Evaluation of Digital Processing Methods for the Display of Digital Mammography

Bradley M. Hemminger, Elodia Cole, Shuquan Zong, Martin Yaffe, Stephen Aylward, Andrew Maidment, Mark Williams, Loren Niklason, Richard E. Johnston, Etta D. Pisano (Department of Radiology, University of North Carolina at Chapel Hill, Chapel Hill, NC, 27599-7510) (EC, SA, Department of Biomedical Engineering, University of North Carolina at Chapel Hill, Chapel Hill, NC, 27599-7575) (MY, University of Toronto, Toronto, Ontario) (AM, Thomas Jefferson University Hospital, Philadelphia, PA), (MW, University of Virginia, Charlottesville, VA)

ABSTRACT

Purpose One of the advantages of digital mammography is the ability to acquire a mammography image with a larger contrast range. With this advantage comes the tradeoff of how to display this larger contrast range. Laser printed film, and video display both have smaller dynamic ranges than standard mammography film-screen systems. This work examines performance and preference studies for display processing methods for digital mammograms.

Methods Processing techniques currently in practice for the display of digital mammography are being evaluated. Two sets of studies are ongoing at UNC as part of the International Digital Mammography Development Group (IDMDG). The first is a series of laboratory studies evaluating human observer detection rates for mammographic features. In these studies, we have conducted performance studies comparing default film screen (unenhanced), Fixed Intensity Windowing, Contrast Limited Adaptive Histogram Equalization, and Histogram-based Intensity Windowing. A second set of multi-center clinical studies is being performed by IDMDG are comparing filmscreen mammography to digital mammography, with the first step evaluating processing methods for the display of digital mammograms. This first clinical study is a preference study comparing analog film screen images taken at the same time as the digital images, with the digital images processed with different methods. The processing methods being evaluated are Manual Intensity Windowing, Histogram based Intensity Windowing, Mixture Modeling Intensity Windowing, Contrast Limited Adaptive Histogram Equalization, Unsharp Masking, MUSICA, Trex, and Peripheral Equalization. All of the processing methods are automatic, with fixed parameter choices, except Manual Intensity Windowing, which is done by an expert mammography technician

Results and Conclusions The data analysis for this clinical preference study is not complete. Preliminary findings support earlier laboratory performance experimental results, and suggest that different algorithms will perform differently for the tasks of screening, mass characterization, and microcalcification characterization. This suggests the need for presenting different processed versions of the images to the radiologist.

Keywords: Image Display, Digital Mammography, Image Processing, Image Presentation

1. BACKGROUND AND SIGNIFICANCE

Digital Mammography Overview

Breast cancer is often quite similar in density to surrounding normal dense breast tissue. Up to 20% of breast cancers are mammographically occult.[1,2] Digital mammography has the potential to improve breast cancer detection.[3] A major limitation of film-screen mammography is the film itself. The film serves as the medium of image acquisition, storage and display. Digital detectors offer improved detection because of improved efficiency of absorption of the incident x-ray photons, a linear response over a wide-range of incident radiation intensities, and low system noise.[4, 5] In addition, once a film-screen mammogram is obtained, it cannot be significantly altered. Radiologists cannot manipulate the image directly. Improvements in image display involve acquiring more images with magnification or focal compression (and thus exposing the patient to more radiation), or looking at the images with a hot light and/or magnifying glass.

Digital acquisition systems directly quantify x-ray photons and de-couple the process of x-ray photon detection from image display. Digital images can be processed by a computer and displayed in multiple formats, on film and/or on a monitor. Lesion conspicuity can be affected by these contrast manipulations. Image processing has been shown to improve visualization of details within medical images in at least one other application.[6] Since the steps of image acquisition and display are separated, each can be optimized. In addition, image storage, transmission and retrieval can be improved. Software to assist the radiologist in interpreting the images can also be utilized.

Image Processing

Contrast enhancement algorithms accentuate or emphasize particular objects or structures in an image by manipulating the grey levels in the display. This is done by transforming the image, so that the differences between structures are amplified and the recorded intensities are re-sampled to enhance the properties of the displayed image.[7] These algorithms are not designed to increase the information inherent in an image, but rather to improve the visibility of important image features to the human observer.[8]

Many investigators have studied the application of image processing algorithms to digitized film screen mammograms.[9-15] Image processing for focal digital images used to guide needle localization has been reported to improve lesion conspicuity.[16] Previous work by members of the International Digital Mammography Development Group (IDMDG) explored the use of Intensity Windowing (IW) and Contrast Limited Adaptive Histogram Equalization (CLAHE).[17-21] Investigators from the University of North Carolina have previously described a laboratory-based method for testing the efficacy of an image processing algorithm. These studies utilized simulated masses, calcifications and spiculations embedded in dense backgrounds derived from digitized mammograms. Laboratory experiments at UNC found that specific Fixed Intensity Windowing processing significantly improved mass and calcification detection performance compared to unenhanced film screen images. Similarly, CLAHE significantly improved spiculation detection performance; however, it significantly worsened calcification detection. [19-21]

Digital Mammography Display

Digital mammograms can be printed to film or displayed on a monitor. Radiologists are not experienced with reading mammograms on monitors, and are more comfortable with printed film images viewed on a lightbox. Typically, current laser-printed films can display 4000X5000 pixels at 12 bits of grey scale. The disadvantages of film display for digital mammography are obvious. Once you print an image, it can no longer be manipulated. The full information available in the digital data might not be evident in the printed image. Recent laboratory studies at UNC have shown that different processing methods are more optimal for different lesion types (masses versus microcalcifications).[17-21] Printing multiple presentations of the same image data with different processing makes it too cumbersome for the radiologists to view all the images conveniently.

High luminance (100ftL+), high resolution monitors (2000X2560 pixels) are available for soft-copy interpretation.[22] With currently available monitors, only a portion of the breast can be displayed at one time at full resolution. In addition, comparing old and new and left and right images is difficult. Roaming and zooming with the computer, while possible, is not trivial to learn, and can be inefficient and time-consuming. In order for readings on monitors to take place, well-designed and thought out computer-human interfaces will be required to accomplish short, clinically acceptable display times for the display of the entire set of images, including the display of previous studies for comparison. Without a usable computer-human interface to the display system, digital mammography cannot reach its full potential. Regardless of whether the images will be printed to film, or displayed on a monitor, the appropriate greyscale presentation must be determined for digital mammography images.

2. METHODS

Image Production

In the laboratory experiments, the image data consisted of digitized film screen mammograms used as the background, and simulated mass targets as the added foregrounds. The mammograms were digitized on a Lumisys Lumiscan digitizer, at 12 bits of contrast per pixel, and a 50 micron spot size per pixel. Sections of the mammograms, 512x512 pixels were used as backgrounds. The mass targets were gaussian blurred circles. See figure 2 for an example background with inserted mass. The observation task was a four alternative forced choice one. The specifics of the experimental methodology for the laboratory experiments are more completely described elsewhere.[17-21]

For the current clinical preference study, the cases were provided from three different full field digital mammography devices at eight different clinical sites. Ten cases were from Trex Digital Mammography System (Trex Medical Corporation, Long Island, NY), ten cases from Fischer Senoscan (Fischer Imaging Corporation, Denver, CO), and eight cases from General Electric Senographe 2000 D (General Electric Medical Systems, Milwaukee, WI). Studies consisted of two views of the breast containing the mammographic finding.

The raw digital data was transmitted to the University of North Carolina, and to other participating institutions for image processing purposes. For Trex images, the image size was 4800x6400 pixels with 40 micron pixel spot size. For GE images, the image size was 1800x2304 pixels with 100 micron pixel spot size. For Fischer images, the image size was 3072x4800 pixels with 50 micron pixel spot size. All three units produce images with 16 bits/pixel.

All images were processed using 8 different algorithms: Manual Intensity Windowing (MIW), Histogram-based Intensity Windowing (HIW), Mixture Model Intensity Windowing (MMIW), Contrast Limited Adaptive Histogram Equalization (CLAHE), MUSICA (Agfa®), Unsharp Masking(UM), Peripheral Equalization (PE) and Trex® processing. MIW, HIW, MMIW and CLAHE processing were carried out by Bradley M. Hemminger, Stephen Aylward and colleagues at the University of North Carolina. MUSICA processing was performed by Loren Niklason and colleagues at Massachusetts General Hospital. UM processing was performed by Andrew Maidment and colleagues at Thomas Jefferson University. PE processing was performed by Martin Yaffe and colleagues at the University of Toronto. Trex® processing was performed by Mark Williams and colleagues at the University of Virginia.

All images were maintained at their original contrast and spatial resolution during processing. HIW, MIW and MMIW, Trex processed images were printed to film without subsequent contrast manipulation of any type. CLAHE, PE and UM images were manually intensity windowed by an experienced mammography technologist before printing. MUSICA images were intensity windowed over a fixed range (0-4095 grey values). A single Orwin Model 1654 high brightness (100ftL) monitor (Orwin Associates, Inc., Amityville, NY), utilizing a Dome Md5Sun Display Card (Dome Imaging, Waltham, MA) and a Sun UltraSparc model 2200 computer (Sun Microsystems, San Jose, CA) was used for all manual intensity windowing. Both the monitor and display card have a display matrix size of 2048 x 2560 pixels and the system was calibrated to adhere to the DICOM Greyscale display function standard (American College of Radiology, Reston, VA and National Electrical Manufacturer's Association, Roslyn, VA). (24) The software application used for manual intensity windowing was "Xim", a program locally developed at the University of North Carolina by Bradley M. Hemminger.

All images except those with Trex processing were printed on Kodak Ektascan HN film (Eastman Kodak Company, Rochester, NY) using a Kodak 2180 EktaScan Laser Film Printer® (Eastman Kodak Company, Rochester, NY) at the University of North Carolina. This printer is capable of 12 bits/pixel. Images that contained a bit range wider than that of the printer were linearly remapped to the range of the printer. Images were bilinearly interpolated by the Kodak printer to its maximum spatial resolution, with a 50 micron pixel spot size and a matrix of 4096 x 5120, and printed by the Kodak printer at this resolution. The printer was calibrated to adhere to the DICOM greyscale display function standard. (American

College of Radiology, Reston, VA and National Electrical Manufacturers Association, Roslyn, VA).[23] The laser film was processed using a Konica Medical Film Processor QX-400 (Konica Medical Corporation, Norcross, GA).

Trex processed images were printed on Agfa Scopix LT-2B Hene film using an Agfa LR5200 film printer (Agfa Division of Bayer Corporation, Ridgefield, NJ) at the University of Virginia. The matrix size for this printer is 4776x5944 pixels, with a 40 micron pixel spot size, and 8 bits per pixel. Trex mammograms were cropped from 4800x6400 pixels to fit the printer matrix size. GE and Fischer images were scaled up using interpolation by factors of 3.5 and 1.35, respectively. The printer is calibrated to the DICOM greyscale display function standard. (American College of Radiology, Reston, VA and National Electrical Manufacturers Association, Roslyn, VA).[23] Films were processed using a Kodak RP-Xomat processor (Eastman Kodak Coporation, Rochester, NY).

Summary of Image Processing Methods Evaluated

Unenhanced: These are the digitized film screen mammograms, re-printed to film using a laser film recorder. They were compared to versions of the same image processed with different processing methods in the laboratory performance experiments, and also printed to film. This methodology was only used in the laboratory performance experiments.

Film Screen Images: These are the analog film screen images taken at the same time as the direct digital mammography images. They were used in the clinical preference study.

Manual Intensity Windowing: An expert mammography technologist (PB), with over 20 years mammography experience, manually intensity windowed the digital mammograms on a Orwin Model 1654 high brightness (100ftL) monitor (Orwin Associates, Amityville, NY), utilizing a Dome Md5Sun Display Card (Dome Imaging, Waltham, MA) and a Sun UltraSparc model 2200 computer (Sun Microsystems, San Jose, California). Both the monitor and display card have a display matrix size of 2048x2560 pixels. The intensity windowing software, Xim, developed by Bradley M. Hemminger of the University of North Carolina, was interactive, and the technologist could choose either a linear or asymmetric sigmoidal within-window intensity mapping curve shape. The video display was standardized to the film printer that printed the images and was calibrated to adhere to the DICOM Greyscale display function standard. (American College of Radiology, Reston, VA and National Electrical Manufacturers Association, Roslyn, VA).[23]

FIW: Fixed Intensity Windowing is a fixed window width and level applied to all mammograms. This is similar to chest CT preset intensity windows. In mammography, though, like general projection Xray, the optical density recorded on film does not correspond to a specific density in the scanned patient. Thus, the histogram of image values recorded can vary significantly across patients, and across acquisitions. FIW demonstrated improvements over unenhanced digitized film screen images, with appropriate window width and level choices (ascertained through pilot experiments). Recently, though, the same laboratory experiments at UNC have shown Histogram-based Intensity Windowing (HIW) methods to be superior to FIW. Thus FIW was evaluated in the laboratory performance experiments, but not in the follow-up clinical experiments where only HIW was evaluated.

HIW: Histogram-based Intensity Windowing (HIW) is an algorithm developed at the University of North Carolina by Bradley M. Hemminger and Shuquan Zong. It is based on the idea of optimizing the intensity window for each digital Xray by analyzing its histogram. In HIW, the histogram for each individual mammogram in a study, is automatically analyzed in terms of its peaks and regions of the histogram representing all breast tissue, as well as components of the breast like the "dense" and "skin edge" portions are recognized from these histogram features. Subsequently, contrast over the selected range of values of breast tissue is enhanced via simple intensity.

MMIW: Mixture Model Intensity Windowing was developed for this project by Stephen Aylward of the University of North Carolina. This algorithm uses a combination of geometric (i.e., intensity gradient-magnitude ridge traversal) and statistical (i.e., Gaussian mixture modeling) techniques. This method isolates the radiographically dense component in each mammogram and based on statistical characteristics of this isolated region sets the parameters of an asymmetric sigmoidal intensity mapping function.

CLAHE: Contrast Limited Adaptive Histogram Equalization (CLAHE) is a variant of Adaptive Histogram Equalization (AHE), both developed by Stephen Pizer at UNC-CH. In AHE, the histogram is calculated for the contextual region of a pixel, and the transformation is that which gives the pixel a new intensity which is proportional to its rank in the intensity histogram. It is designed to provide higher contrast for pixel intensities which occur more frequently and to provide a single displayed image in which contrasts in all parts of the range of recorded intensities can be sensitively perceived. CLAHE limits the contrast increase factor produced by AHE to a user-specified unit. The CLAHE parameter settings (clip 4, region size 32) used in this study were based on our prior experiments.[19]

MUSICA®: MUSICA processing is a multiscale wavelet based contrast enhancement technique developed by Agfa® (Agfa Division of Bayer Corporation, Ridgefield Park, NJ). It involves variable enhancement of various spatial scale components of the image, followed by additive reconstruction. MUSICA processing was performed on an Agfa image processing workstation. Three of its four image processing parameters, namely Edge Contrast, Latitude Reduction and Noise Reduction were turned off by setting their levels to 0. The parameter for MUSICA was set to a maximum level of 5.

Unsharp Masking: A standard unsharp Masking was performed using software developed by Andrew Maidment at Thomas Jefferson University. Unsharp Masking is a technique used for crispening edges. A signal proportional to the unsharp, or low-passed filtered (blurred), version of the image is subtracted from the original image to yield a "sharpened" resulting image. In our experiment a region size of 600x600 pixels was used for the calculation of the low-pass image. The low-pass image was subtracted from the original image to yield the high-pass image. The final image is produced by combining the original image (50% weighting) and the high-pass images (50% weighting).

Peripheral Equalization (PE): Peripheral equalization, developed by Byng, Critton and Yaffe of the University of Toronto,[24] suppresses the effect of thickness variation of the breast approximating its thickness using a smoothed version of the mammogram with resolution of about 3mm. Within the perimeter of the breast determined by thresholding applied to the smoothed image and dilating by a few millimeters. In this perimeter the thickness effect is removed essentially by dividing the original image values by those in the smoothed image. Areas within the center of the breast are left at their original values. A damping factor, which limits the magnitude of the correction, is applied to the pixels immediately adjacent to the edge of the breast to reduce ringing.

TREX® Digital Mammography Image Processing: The Trex processing used in this study is the proprietary processing applied as part of the Trex full-field digital mammography system. The algorithm is a weighted unsharp masking based on histogram data.

3. RESULTS AND DISCUSSION

At this time, the analysis of the clinical preference study is not complete. Several things, though, are suggested from the previous laboratory detection performance experiments and the preliminary results of the clinical preference study.

The laboratory experiments showed that different processing techniques, or different parameters to specific processing techniques, resulted in different lesion (masses, microcalcificaiton, spiculations) detection performance. The preliminary findings from the clinical preference study support this, in suggesting that radiologists prefer different processed versions of the digital mammogram depending on the task (screening, mass characterization, and microcalcification characterization). In both the laboratory and clinical studies, the choice of the parameters to the processing method were crucial. In the laboratory studies research, a series of mini-experiments first evaluated parameters to the different methods (FIW, CLAHE, HIW). With optimal parameter settings, each of these methods demonstrated improvement in lesion detection over the unehanced film screen images. However, most all other settings result in poorer performance of the processing method compared to the default film screen. Similarly, in development of the different methods tested in the clinical preference study, each set of the parameters for each algorithm was chosen either from the results of the laboratory performance experiments, or by expert analysis of the specific technique. Again, if suboptimal parameter choices were made, the results were clearly inferior to the analog film screen. Both the performance and preference study results suggest that different processing is optimal for different mammography tasks, implying that digital mammograms would best be displayed using a monitor system that allows flexibility and easy, quick access to different processed versions of the images. However, if soft-copy interpretation is to take place, ergonomic issues regarding image display using monitor systems must be overcome.

Differences between the image processing methods can be appreciated by examining their result on the same image. The pictures below demonstrate two example cases from the laboratory performance studies, and one case from the clinical preference studies. An example mammographic background image with a microcalcifications target from the laboratory study is depicted with unenhanced (1A), and best performing FIW processing (1B). An example mammographic background image with a mass target from the laboratory study is depicted with the unenhanced (2A), and best performing CLAHE parameters (2B). The third set of figures (3A-3I) shows the results of the different processings applied to an example cranio-caudal image from the preference study, and the corresponding film screen image.

In figures 1 and 2, it is clear that on the processed subparts of images, the lesions (microcalcifications and masses) can be made much more readily apparent than on the unenhanced images. When looking at complete mammograms, though, it is not clear that the processed images are any better than the film screens. In many cases, the processed images are not able to capture the contrast throughout the mammogram, that is currently produced on film screen images. For instance, the strict intensity windowing only methods (MIW, HIW, MMIW) fail to reproduce contrast throughout the breast in all cases. If the dense areas of the breast are well visualized, for instance, then the skin edge is usually not. Thus, the intensity windowing methods may improve visualization of selected portions of the breast, at the cost of not depicting others. The locally adaptive methods (Unsharp masking, PE, MUSICA, CLAHE, Trex) on the other hand, generally do a good job of visualizing the complete breast. The accompanying tradeoff is that the contrast within the breast tissue is generally not as good as with the intensity windowing methods. Another drawback of the automatic intensity windowing methods is that they sometimes may not be optimal visualizations. For instance on occasion the window level may be set too low (as in the intensity window examples of figure 3 where image burnout can be seen in the dense areas), or too high (resulting in a dark image).

Figure 1A. Unenhanced section of a mammographic background with a microcalcifiction target inserted. The simulated microcalcification is in the upper left portion of the image. (top left next page).

Figure 1B. Same mammographic background with a microcalcifiction target as Figure 1A, but with Fixed Intensity Windowing applied (based on best parameters settings from our laboratory experiment). (top right next page).

Figure 2A. Unenhanced section of a mammographic background with a mass target inserted. The simulated microcalcification is in the upper left portion of the image. (bottom left next page).

Figure 2B. Same mammographic background with a mass target as Figure 2A, but with CLAHE applied (based on best parameters settings from our laboratory experiment). (bottom right next page).

Figures 1A (top left), 1B (top right), 2A (bottom left), 2B (bottom right).

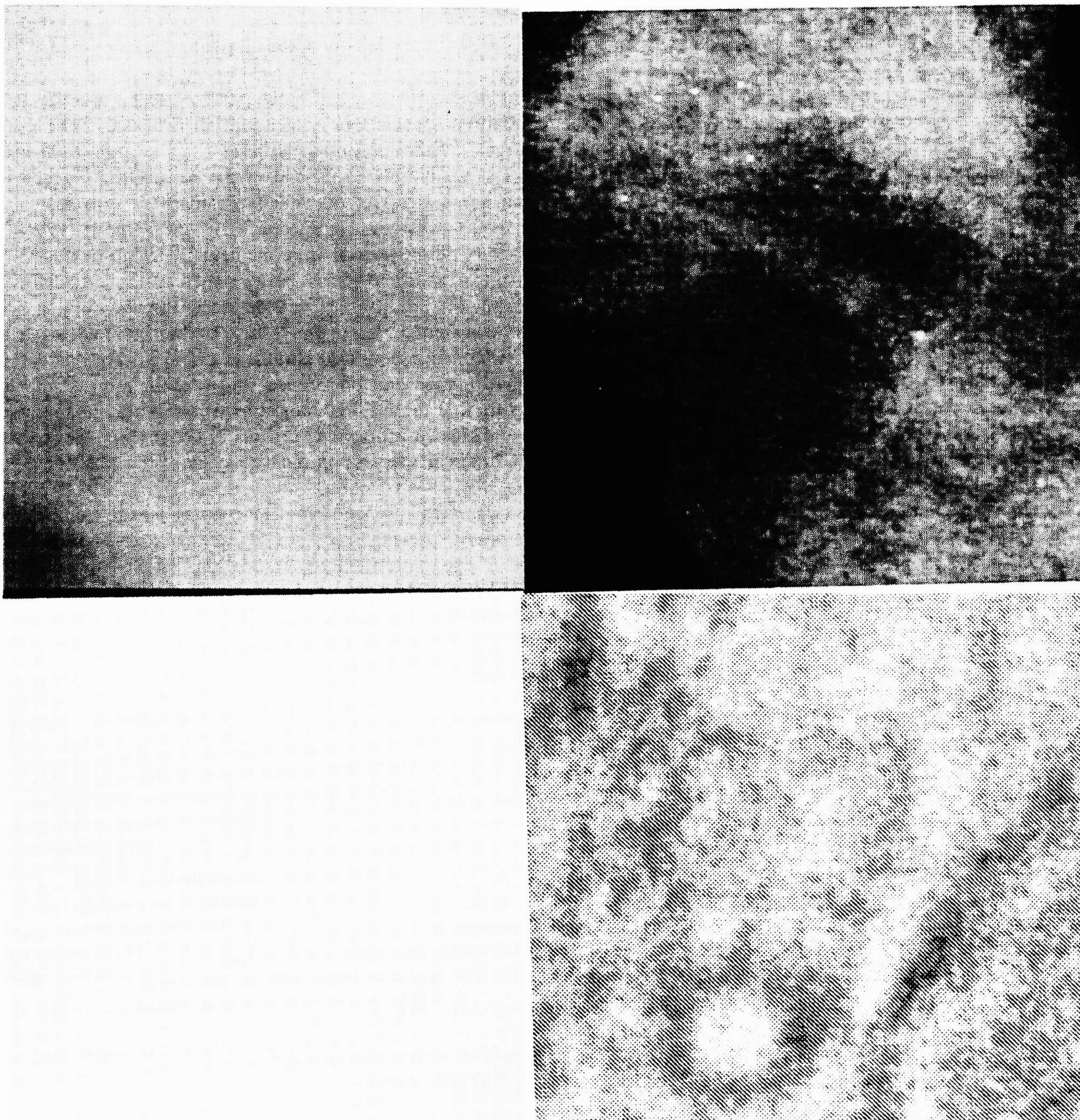


Figure 3A. Example cranio-caudal digital mammogram processed with MUSICA. (top)
Figure 3B. Example cranio-caudal digital mammogram processed with Trex. (middle)
Figure 3C. Example cranio-caudal digital mammogram processed with Hand Intensity Windowing (MIW). (bottom).

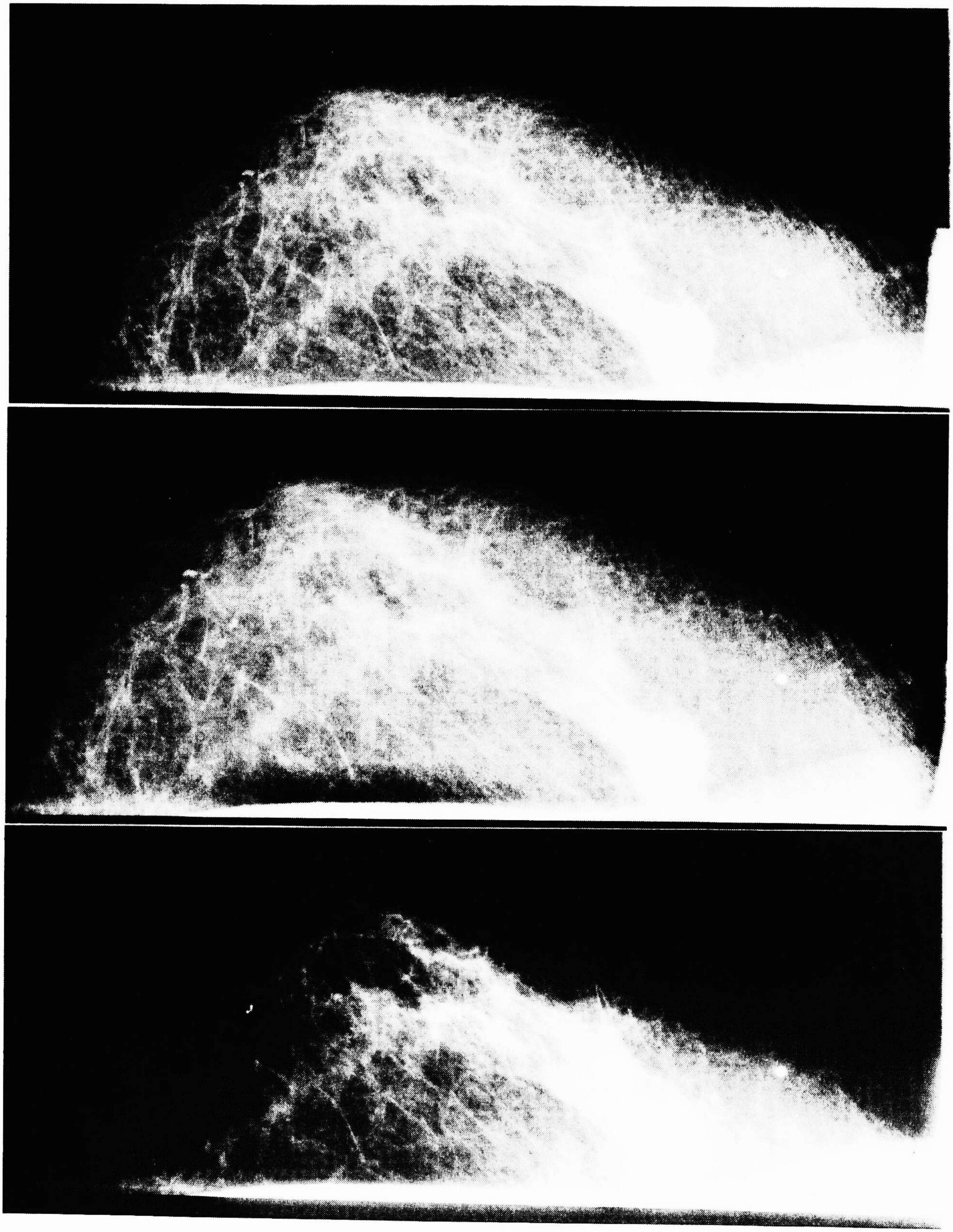
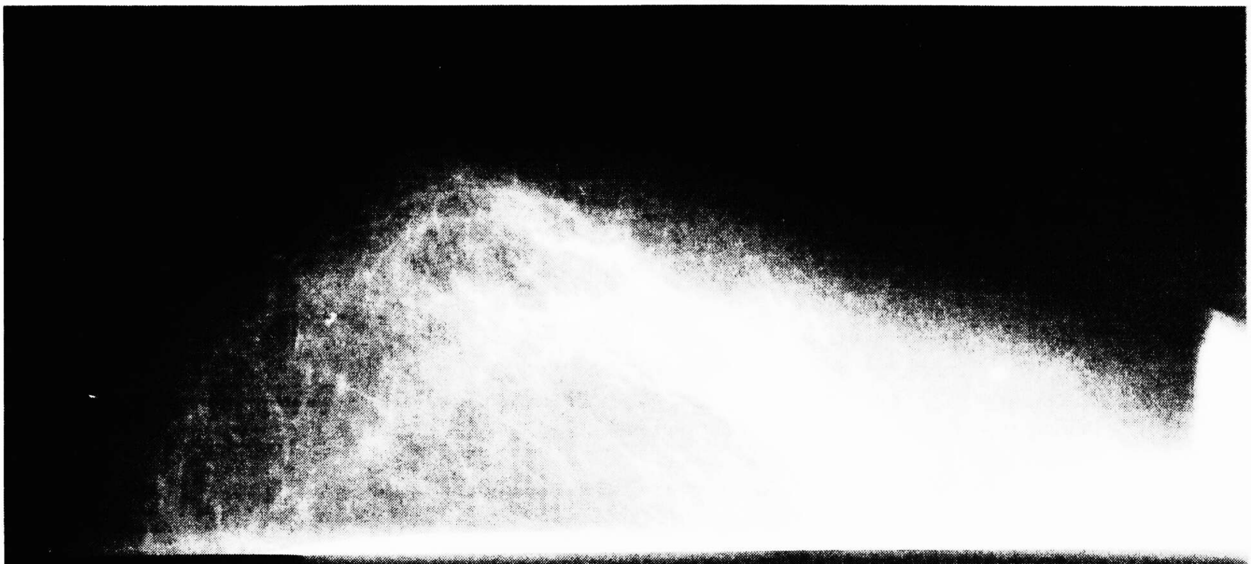
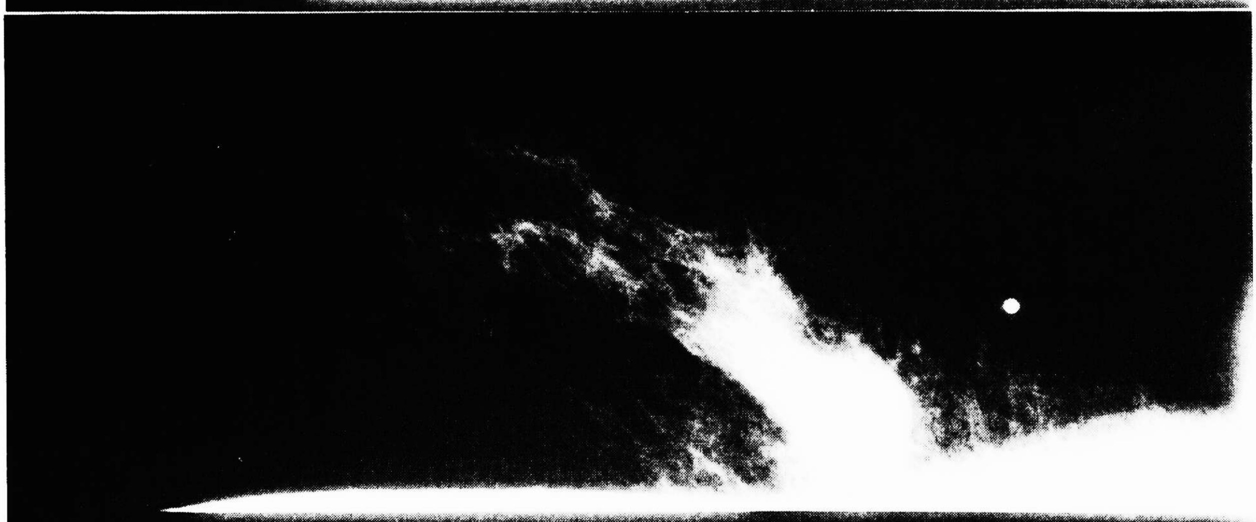
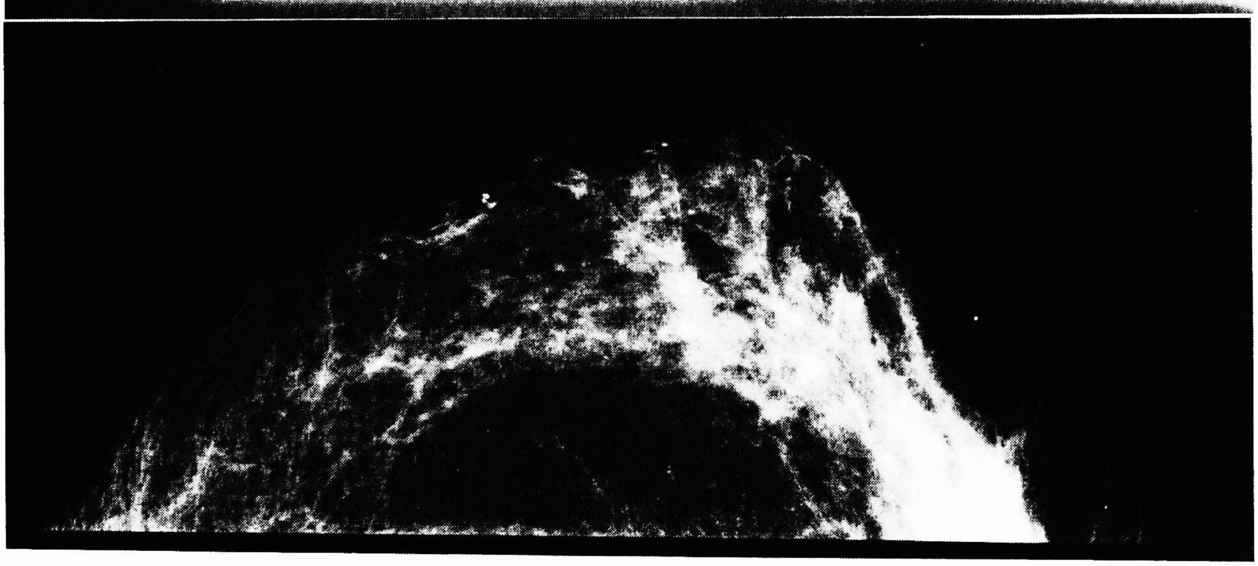


Figure 3D. Example cranio-caudal digital mammogram processed with HIW. (top)
Figure 3E. Example cranio-caudal digital mammogram processed with PE. (middle)
Figure 3F. Example cranio-caudal digital mammogram processed with unsharp masking. (bottom).

Figure 3G. Example cranio-caudal digital mammogram processed with CLAHE. (top)
Figure 3H. Example cranio-caudal digital mammogram processed with MMIW. (middle)
Figure 3I. Film Screen of same cranio-caudal view of breast taken with digital (Figures 3A-3H). (bottom).







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Correspondence: Bradley Hemminger, bmh@rad.unc.edu, (919) 966-2998