otherwise would be considered unacceptable image quality.

Image archival and retrieval. A major advantage of digital over conventional film imaging is its ability to conveniently store and retrieve images. This electronic archival process can permit substantial cost savings, especially for high-volume operations, despite the initial large expenditure for digital equipment. In addition, costs of film and film processing are eliminated, as is the cost of film storage. Since archival and retrieval activities involve electronic rather than hard-copy transfers, costs for file room personnel also are reduced. Finally, digital data storage is much more rapid and reliable than film-based methods. This is particularly noticeable when prior studies are needed for comparison. Retrieval time is measured in seconds-to-minutes rather than in hours-to-days. Furthermore, it would be most unusual for digital examinations to be misfiled, lost, damaged in storage, or signed out to another location.

Teleradiology applications. Electronic transfer of digital images to remote viewing sites can be accomplished almost as rapidly as occurs between the standard display workstation and computer storage. Numerous activities utilizing teleradiology have been devised, many of which are clearly applicable to mammography practice. Radiologists who work in several different offices or hospitals will be able to monitor and interpret examinations that are carried out in a nearby or even distant location or locations. Mammography screening in mobile units will be made more efficient not only by overcoming the need to transport films from the site of examination to the site of interpretation, but also by permitting image interpretation while patients are still available for repeat or additional exposures. In addition, teleradiology can be used to facilitate second-opinion interpretation, in effect making world-class mammography expertise immediately accessible to community practice radiologists. Last but not least, digital image transmission can be the cornerstone upon which multi-

site teaching conferences are built, from applications as simple as the simultaneous conduct of teaching rounds among the nearby hospitals that participate in a residency training program to intercontinental multi-institution conferences supported by satellite transmission of digital mammograms.

Dual-energy subtraction imaging. Dual-energy subtraction mammographic techniques are based on the principle that if both high and low kVp exposures are taken using the same radiographic projection, that depending upon atomic composition, some breast structures will exhibit greater absorption of low-energy compared with high-energy photons. Thus, if there is no patient motion between exposures, one digital image can be electronically subtracted from the other, causing common elements (those that do not exhibit differential absorption) to cancel out completely. In this fashion, dual-energy subtraction mammography has the potential to increase the conspicuity of selected subtle findings, not only by showing some low contrast objects with increased clarity but especially by removing the superimposed "clutter" of background breast structures. This is particularly useful in demonstrating the tiny calcifications that can be the earliest indicator of a breast cancer, because the relatively high atomic number of calcium results in increased absorption of low-energy photons.

Digital Tomosynthesis. During tomography, the x-ray source and imaging detector move relative to each other, so that radiographic features in only one plane remain in sharp focus. One exposure is necessary for each imaged plane. The ability to shift and add digital images electronically permits computer-assisted tomographic reconstruction (tomosynthesis), and the availability of full-field (whole-breast), flat (non-curved) digital detectors has made this technology practical for use in imaging the breast. The first digital tomosynthesis methods to achieve preliminary success in breast imaging involve taking multiple exposures of the entire breast with the x-ray tube at different angles along a single arc, utilizing a full-field digital detector that is fixed in position. This method produces a series of reconstructed digital tomographic images at a total radiation dose only slightly

higher than that of standard film-screen mammography. Other whole-breast digital tomosynthesis methods also are likely to prove successful in the near future.

One potential role for digital tomosynthesis is to provide more effective imaging of areas of dense fibroglandular tissue within a breast, to make noncalcified masses more readily visible by eliminating superimposed isodense structures. Another is to permit rapid and reliable differentiation between summation artifact and true mass for nonpalpable lesions detected at screening mammography on only one standard projection. However, clinical utility has not yet been demonstrated for these or for any other potential applications of digital tomosynthesis.

Computer-aided image analysis. Recently, there has been considerable interest in developing computer-executed algorithms that detect abnormal findings on mammograms. Most such attempts have been directed at the identification of clustered microcalcifications and spiculated lesions, although several computer programs also have been written to detect poorly-defined masses, asymmetries, and developing asymmetries. Current applications are designed to indicate suspect findings by superimposing arrows, circles, or other marks at appropriate locations on digitized mammograms. The most successful of these programs presently are capable of identifying approximately 85% of mammographically visible cancers, but also falsely indicate approximately 2 to 4 suspect areas on each 4-view mammography examination.

These computer-based applications can be used by radiologists as second-interpretation devices to avoid missing identifiable mammographic abnormalities. It is probable that this approach will be less expensive than double readings done by another radiologist, especially when the applications are integrated into full-field digital mammography units. However, it is unlikely that computer-aided detection (CAD) programs will be used for the first-pass interpretation of digital mammography screening examinations in the United States, sending only those cases with suspect findings on to a radiologist for definitive interpretation, because the responsible radiologist (and the providers of the CAD software) then would face malpractice exposure for missed can-

cers, a risk that they are unwilling to accept.

Computer-aided image interpretation programs also are being developed to further characterize already detected lesions, to determine whether subsequent management should involve biopsy or less invasive procedures. Again, these efforts have been directed principally at the analysis of clustered microcalcifications and spiculated lesions. Applications begin by quantitating the digital data within suspect lesions that already have been flagged either by radiologists or by computer detection programs. Formulas then are used to describe a wide variety of lesion characteristics; for calcifications these include not only the standard parameters assessed by radiologists (particle size, number, density, distribution, and shape) but also several more complex measures of calcific particle irregularity (for example, compactness, eccentricity, coefficient of convexity, elongation). Finally, numeric scores derived for these various parameters are weighted by pre-determined algorithms and combined to yield a likelihood of malignancy index, upon which management decisions can be based. Currently, the most successful of the calcification and spiculation characterization programs operate at diagnostic accuracies that usually approximate but occasionally even exceed those of expert mammographers; for other types of suspect lesions, today's computer-aided diagnosis programs are less fully developed and also less successful.

Computer-aided instruction. Rapid, inexpensive, computer-based storage of digital mammography examinations facilitates the creation and utilization of computer-aided instruction packages, since selected sets of images can be readily catalogued and retrieved for display. The simplest application represents the digital counterpart to the conventional film mammography learning file. This involves an organized library of interesting case material (digitized mammograms), supplemented by hard-copy text descriptions of mammographic findings, suggested interpretation, pathologic correlation, additional discussion, and literature reference material for each case or group of cases. Tens of thousands of mammography cases can be stored on a single optical disk. In a somewhat more sophisticated system, the text material itself is stored electronically,

so that cases can be viewed with equal ease either in random sequence (as unknown cases) or in sequences organized either by diagnosis or by specific mammographic finding.

Instructional programs also have been developed to provide the user with response-driven self-instruction modules, in which incorrect answers trigger the display of remedial material and additional questions before subsequent cases can be viewed. Such systems can track the progress of individual users, compiling grades and documenting that proficiency has been achieved.

Finally, the most ambitious of instructional packages interface directly with the day-to-day interpretation of digital mammograms. Such systems would be activated either by request of the radiologist or whenever computer-recorded interpretations describe specific mammographic findings. In either circumstance, description of a particular mammographic finding could call up related image and text materials from expert learning databases, to compare with the case under consideration. Thus, the radiologist could view pathology-proved cases in which mammograms display similar if not identical radiographic findings. Embedded text also could suggest strategies for further evaluation and interpretation of the mammographic findings.

Future Developments in Digital Mammography

The major deficiency of current digital mammography equipment involves limited spatial resolution of display monitors, and there is also a need to reduce the cost of both image display and full-field image acquisition. Teleradiology applications should benefit from improved software techniques to compress and store digital data, as well as from development of more efficient software protocols to accelerate image transmission. Computer-aided diagnosis applications also will continue to increase in effectiveness as existing algorithms are refined and new ones are developed, driven at least in part by the use of neural networks and other forms of machine intelligence.

Digital mammography systems are expected eventually to replace conventional film imaging. We do not yet know the specific characteristics of the hardware and software that will achieve clinical success, nor the timetable by which needed improvements will take place. Several full-field digital mammography units have already been approved by the FDA for sale and use in the United States, and the units of other manufacturers are on the threshold of receiving FDA approval. Clinically acceptable digital mammography already is a reality, and substantial enhancements likely will become available within the next 10 years, probably much sooner.