Potential Usefulness of Digital Imaging in Clinical Diagnostic Radiology: Computer-Aided Diagnosis

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TO IMPROVE the diagnostic accuracy and the consistency of radiologists' image interpretations, we are developing computer-aided diagnositic (CAD) schemes for automated detection of lesions and characterization of normal and abnormal patterns.[1-3] Computer output would be used as a second opinion before a radiologists' final decision. CAD schemes include the automated detection of masses and clustered microcalcifications in mammograms; detection of nodules, interstitial infiltrates, cardiomegaly, and pneumothoraces in chest radiographs; analysis of stenotic lesions in angiograms; and analysis of risk of fracture and osteoporosis in bone radiographs. In this report, we show the current performance in terms of sensitivity, specificity, and speed using a real-time (on-line) prototype intelligent workstation that includes a laser digitizer, a high-speed computer, a jukebox library and a six-cathode-ray tube (CRT)–monitor viewstation. The summary of current levels of performances is illustrated in Table 1.

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MAMMOGRAPHY

Automated Detection of Clustered Microcalcifications

We are developing a computer program that can automatically locate clustered microcalcifications on mammograms.[4-9] With our method, a digital mammogram is processed by a linear filter to improve the signal-to-noise ratio of microcalcifications on the image. Gray-level thresholding techniques, which combine a global gray-level thresholding procedure and a locally adaptive gray-level thresholding procedure, are then used to extract potential signal sites from the noise background. Subsequently, signal-extraction criteria are imposed on the potential signals to distinguish true signals from noise or artifacts. The computer then indicates locations that may contain clusters of microcalcifications on the image. Initially, for 60 mammograms used in the study, the true-positive cluster detection accuracy of our automated detection program reached 87% at a false-positive (FP) detection rate of four clusters per image. A receiver-operating characteristic (ROC) study was performed to determine whether this performance level could result in an improvement in radiologists' performance when the CAD results were displayed on images. The results of the ROC study showed that CAD, as implemented by the computer code in its present state of development, does significantly improve radiologists' accuracy in detecting clustered microcalcifications under conditions that simulate the rapid interpretation of screening mammograms. Recent improvements, including the use of a shift-invariant artificial neural network, have reduced the number of FPs detected by our program by a factor of 4.

Automated Detection of Mammographic Masses

We are developing a computerized scheme for the detection of masses in digital mammograms.[10-13] Based on the deviation from the

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normal architectural symmetry of the right and left breasts, a bilateral-subtraction technique is used to enhance the conspicuity of possible masses. The scheme uses two pairs of conventional screen-film mammograms (the right and left mediolateral oblique views and craniocaudal views), which are digitized. After the right and left breast images in each pair are aligned, a nonlinear bilateral-subtraction technique is used that involves linking multiple subtracted images to locate initial candidate masses. Various features are extracted and merged using an artificial neural network to reduce FP detections resulting from the bilateral subtraction. In an evaluation study using 154 pairs of clinical mammograms, the scheme yielded a sensitivity of 95% for detection at an average of 2.5 FP detections per image.

CHEST RADIOGRAPHY

Computerized Detection of Pulmonary Nodules

Currently, radiologists can fail to detect lung nodules in up to 30% of actually positive cases.[14-19] If a computerized scheme could alert the radiologist to locations of suspected nodules, then potentially the number of missed nodules could be reduced. We are developing such a computerized scheme that involves a difference-image approach and various feature-extraction techniques. The method involves producing two processed digital images from one chest radiograph: one in which the signal of the nodule is enhanced and the other in which it is suppressed. Both linear and nonlinear filtering operations are used. The difference between the two processed images yields an image of the signal superimposed on a simplified background. Feature-extraction techniques are then applied to the difference image to distinguish nodules from normal anatomic background patterns. The computerized detection scheme was used in the evaluation of posteroanterior chest radiographs from 60 clinical cases. Thirty cases were normal, and 30 had nodules of various subtlety and sizes (5 to 30 mm). The presence and location of the nodules were verified by means of computed tomography or follow-up radiography. The computer program achieves a true-positive detection rate of ~70% with an average of two to three FP detections per chest image. Computer outputs indicating locations of potential lesions are marked by arrows on the chest images.

Table 1. Current Levels of Performances of CAD Schemes in Chest Radiography and Mammography Derived From Our Databases of Selected Clinical Cases

	Sensitivity (%)	Specificity or No. of FPs	CPU Time (s)
Chest Radiography			
Detection of lung nodules	70	2.5/image	25
Analysis of interstitial infiltrates	90	90%	6.5
Detection of cardiomegaly	90	90%	0.25
Detection of pneumothorax	80	70%	17
Mammography			
Detection of clustered microcalcifications	85	1.0/image	22
Detection of masses	95	2.0/image	20

Computerized Detection and Characterization of Interstitial Disease

Evaluation of diffuse interstitial disease in chest radiographs is one of the most difficult problems in diagnostic radiology.[20-24] This difficulty is caused by (1) the numerous patterns and complex variations that are involved, (2) the lack of firmly established correlation between radiologic and pathologic findings, and (3) variations among radiologists in terms that they use to describe radiographic patterns that are not defined objectively. We are developing an automated method for determining physical measures of lung textures in digital chest radiographs to detect and characterize interstitial lung disease. Multiple regions of interest are selected automatically (using a gradient-distribution technique) and analyzed throughout the lung region. With our method, we correct for underlying background density variations caused by the gross lung and chest wall anatomy to isolate the fluctuating patterns of the underlying lung texture for subsequent computer analysis. The power spectrum of lung texture, which is obtained from the two-dimensional (2D) Fourier transform, is filtered by the visual system response of the human observer. The magnitude and coarseness (or fineness) of the lung textures are then quantified by the root-mean-square (rms) variation and the first moment of the power spectrum, respectively. Results indicate that the rms variations and/or the first moments of the texture of abnormal lungs with various interstitial diseases are clearly different from those of normal lungs. Computer outputs are marked on the chest image using symbols that indicate the severity and pattern type of the infiltrates.

Computerized Automated Analysis of Heart Sizes

Cardiac size is an important and useful diagnostic parameter in chest radiographs.[25] We are developing an automated method for determining a number of parameters related to the size and shape of the heart and lungs in chest radiographs. To obtain standard patterns of the cardiac shadow as "gold standards," four radiologists traced their best estimates of the entire contour of the heart, including the largely invisible inferior margin, on 11 radiographs. These contours were analyzed by Fourier transform, and the results were used as a guide to obtain a shift-variant cosine function that was applied to predict the cardiac contour by fitting a limited number of detected heart boundary points. These points were obtained from analysis of edge gradients in two orthogonal directions. A simple observer study indicated that the contours of the heart shadows computed for 60 chest radiographs were generally acceptable to radiologists for estimation of the size and area of the projected heart. We also detected the edges of the rib cage and the diaphragm, which enabled us to determine the projected thoracic area. From these results, we calculated the cardiothoracic ratio and other parameters, such as the ratio of the projected heart area to the projected thoracic area. Using this information, the probability of cardiomegaly is calculated.

Computerized Detection of Pneumothorax

To aid radiologists in the diagnosis of pneumothorax from chest radiographs, an automated method for detection of subtle pneumothorax is being developed.[26] The computerized method is based on the detection of a fine curved-line pattern that is a unique feature of radiographic findings of pneumothorax. Initially, regions of interest are determined in each upper lung area, where subtle pneumothoraces commonly appear. The pneumothorax pattern is enhanced by the selection of edge gradients within a limited range of orientations. Rib edges included in this edge-enhanced image are removed, based on the locations of posterior ribs that are determined separately. A subtle curved line caused by pneumothorax is then detected by means of the Hough transform. The detected pneumothorax pattern is marked on the chest image displayed on a CRT monitor. With the present computer method applied to 50 chest images (28 normals and 22 abnormals with pneumothorax), we were able to detect 77% of pneumothoraces, with 0.44 FPs per image.

ANGIOGRAPHY

Computerized Analysis of Stenotic Lesions

We are developing an iterative deconvolution technique to determine the sizes of "blurred" vessels in angiographic images by taking into account the unsharpness of the imaging system.[27-29] A selected vessel segment is tracked and the center line is determined by fitting the tracking points with a polynomial curve. The nonuniform background in the vicinity of the vessel is estimated by a 2D surface and subtracted from the original image to yield a DSA-like image. The blurred-image profile is then obtained from pixel values across the vessel in a direction perpendicular to the center line. This image profile is compared iteratively with calculated profiles for vessels of various sizes that are obtained by convolving a cylindrical vessel model with the line-spread function, until the rms difference between the two profiles is minimized. The size of a cylindrical vessel yielding the matched profile is considered the best estimate of the unknown vessel size. Studies with a blood vessel phantom indicate that vessels larger than 0.5 mm can be measured with an accuracy and precision of ~0.1 mm, which is about a third of the pixel size of our system.

Automated Tracking of Vessels

Angiographic images can be analyzed by means of computer-aided methods to provide diagnostically useful information, such as the degree of stenosis, the extent of cardiac wall motion, and blood-flow parameters.[30-34] In addition, 3D representations of vascular trees can be generated from bi-plane angiograms or stereoangiograms for use in treatment planning. The diagnostic information could be obtained more efficiently and reproducibly if these analyses were automated. However, for automation, a reliable method of computerized detection and identification of the vascular structures in angiographic images is required. We are developing an automated vessel-tracking method based on the double-square-box region-of-search technique, for efficient tracking of the connected vascular tree in an image. Tracking points and branch vessels are located by searching the perimeter of the boxes, which are centered on previously determined tracking points. The tracking points are verified as connected by region growing. In relatively straight regions of vessels, a large box is used for efficient tracking; in curved regions of vessels, a small box is used to ensure accurate tracking. When tracking is completed, accurate vessel information (ie, the vessel position, size, and contrast determined at each tracking point) is available for further quantitative analysis.

Determination of Instantaneous and Average Blood-Flow Rates

We are developing a new method for quantitation of blood flow rates based on determination of the spatial shift of the distribution of the contrast material in opacified vessels in angiographic images that are acquired while a bolus of the contrast material proceeds through the vessel.[35,36] The distance that the contrast material travels during the time between two image acquisitions is determined by comparison of distance-density curves, which represent the distribution of the contrast material along the length of the vessel in the respective images. The flow rate between image acquisitions is calculated by multiplication of the traveled distance by the frame rate and the vessel cross-sectional area. Therefore, for high-frame-rate acquisitions, instantaneous blood-flow rates can be determined. For vessel-phantom studies in which angiograms were obtained at 15 frames/s, the instantaneous flow rates measured with our technique agreed with those measured with an electromagnetic method to within an average of 2.3 cc/sec for pulsatile flow conditions with peak flow rates of up to 20 cc/sec; average flow rates agreed to within an average of 11%. For pulsatile-flow conditions, the accuracy of this new technique surpasses that of conventional methods in which the time shift of the distribution (based on the so-called "time-density" curves) is analyzed.

BONE RADIOGRAPHY

Measurement of bone mass is important in determining the risk for fracture and in following the course of patients undergoing therapy for osteoporosis.[37] Bone mineral densitometry (BMD) is a good predictor of fracture risk, but there is considerable overlap in BMD measurements between individuals with fracture risk and those without. In this study, computerized texture analysis of the trabecular pattern on conventional spine radiographs was used to evaluate bone structure as a determinant of fracture risk. Standard lumbar spine radiographs of 43 individuals were analyzed and compared with BMD measurements obtained with dual-photon absorptiometry. This method was more effective than BMD in differentiation of patients with fractures elsewhere in the spine from those with no fracture. These preliminary results suggest that this method of bone-structure analysis, combined with BMD, may lead to a more sensitive and specific predictor of osteoporosis and risk of fracture.

Display System for CAD

Practical use of CAD presents new requirements for soft-copy image display. The desired system would allow the radiologist to form an initial impression without CAD, and then display CAD-generated annotation to point out areas that may deserve further scrutiny. The display system would also need to maintain or improve radiologists' productivity comparable with that possible with present film-based practice. We have been working with Laboratory Automation Inc. (Chicago, IL) in the development of a multiscreen viewstation meeting these criteria. The system architecture was optimized for fastest image retrieval and display in a low-cost unit. Disk-cache and data-compression techniques are used to extract maximum performance from conventional disk drives. Similarly, zoom and roam capabilities are used to realize maximum clinical utility from 1,024-line monitors. The viewstation can be configured with one to eight screens. A six-screen prototype of this system is used to display CAD results in our lab.

Incoming images are converted and stored in a format for fast retrieval. The main features of the format include (1) images stored in tiles of 128 × 128 pixels to enable retrieving image segments; (2) precomputed and stored lower resolution views; and (3) tile compression using a lossless algorithm. Special hardware decompresses images while they are loaded into the video-frame buffers. The image disk is contained in the display system, keeping display data traffic off the host computer bus. A large disk cache enables rapid access to repeat images. The video-frame buffer is reloaded from cache for gray-scale change or zoom; additional tiles are loaded as needed for roam operations. Specifications of the six-monitor viewstation are as follows: Host (platform) computer, 803686/486-based personal computer; host operating system, Unix system V or MS-DOS 5.0; display processor CPU, Intel 80960CA, 25 MHz (50 MIPS); display processor memory, DRAM, 32 or 64 Mbytes; image disk interface, SCSI, 5 Mbyte/sec synchronous; image disk drive, SCSI, 665 Mbytes, 1.5 Mbytes/s; decompression engine, Lossless, 25 million pixels/s; gray scale lookup table: 14 bits input, 8 or 16 bits output; Frame buffer interface bus: 32 bits wide, 32 Mbyte/s; Frame buffers (one per monitor): image memory, 4,194,304 pixels, 8 bits/pixel; overlay memory, 2,097,152 pixels, 4 bits/pixel; and display format, 1,024 (horizontal) × 1,360 (vertical), 70 Hz; size of image (on disk), 16,384 × 16,384 maximum; Image load time (1,024 × 1,360 view): from disk, less than 1.0 s, and from disk cache, less than 0.08 s.

CONCLUSION

Our results obtained with various CAD schemes are very encouraging. It seems now feasible to begin an initial clinical evaluation of some CAD schemes, such as that for detection of clustered microcalcifications in digitized mammograms, to gain more experience in computerized analysis of a very large number of clinical cases. In fact, we are currently implementing the first intelligent mammography workstation in the mammography section of our department.

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