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PRINCIPAL INVESTIGATION: David J. Getty, Ph.D.

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A Division of Bolt, Beranek and
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Cambridge, Massachusetts 02138

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We have developed a stereoscopic mammography system using state-of-the-art digital technology that enables a mammographer to view the internal structure of the breast directly in depth. The primary aims of this project are to further develop and refine this system and then to evaluate its effectiveness in increasing the accuracy of diagnosis of breast cancer relative to the diagnostic accuracy afforded by standard, non-stereo film views. The expected increase in diagnostic accuracy could increase the yield of biopsy substantially by allowing the radiologist to more confidently recommend accelerated follow-up of truly benign disease and biopsy of truly malignant disease. Our accomplishments in Year 3 consist of progress in six areas: (1) continued accrual of stereo mammographic images from enrolled patients, (2) development of computer-assisted methods for processing of the raw stereo mammographic images, (3) improvements to the user interface of the stereo display workstation, (4) further research on the design of a new stereo display workstation, (5) identification and development of new stereo-based visual features, and (6) design, conduction and analysis of a preliminary reading study.

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David J. Getty 7/12/99

PI - Signature Date

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## INTRODUCTION

In this project, we are investigating a stereoscopic mammography system we have developed using state-of-the-art digital technology that enables a mammographer to view the internal structure of the breast directly in depth. Stereo mammograms are obtained by taking two x-rays of the breast from viewpoints separated by about 6 degrees, each view captured by a new GE digital full field-of-view mammography unit. The two digital images are viewed on a stereo display workstation by a radiologist wearing stereo-viewing eye-glasses. The system provides the user with control over many display parameters such as brightness, contrast, grayscale polarity, and inversion of depth. The primary aims of this project are to further develop and refine this system and then to evaluate its effectiveness in increasing the accuracy of diagnosis of breast cancer relative to the diagnostic accuracy afforded by standard, non-stereo film views. The expected increase in diagnostic accuracy could increase the yield of biopsy substantially by allowing the radiologist to more confidently recommend accelerated follow-up of truly benign disease and biopsy of truly malignant disease.

## BODY OF REPORT

In Year 3 of this project, we have made progress in six major areas: (1) continued accrual of stereo mammographic images from patients enrolled in this project, (2) development of computer-assisted methods for processing of the raw stereo images, (3) improvements to the user interface of the stereo display workstation, (4) further research on the design of a new stereo display system, (5) identification and development of stereo-based visual features, and (6) design, conduction and analysis of a preliminary reading study. We discuss our work in each of these areas below.

1. Accrual of Stereo Mammographic Images from Patients Enrolled in this Project (Task 4)

To date, we have obtained stereo mammographic images of 166 lesions from patients enrolled in this project. The breakdown of stereo-imaged lesions is shown below in Table 1 for 152 of the 166 imaged lesions. (Of the other 14 lesions, we have not yet received the pathology reports on 3, and 11 cases have been dropped either because the diagnostic films are not available to us or because the lesion was palpated but not seen mammographically.) Of the 152 lesions with known pathology, 48 are malignant and 104 are benign. With respect to mammographic appearance of the lesion, 63 of the lesions are seen as a mass (with or without associated calcifications, 77 as microcalcifications alone, and 12 are seen as architectural distortion (with or without associated microcalcifications).

Table 1. Distribution of imaged lesions by type and pathology.

| Lesion Type | Pathology | | Total |
|---|---|---|---|
| | Benign | Malignant | |
| Mass | 32 | 22 | 54 |
| Mass + calcifications | 3 | 6 | 9 |
| Calcifications | 65 | 12 | 77 |
| Architectural Distortion | 3 | 5 | 8 |
| Arch. Dist. + calcifications | 1 | 3 | 4 |
| Total | 104 | 48 | 152 |

In addition to the pair of digital stereo images obtained for each enrolled patient, we are continuing to collect three documents: (1) a study form filled out by the mammographer indicating the radiographic nature of the biopsied lesion and its locus in the cranio-caudal view (the point-of-view of the stereo mammogram), (2) the full mammographic report from the study that led to the biopsy, and (3) the final pathology report.

We have completed the development of a case database for the project. The database contains fields of relevant information for each case, including serially-assigned case study number, date of diagnostic study, date of stereo imaging/biopsy, breast biopsied, mammographic lesion type, lesion locus, pathology truth, and several parameters describing the transformation of the raw digital images to a viewable stereo pair. We will continue to populate this database with new cases as they are acquired.

2. Development of Computer-Assisted Methods for Processing Raw Stereo Images (Task 4)

During Year 3, we developed a software application to semi-automate the processing of raw stereo images into viewable stereo pairs. Each digital mammographic image captured on the GE unit at UMMC is 2304 pixels wide by 1800 pixels high, with a grayscale resolution of 16 bits stored in a 16-bit word. Captured digital images are stored as 16-bit TIFF-format files and burned onto a CD-ROM which is then sent to BBN. Because of limitations of the stereo display card in our workstation, we need to process the raw digital images to reduce the size of each image to 1024 by 1024 pixels and to reduce the grayscale from 16 bits to 8 bits.

A number of steps are involved in this processing. First, the left-eye image of a pair is opened and visually examined to judge the adequacy of the image. Then, an image-processing algorithm is applied to the image to segment the breast tissue from the surround. The user can iteratively modify the threshold used in this process until a satisfactory segmentation is achieved. The program then calculates a cumulative histogram of grayscale values for the pixels representing breast tissue and determines the minimum, median, and maximum grayscale values. This process is then repeated for the right-eye image. The program then determines the offset between the median grayscale value of breast tissue in the two images and applies it as an additive correction to all of the pixels in the appropriate one of the two images, in order to equalize their median values. We found this correction necessary because software within the GE mammographic unit apparently attempts to optimize mapping of x-ray density to grayscale usage independently for each newly acquired mammogram. Consequently, we frequently find differences in the grayscale histograms between the two images of a stereo pair, even though the two images are of the same breast, with no breast re-compression between images. The only difference in the two images is the small 6-degree movement of the x-ray source between images. We have also encountered systematic changes in the use of the 16-bit grayscale range over the past months of image acquisition. We believe that these are due to frequent updates of the image-capture software in the GE mammographic unit as the GE engineers learn more about the performance of the unit.

In the next step, the program reduces the grayscale of both images from 16 bits to 8 bits. A linear re-mapping of the grayscale is used, extending from the minimum 16-bit grayscale value to the maximum 16-bit value. The transformed versions of both images are saved as 8-bit TIFF files. The program next saves a stereo-viewable 1024 x 900 pixel overview of each of the two images by sampling every other pixel and every other line. This pair of images is useful to the mammographer to obtain a stereo view of the entire breast, albeit at reduced spatial resolution.

The program then places a 1024 by 1024 region-of-interest outline into the full left-eye image and permits the user to move this outline around within the larger image until the user is satisfied that the lesion and surrounding tissue are appropriately enclosed within the window. The coordinates of the user-selected location of the outline are recorded, and the region-of-interest is then extracted and saved as a 1024 x 1024 8-bit TIFF file. This process is repeated for the right-eye image, except that the coordinates used for positioning the 1024 x 1024 window in the image are the same ones determined from the left-eye image. This pair of images is of primary importance to the mammographer since it permits a stereo view of the lesion at full spatial resolution.

3. Improvements to the User Interface of the Stereo Display Workstation (Task 3)

In Year 3, we completed the design of the user interface for the stereo display workstation and rewrote the software application that implements this design. We have included the User's Manual for the application as Appendix A. During the year, the design was refined based on comments from our expert mammographers as they used the system. The design allows the user of the display workstation to control it using either a 3-button mouse, in combination with a few marked keys on the system keyboard, or by point-and-click interactions with controls displayed on the system monitor (not the image display monitor). Most operations can be executed in two ways: either using the mouse by itself (Mouse Mode) or by clicking on displayed controls on the system monitor (GUI Mode). A guiding principal in the design of the interface has been to make the most frequently used operations immediately and conveniently accessible to the user, and to move infrequently used operations off the main window onto secondary windows accessible from a pull-down menu.

We have removed speech-control of the system from the application. Our experience with using speech during the first two years of the project revealed that mammographers did not like having to wear a headset with attached microphone and they did not like having to use a push-to-talk button to enable the speech-recognition system. The possible gains from hands-free spoken control over some parts of the system were more than offset by the inconveniences and by imperfect speech recognition.

An important conclusion we reached in our human factors studies, conducted during Years 2 and 3, was that control over continuous parameters, such as brightness and contrast, is best accomplished using movements of a mouse. In our system, horizontal movement of the mouse controls displayed brightness while vertical movement controls displayed contrast. We have found that users quickly develop a cognitive model of this 2-dimensional space in which the mouse is placed, and can move it effectively to achieve a desired combination of brightness and contrast. As a further aide, when in this mode, the location of the mouse in the 2-dimensional space is shown by a cursor on the system display screen. An optimal brightness/contrast setting, saved individually for each case, is indicated by an icon located at the appropriate position on the system display. This provides the user with a landmark to move towards in case they lose track of where they are in the control space. In addition to controlling brightness and contrast, the user can invert the grayscale by pressing the left mouse button, and invert depth by pressing the right button.

A number of other controls have been made available to the user. In stereo display mode, the system is able to display only 512 of the 1024 available lines of the stereo image. In order to see other parts of the image, the user can hold down the up or down arrow keys to scroll the image. The user can also choose to zoom the image by factors of 1X, 2X or 4X. The user can enable a crosshair cursor that can be positioned in a frontal plane by movements of the mouse. The location of that plane in depth can be moved back and forth by holding down the left or right mouse buttons. This in-depth cursor is very useful with a group of users viewing the display when one user wishes to point to particular structures. Using the middle mouse button, the user can also draw line segments or freehand lines, in depth, to point to or outline areas of interest within the display volume.

4. Further Research on the Design of a New Stereo Display Workstation (new task)

In Year 3, we have continued the task of designing a new stereo display workstation. The current system is based on a Matrox Image-1280 display card that is no longer manufactured by Matrox, and requires an EISA-bus PC that is now obsolete. More recent image display cards introduced by Matrox do not directly support stereo display. However, several other companies manufacturing high-end display cards have begun including direct support for stereo displays in one or more of their PC display controller cards. Last year, we identified several display controller cards that include support for stereo display: (1) Gloria-XXL (ELSA AG), (2) Oxygen 3D (Dynamic Pictures, Inc.), and (3) Fire GL Pro (Diamond). This year, we have identified another card that will soon be released, the P1760S card from Metheus/Barco. This controller seems the most promising since it was designed with medical imagery in mind.

We have also been investigating a new monitor to replace the current Hitachi 21" color monitor. In the course of conducting a Preliminary Reading Study this year, described below, we have found that the spatial resolution of our displayed stereo images is being degraded by the shadow mask of the color monitor. The solution to this problem is to replace the color monitor with a high-resolution grayscale (monochrome) monitor. We have determined that three companies are making such monitors, mostly for the medical imaging market: (1) Barco, (2) Siemens, and (3) Clinton (Orwin). We are currently exploring whether any of these monitors are able to meet the requirements for stereo imaging; namely, ability to synch to a 120 Hz vertical refresh rate, capability to adjust vertical picture height to one-half screen, and incorporating a fast-decaying phosphor to prevent image ghosting during stereo viewing.

The goal is to configure a new system that will duplicate the current system's functionality with minimal rewriting of our software. Our interest in developing this alternative display workstation is both to provide a backup for our current system and to make a stereo display system available to the mammographers at UMMC where the stereo images are being acquired.

5. Identification and Development of Stereo-based Visual Features (Tasks 5,6,7)

Our plan for meeting this objective called for the completion of three Tasks (5, 6 and 7). Task 5 required conducting individual interviews with our three expert mammographers as they closely studied a representative set of stereo-imaged cases to evaluate them in general and to identify all promising new features of stereo-based diagnostic information. Task 6 required conducting a consensus meeting of the three experts to develop an explicit description and final listing of all identified features. Task 7 required developing scales for those features and assembly of a new feature checklist/questionnaire to be employed in the Final Reading Study. The plan, revised in Year 2 to reflect delays in case accrual, called for all three of the these tasks to be completed by the end of Year 3.

We accomplished a first round of interviews with the three experts earlier in Year 3. Then, based on the experts' general evaluations of the stereo display, particularly their uncertainty about how well calcification clusters could be rendered in the digital soft-copy display, we decided to interrupt Task 5 to conduct a Preliminary Reading Study. The point of the preliminary study was to give us a better sense of the stereo display's adjunctive effectiveness in diagnosing each of the three main types of lesion, as well as to give the experts some intensive experience at reading with the stereo displays before proceeding further with Task 5. The plan now is to complete Task 5, and to go on, in short order, to completion of Tasks 6 and 7 early in Year 4.

5.1 Interviews and studies with mammography experts (Task 5)

Each expert was interviewed individually. The general plan was to conduct the interviews in two stages: (1) an open-ended interview that encouraged the experts to express their thoughts in whatever terms, and with whatever emphasis, seemed fitting to them individually, and (2) a guided interview that allowed us to bring to the discussion the ideas and terminology of the other two experts. The original plan was to conduct the second stage of interviewing as soon as we had completed the interviews of all three experts in the first stage. We then decided to insert the Preliminary Reading Study in between the two stages.

*Open-ended interviews.* The general approach was to have the experts read the conventional films and stereo images of each of a representative set of cases of each lesion type. They were asked to think aloud as they read each case, to identify and describe all features of diagnostic interest, particularly those newly available in the stereo display, or where the stereo display made a significant adjunctive clarification of features perhaps only weakly visible in the films. They were also asked to evaluate the stereo display in more general terms, to express any and all thoughts on its strengths and weaknesses for mammography.

To prepare the experts for these interviews, we first reviewed with them the technology of the stereo imaging, how the images are obtained and displayed. We also explained the nature of the display interface and had each expert operate the system and practice with the various options for manipulating the stereo images.

We then systematically reviewed the nature of the volumetric information potentially retrievable from these displays—with respect to a lesion's locus and orientation in depth in the breast parenchyma, with respect to its volumetric shape, with respect to the layout and arrangement in depth of its constituent parts, and with respect to size, shape and orientation in depth of the individual parts—potentially an enormous amount of new diagnostic data. Some of this information, of course, like the volumetric shape of a mass, would not be entirely new, in the sense that it is retrievable, at least in a crude fashion, by merging information retrieved separately from the two films. But even so, improvement in comprehension and precision of that information in the stereo display might well support new nuances of discrimination and interpretation not feasible with the films. Our aim in this review was to encourage the experts to consider all of these new possibilities. Some of the information provided by the stereo display would, of course, potentially open entirely new doors of analysis and interpretation, and we encouraged the experts particularly to consider those possibilities. To illustrate this point, we brought specifically to their attention new options that the stereo display provides for analyzing calcification clusters. In the films there is no way for the mammographer to discern the actual arrangement in depth of the individual elements. This is because in the films there is no way to reliably pair an element in one view with itself in the other. The stereo enables pairing every element with itself and thereby reveals details of structure not retrievable from the films. We pointed out similar new possibilities with respect to intricacies of the arrangement of linear elements comprising architectural distortion, where, again, there is no way to pair up the elements seen separately in the films.

Then, working with a representative set of six benign and six malignant cases of each lesion type (mass, calcification cluster and architectural distortion), we had each expert conduct a careful examination of the stereo images. Each case was complete with the full set of stereo images, diagnostic films and pathology report. Taking into consideration the pathology truth data and the appearance of the lesion on the films on which the lesion was diagnosed, the expert's task was to consider every aspect of appearance of the lesion in the stereo display that helped to advance the accuracy of diagnosis beyond what would have been achieved by conventional film mammography alone, either by strengthening what might have been a true diagnosis or weakening what might have been a false one. The experts were asked to think aloud as they read the stereo images, made back and forth comparisons to the conventional films and considered the pathology truth data. We recorded their comments, interacted with them to clarify particular points, and developed an overview of their thoughts by lesion type.

For masses, their comments centered mainly on how the stereo display helped to separate the mass from extraneous dense tissue lined up with it in the volume, but located elsewhere in depth. They commented on how that separation helped, in turn, in determining the shape of the mass and also in differentiating mere obscuration of the boundary by those unrelated but overlapping densities, as opposed to truly worrisome indistinctness of the boundary. They also commented on how the stereo display helped them to discern spiculations emanating from the mass and to detect protrusions that were not evident from analysis of the shapes of the two film views.

For calcification clusters, the comments centered on two main contributions of the stereo display. First, were comments, akin to those with respect to masses, on how the stereo display helped in separating the cluster of interest from elements of calcification that were lined up with it in the volume, but located elsewhere in depth. Second, were comments on how the stereo display provides a compelling sense of the volumetric arrangement of the elements comprising the cluster and how this helps in a variety ways to increase the accuracy of diagnosis. In one case, a cluster seen on the conventional films as large and worrisome could be seen in the stereo images as two separate and benign appearing clusters. In another case, elements that appeared in the conventional films to be distributed randomly in the cluster could be seen in the stereo display as in a benign, dome-like arrangement. The experts also reported repeatedly on how the stereo display was helpful in revealing linearity and branching not evident, or not as clearly evident, in the conventional films. The experts also commented on how the stereo display helped to see large-scale arrangements of calcifications, to detect worrisome segmental patterns, and to integrate more confidently the extended collections of benign vascular calcifications.

For architectural distortion, the experts' comments also centered on the stereo display's help in separating components of the lesion from extraneous material lined up with it in the volume but located elsewhere in depth, and to detect the presence of a subtle central focus that could be missed on film. Here the components are the strands of dense tissue that appear to radiate from a central point. The comments also suggest that the stereo display helps to determine whether the strands that are seen to be at the same level in depth also originate at the same locus in depth.

While these specific reactions to the stereo display were all quite positive, the experts did convey two general concerns about inherent limitations of the stereo display. Their primary concern was with respect to lower spatial resolution of the stereo display compared to the conventional films, a matter most apparent to them in often not being able to see all of the calcifications visible on the conventional films. This lack of resolution limited their ability to see the full arrangement of the elements. It also degraded their ability to see clearly the orientations and shapes of those individual elements that were visible. Their second concern, and one, again, that seemed to them most significant with respect to calcifications, was the aspect-ratio distortion inherent in the current stereo display configuration. The vertical stretching of the stereo display had the effect of distorting the shapes of the masses, the distribution of the calcification clusters and the shapes of the individual elements of calcification. While to some extent the experts could be expected take those known distortions into account, it is clearly not something that is fully amenable to mental factoring, and the experts found it particularly deleterious with respect to assessing the shapes of the elements of calcification. These concerns led them and us to some significant uncertainty about just how effective the stereo display would be, despite the many promising ways in which it could potentially help, and particularly in regard to its effectiveness in diagnosing calcification clusters. As a consequence, we decided it would be wise to do a Preliminary Reading Study just to see where we stood. We also sought the benefit, before going further with the feature explorations of Task 5, of having the experts do some intensive reading with the stereo display—intensive in the sense of their being blinded to the truth and scored for accuracy.

*Debriefings of the experts and analyses of the logs of their case-by-case comments following the Preliminary Reading Study.* The Preliminary Reading Study had two main purposes. One was to obtain a rough indication of the stereo display's adjunctive contribution to diagnostic accuracy. This was to provide guidance, in light of the suggested weaknesses of the stereo display, particularly for conveying information on calcifications, on the possible need to adjust our approach to the Final Reading Study. The other aim was to expand our effort in Task 5—to explore further for features newly available or significantly clarified with the stereo display, and to assess further the general effectiveness of stereo as an adjunctive contributor to mammography. The design of the Preliminary Reading Study, the overall results and their implications for our approach to the Final Reading Study are given below in Section 6. Here we describe contributions of the Preliminary Reading Study to the aims of Task 5.

We interviewed each of the four readers at points during the scheduled readings and after they had completed the study. The debriefings were generally consistent with the findings of the open-ended interviews—recognition of stereo's several contributions and a voicing of some fundamental concerns. One concern brought up anew in these interviews was in regard to the limited brightness and contrast of the display monitor. The concern was that it was much lower than what can be achieved with the films, limiting the gray scale distinctions that can potentially be made with the stereo and also probably a big factor in the loss of visibility of small calcifications.

We also had the readers keep a log of comments on a case-by-case basis. The case-by-case comments were also generally consistent with what we learned in the open- ended interviews. The specific comment on many of the cases was that the stereo display did not show calcifications as well as the films did, though on occasion, the stereo showed calcifications not visible on the films. The stereo display was repeatedly found to help in interpreting masses – improving the visibility of spiculations and interior fat, clarifying the nature of the boundary, helping to localize and associate calcifications with the mass, and clarifying associated architectural distortion. Despite the shortcoming of not showing all of the calcifications visible on the films, the stereo display was repeatedly reported to clarify how the elements of a cluster were arranged. While in a few cases, architectural distortion evident in the films was not visible in the stereo, generally stereo was found to bring out architectural distortion.

The improved understanding of the strengths and weaknesses of the stereo display that the Preliminary Reading Study has provided in these various comments puts us in a much better position to conduct the guided interviews. Also, of our three experts, only Dr. D'Orsi had any prior experience reading the stereo displays. So, Drs. Meyer and Sadowsky, having participated in the intensive reading experience and critique of the Preliminary Reading Study, are now much better equipped to proceed to the guided interviews and into the consensus meeting.

*Guided Interviews.* To complete Task 5, we will conduct a guided interview of each our three experts early in Year 4. We will use as the primary guide the old version of our mammography checklist/questionnaire developed for use in diagnosing lesions seen on films alone. The general approach will be to walk through the old questionnaire, considering with the expert how each of the features might appropriately be modified to reflect the expanded perception and knowledge of the features afforded by addition of the stereo information. For each of the old features, we will look for descriptions and terminology that are sensitive to the newly accessible volumetric information. We will also probe carefully for the possibility of entirely new features, emergent properties that are perhaps only visible in stereo. After completing these guided interviews, we will circulate the questionnaires, with the suggested changes highlighted, to the other experts for their review prior to the consensus meeting.

## 5.2 Consensus meeting (Task 6)

At the consensus meeting, we will systematically review the various changes and additions to the old questionnaire that were suggested in the guided interviews of Task 5 and work to achieve consensus on those that will be incorporated in the new version.

## 5.3 Construct new Checklist/questionnaire (Task 7)

In constructing the new checklist/questionnaire, we will draw heavily on the design of the old one. Those features that remain unchanged will be incorporated directly into the new questionnaire. Where the wording of a question has been changed, we will review carefully whether the changed wording requires changes in the design of the reference rating scale and make changes accordingly, e.g. change the wording or graphics of the anchor points on the scale. We will also utilize the same overall arrangement and formatting as on the old questionnaire, unless any of the new questions, or any of the changes to old questions, require us to depart from that.

## 6. Design, Conduction and Analysis of a Preliminary Reading Study (Tasks 10, 11, 12)

## 6.1 Design of the Study

*Cases.* The case set for the preliminary study consisted of 76 cases with pathology-proven lesions. For each of these cases, we had acquired the set of diagnostic films that had led to the biopsy of the lesion. The distribution of lesions by type and by pathology truth is shown below in Table 2.

Table 2. Distribution of lesions by type and pathology.

| Lesion Type | Truth | | Total |
|---|---|---|---|
| | Benign | Malignant | |
| Mass | 22 | 12 | 34 |
| Calcifications | 29 | 4 | 33 |
| Architectural Distortion | 2 | 7 | 9 |
| Total | 53 | 23 | 76 |

*Readers.* Four highly experienced mammographers participated in this study. Two of these mammographers were two of the three expert consultants to the project, namely, Dr. Jack Meyer and Dr. Norman Sadowsky. The other two mammographers were Dr. Larry Moss from the University of Massachusetts Medical Center and Dr. Elsie Levin from Faulkner Hospital.

*Study design.* Each reader participated in two reading sessions (each approximately a half day in length) reading half of the cases in the first session and the other half of the cases in the second. The cases were read without knowledge of pathology truth, and none were ones that the two experts had previously seen, with pathology truth, in the guided interview. Each set was arranged in a single random order. At the start of the first reading session, we provided a brief training session in which the reader was familiarized with the operation of the stereo display workstation and given an opportunity to practice with its keyboard controls.

Each case was read in three phases, in immediate succession. In the first phase, the reader was shown the set of available film images from the diagnostic study (mounted on an automated film viewer) and told the patient's age. The reader was then required to estimate the probability, on a 100-point scale, that the lesion was malignant and to enter that value via the keyboard for recording by the system.

In the second phase of reading a case, the reader could view one or the other of the two available digital images for the case in non-stereo mode on the display monitor. In this phase, only non-stereo viewing of the images was allowed; both eyes always saw the same image. The reader was allowed to switch between the two images, but was only able to see one at a time. The films for the case were still available to the reader for reference. The reader was also able to control aspects of the display, including brightness, contrast, and grayscale inversion. After viewing the non-stereo presentations of the digital images, the reader was required to make a new assessment of the probability that the lesion was malignant, taking into account the information available both on the films and on the non-stereo display, and to key that assessment into the system.

In the third phase, the display was enabled to show the reader the two digital images as a single stereoscopic pair. The reader put on the stereo-viewing eyeglasses (StereoGraphics CrystalEyes LCD glasses) to view the images in this stereoscopic mode. The case's films remained available to the reader for reference. The reader was able to control aspects of the stereo display, including brightness, contrast, grayscale inversion, plus, in this condition, depth inversion. After viewing the stereo image, the reader again was required to assess the probability that the lesion was malignant, this time taking into account the additional information provided by seeing the lesion in stereo.

## 6.2 Results of the Study

*Accuracy analyses.* We conducted ROC analyses on the pooled data of our 4 readers. We used as our measure of diagnostic accuracy, Az, the area under the fitted ROC curve. The estimated values of Az for film alone, film + non-stereo digital, and film + stereo digital were 0.73, 0.72 and 0.76. The film-alone accuracy of 0.73 is relatively low for standard mammography, indicating that this case set is relatively difficult to diagnose. Statistical analysis of the results showed that film and film + non-stereo digital were not significantly more accurate than film alone ($p>.83$). On the other hand, film + stereo digital was significantly more accurate than film alone ($p<.04$). Thus, the stereo mammogram added a significant amount of adjunctive diagnostic information to that obtained from the films alone. Furthermore, we believe that several limitations of the digital images and of the digital display, discussed below in our analysis of the reader logs, have resulted in an underestimation of the potential adjunctive accuracy afforded by the stereo display.

We would have liked to examine the accuracy results broken down by type of lesion. However, we were unable to carry out this analysis because the number of cases in each of the resulting subsets is too small to obtain reliable results. We note that we will be able to conduct this type of analysis on the results of the final reading study, where we will have available a much larger case set.

*Analysis of reader logs.* We have read carefully through the log of comments written out by each reader as he/she read cases. From their comments, we can draw several general conclusions, as well as observations about particular cases. The most important conclusion, commented on by all four readers, is that the spatial resolution of the digital images (whether stereo or non-stereo) is poorer than that of the films. This is manifest largely in cases presenting with small, fine micro-calcifications. Our readers frequently commented that some of the calcifications visible in the films were simply not visible in the digital images. (However, we should note also that occasionally readers remarked that calcifications were more clear or more visible in the digital images than on the film). We believe that there may be two reasons for the apparently poorer spatial resolution in the digital images. The first is a possible limitation of the 100-micron spot size of the GE digital mammography unit. There is some reason to think that 100 microns is too large a spot size to adequately capture very small calcification elements. A second reason—perhaps the more important one here—is a degradation of available spatial resolution by the shadow mask in the color display monitor used in the stereo display workstation. The fact that each grayscale pixel on our color monitor necessarily is composed of triads of equally illuminated color dots, guarantees some loss of spatial resolution available in the image. We think that this problem is sufficiently serious that, before we conduct the final reading study, we hope to replace the color monitor with a high-resolution grayscale (monochrome) monitor.

A second general observation was that vertical elongation present in the display—an uncorrectable distortion characteristic of this monitor—sometimes created a problem in interpreting a displayed lesion. The distortion arises because in order to present a correct aspect ratio, the vertical size of the displayed image needs to be half of the screen height rather than full height. The autosync circuits in this (and, in fact, in most) monitors attempt to automatically cause the image to fill the screen vertically. Unfortunately, the manual vertical size control on our Hitachi monitor will only permit reduction of the vertical image size to about two-thirds of the full screen height, causing a displayed circular area to appear as an ellipse, elongated vertically. While our readers could take this known distortion into account fairly well, it did make it difficult to decide, sometimes, whether an apparently linear calcification element was truly linear or only optically stretched. Similarly, a mass that was truly spherical would take on the appearance of an ovoid. We regard this as a serious problem, too, and will hope to solve it when we find an appropriate grayscale monitor.

Perhaps the most impressive finding from our review of the case-by-case comments was that in 10 of the 76 cases read, an additional lesion was detected in the stereo display by one or more readers that could not be seen in the films. In 3 of the cases, a mass was visualized that was not evident on the film. In another 3 cases, architectural distortion was seen on the stereo image but not on the film. And in the other 4 cases, (additional) calcifications were detected that were not visible on the film. This finding suggests that a significant role for stereo mammography may lie in increasing the detectability of early, subtle lesions that are not visible in standard two-dimensional films. While the increased usage of needle and large-core biopsies is currently reducing the need for improved mammographic characterization of lesions, that advantage holds only if the lesion is detected and localized. Stereo mammography may offer substantial aid towards improved detection.

7. Level of Effort and Schedule

The project ran at a level of effort and expenditure through Year 3 of close to 100% of budget. All staff continue with the project as planned. One of our three expert mammography consultants, Dr. Thomas Frenna, left his position on the mammography staff of Brigham and Women's Hospital (BWH) in Boston last year and moved to a practice in New York. We are pleased that Dr. Norman Sadowsky, Director of the Faulkner-Sagoff Centre at Faulkner Hospital, agreed to replace Dr. Frenna on the project as an expert consultant on mammography.

Because our expert mammographers had no prior experience with viewing and interpreting stereo mammograms, our progress in developing a checklist of visual features, perceptible in stereo, has been slower than we had hoped. In order to give them some intensive experience looking at stereo mammograms, we decided to run the Preliminary Reading Study described above. We will now complete the feature and checklist-development work early in Year 4 and move on to the Final Reading Study. Consequently, we are proposing to modify the timeline as shown below in Table 3. The work to be completed within the set of project tasks remains as originally proposed; only the timeline for when several of the tasks begin and end has been modified.

Table 3. Revised Timeline and Status of Project Tasks

| Task # | Original Period | New Revised Period | Status | Task Description |
|---|---|---|---|---|
| Task 1 | Months 1-8 | Months 1-12 | Completed * | Reorganize user interface |
| Task 2 | Months 9-18 | Months 1-18 | Completed * | Add new functionality to control software |
| Task 3 | Months 1-18 | Months 1-24 | Completed * | Explore joystick and speech control |
| Task 4 | Months 1-36 | Months 11-48 | Ongoing | Acquire stereo-imaged cases |
| Task 5 | Months 6-11 | Months 18-41 | Mostly completed | Interviews and studies with mammo. experts |
| Task 6 | Month 12 | Month 42 | To be done | Consensus meeting with mammo. experts |
| Task 7 | Months 13-18 | Months 30-42 | To be done | Develop checklist of stereo features |
| Task 8 | Months 19-24 | Months 19-32 | Completed* | Explore stereo display modes with experts |
| Task 9 | Months 25-30 | Months 25-36 | Completed* | Modify display software for new modes |
| Task 10 | Months 25-30 | Months 36-43 | Prelim study completed | Prepare case set and reading study materials for final study |
| Task 11 | Months 31-42 | Months 43-45 | Prelim study completed | Conduct final reading study |
| Task 12 | Months 43-48 | Months 46-48 | Prelim study completed | Analyze final reading study results |
| Task 13 | Months 43-48 | Months 46-48 | To be done | Train statistical prediction rules on feature data and measure accuracies |

* Work originally proposed within these tasks has been completed; however, we will continue to work on them as needs arise within the project.

8. Plans for Year 4

As indicated by the proposed timeline shown above, we will continue accruing cases (Task 4) throughout Year 4.

Over the early months of Year 4, we will conduct guided interviews with our three mammography experts, to identify visual features perceptible in the stereo images (Task 5). This activity will culminate in a consensus meeting with the three experts in Month 42 to arrive at a master feature list (Task 6). As we identify these features, we will construct the checklist/questionnaire for use in the Final Reading Study (Task7).

Finally, in the third quarter of Year 4, we will conduct the Final Reading Study using all cases acquired at that time (Tasks 10, 11). In the final quarter, we will analyze the results of the study and train statistical prediction rules using the feature data provided by the readers (Tasks 12, 13).

## KEY RESEARCH ACCOMPLISHMENTS

- Acquired 166 stereo-imaged lesions at end of Year 3.
- Developed semi-automated software to aid in processing of raw digital stereo images for viewing.
- Completed development of new application software that improves the user interface of the stereo display workstation.
- Conducted interviews with three expert mammographers to explore and understand new information visible in stereo mammograms.
- Designed, conducted and analyzed a Preliminary Reading Study (4 mammographers, 76 cases) comparing film alone, film plus non-stereo digital images, and film plus stereo digital images.
- In the Preliminary Reading Study, we obtained a statistically significant gain in diagnostic accuracy from stereo versus film alone.
- In the Preliminary Reading Study, additional lesions—not visible on the films—were detected on the stereo mammogram, in 10 of the 76 cases.

## REPORTABLE OUTCOMES

Dr. Getty presented the research efforts of this project at the Eighth Far West Image Perception Conference held at the Nakoda Lodge in Alberta, Canada on May 28-30, 1999. In particular, he described the results of the preliminary reading study to the meeting, in a talk entitled "Stereoscopic Digital Mammography: What Can You See in a Stereo View of the Breast That You Can't See in Two Standard Orthogonal 2D films?" Textual slides from this talk are included as Appendix B of this report. Dr. Getty also set out an exhibit at the meeting consisting of six sample stereo mammograms captured on 35mm slides and presented in hand-held stereoscopic viewers. Meeting participants were invited to come view the stereo mammograms at their leisure over the next several days.

## CONCLUSIONS

We have four main conclusions to draw from the work accomplished to date.

First, we have initial evidence that stereo can improve accuracy in diagnosing breast cancer. Even with a relatively small number of test cases, our carefully controlled Preliminary Reading Study found a statistically significant adjunctive improvement in diagnostic accuracy using the stereo display. That gain is relatively small, but still very encouraging considering that the stereo display, as implemented in this project, has the two significant but correctable limitations described below. A much larger gain can be expected when those limitations are corrected.

Second, stereo has a strong potential for improving cancer detection. Very important, in our view, was the finding in our case-by-case analyses that for ten different cases the mammographers detected additional lesions in the stereo display that were not visible at all on the films. This suggests that stereo has a very important potential for cancer detection. The current strategy of increasing the accuracy of detection by relying on the biopsying of more and more marginal radiographic evidence can not protect the patient in situations where even marginal evidence of a tumor is absent the films. Stereo apparently could have a very important role to play in catching many of those cases.

Third, stereo is likely to be easily and enthusiastically accepted by mammographers in the field. All of our readers were very intrigued by the stereo display and quickly found it easy to control the system and interpret the images. The stereo display provides a way for them to derive volumetric information clearly and validly via an effortless perceptual process, something they can only struggle to do crudely by looking back and forth between the two film views. Yet, the stereo display has all same familiar feel as the films and so brings no additional burden to the interpretive process.

Fourth, we have found that the version of stereo employed in this study suffers two main, but correctable limitations. The first main limitation is with respect to the resolution and brightness contrast achievable with the present display. It shows much less of the fine detail visible on the films than we had expected it would. We are confident though that this problem can be corrected with a better, grayscale-only monitor. The second main problem is that because of a limitation in adjustability of the present monitor's vertical image height, the display distorts the shapes of lesions and lesion components. The readers have found that it is difficult to factor that distortion into their thinking, and that it hinders their interpretations. We are looking into obtaining a new monitor that can correct both of these limitations before proceeding to the Final Reading Study.

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# User's Manual
# Stereoscopic Mammography Workstation

## 1.0 Introduction

The Stereoscopic Mammography Workstation is a Visual Basic application for displaying a pair of digitized x-ray images stereoscopically. It gives the user control over the brightness and contrast of the stereo image as well as other aspects of the stereo display through two types of interfaces:

- A Graphical User Interface (GUI Mode)
- A mouse interface (Mouse Mode).

The GUI mode provides the user with standard graphical controls such as menus and buttons to execute commands. However, the GUI is not convenient for executing commands that control the stereo display for two reasons:

- The special eyeglasses required for viewing the stereo display are problematic when viewing the GUI screen because of flicker.
- The user has to look away from the stereo display while making changes to the stereo image from the GUI.

Consequently, a second mode of interaction, Mouse Mode, is provided for making changes to the stereo display. In this mode, the user can focus solely on the stereo image while moving the mouse or clicking mouse buttons to enhance it.

## 1.1 GUI Mode

The application provides a Main Window on the monitor from which the user can:

- Load and display a stereo image from a pair of files.
- Load and display a stereo image from a database of cases.
- Control various functions related to the stereo display such as setting the brightness and contrast, inverting grayscale, inverting depth, invoking highlight mode, and changing the magnification factor.
- Invoke Mouse mode in either of two initial functions: Brightness/Contrast control or Stereo Cursor control.

The GUI Main Window is used primarily for loading cases. Although the GUI provides controls for enhancing the stereo display, it is more convenient to use Mouse Mode for such commands. The Main Window on the monitor is replaced by the Mouse Mode Window when the application is in Mouse Mode. Pressing the space bar will bring back the GUI Main Window.

## 1.2 Mouse Mode

In Mouse Mode, the user can move the mouse and click the mouse buttons to execute commands that control two separate functions:

- Changing the brightness and contrast of the display (Brightness/Contrast Mode)
- Moving the stereo cursor (Cursor Mode).

Mouse Mode is invoked automatically in Cursor Mode after a stereo image is loaded. It can also be invoked explicitly from the Main Window. Pressing the space bar terminates Mouse Mode and returns to the GUI Main Window.

### Switching between Mouse Functions

The user can toggle between the two types of Mouse Mode functions by pressing the **F12** key. The two functions are mutually exclusive and each uses the mouse movement and mouse buttons for different purposes. When the application is in Mouse Mode, the Mouse Mode Window replaces the Main Window on the monitor.

When the Brightness/Contrast Mode is active, the user can affect the stereo display as follows:

- Move the mouse to change the brightness (horizontal movement) and contrast (vertical movement).
- Click the left mouse button to invert the grayscale map.
- Click the right mouse button to invert depth.
- Click the middle button to temporarily set the display to the default grayscale values.

In Cursor Mode, the user can:

- Move the mouse to move the stereo cursor up, down, left or right.
- Hold down the left or right mouse buttons to move the stereo cursor backward or forward respectively.
- Hold down the middle mouse button to draw a straight line.
- Hold down the ENTER key on the keyboard while moving the mouse to draw freehand lines.

# 2.0 Stereo Display Windows

The Stereo Display application begins by initializing the stereographics hardware and software. Upon completion of the initialization, the user sees the application's Main Window.

## 2.1 The GUI Main Window

The Main Window is the primary GUI window for the application. From this window the user can:

- Load a case for viewing from a pair of files.
- Load a case for viewing from a database.
- Get information about the case currently being viewed.
- Save a new case to the database.
- Edit an existing case in the database.
- Execute commands that affect the stereo display.

Initially, the Main Window only contains a Case Selection Frame with controls for selecting a case for viewing. Once a case is selected, the application enters Mouse Mode and the Main Window is replaced by the Mouse Mode window. When the user exits Mouse Mode, the Display Controls Frame is added to the Main Window. In the Display Controls frame are controls for:

- Changing the brightness and contrast of the stereo image
- Inverting the grayscale
- Inverting depth
- Changing the magnification factor
- Invoking Mouse Mode

The Brightness/Contrast controls on the GUI are useful in that they allow the user to set the grayscale parameters to exact values. In general, however, Mouse Mode is much more convenient for manipulating the stereo display.

The Main Window also provides an Auto-Select Case Frame that allows the user to move forward or backward sequentially through the case database to select cases for viewing.

## 2.2 The Mouse Mode Window

The Mouse Mode window is used when the application is in Mouse Mode. The location of the mouse pointer in the window controls various values of the display such as the brightness or contrast settings, the X and Y position of the stereo cursor, and the location of lines drawn in the display.

When in Brightness/Contrast Mode, a small square is drawn into the Mouse Mode Window. The square is located at the default brightness/contrast settings associated with the case. The user can quickly view the stereo image using the default settings by placing the mouse cursor in the box.

## 2.3 The Registration window

This window contains the controls for aligning the images, for panning/scrolling, and for magnifying. This window is invoked from the **Tools->Registration** menu on the Main Window.

# 3. Stereo Display Commands

The commands provided by the Stereo Workstation fall into four general categories:

1. Case selection
2. Display mode
3. Stereo display enhancements
4. Stereo cursor control

The following sections describe the commands in each of the categories and how they are implemented in both GUI mode and in Mouse Mode.

## 3.1 Case Selection

A case is comprised of two x-ray image files: the left eye sees one image file and the right eye sees the other image file. A case can be selected for viewing in two ways:

- Explicitly selecting the two image files associated with the case from disk
- Selecting a previously saved case from a database.

### 3.1.1 Select Case Files from a Disk

GUI Main window:
Load Stereo Pair button
File->Load Stereo Pair menu

This command allows the user to specify the two image files for viewing. The image on the stereo screen shows the data as they are in the raw image files, without any enhancements.

The command brings up a custom file selection dialog that allows the user to specify the two image files at once. The first file selected is seen by the left eye and the right eye sees the second file. If you save this case to the database, the full pathnames of these files are saved for that case. Whenever you select that case from the database, those files will be reloaded.

### 3.1.2 Select a Case from a Database

GUI Main window:
Select Case from Database... button

The user can select a case from a database of cases viewed previously by the user and saved. When the user selects a case from the database, the system loads the two image files whose names were saved with the case and initializes the display to the default settings that were saved with the case. On the Main Window, the system displays the case number, the patient ID, the case description, and the names of the image files that the user is viewing. All of this information was obtained from the database when the case was selected.

This command brings up the "Select A Case" dialog window with the database of cases shown in a table. The user selects a case by clicking on the row that describes the case. When the user clicks the OK button, the case is displayed.

**Note:** See Section 3.1.4 *Create a Database* for how to create a database file.

### 3.1.3 Save a Case to the Database

GUI Main window:
Save Case... button
Case->Save Case menu

The system allows the user to build a database from cases that were read from disk (see the method above), or to change the information for a case that was read from the database. After loading a case, either from disk or database, the user can optimize the image by changing grayscale settings and registration. When the display is optimized, the user can then save the case under a unique case ID number. This command requires the user to confirm the "save" because this action will overwrite any data previously stored for this case. Before saving the case, the user can also supply a patient ID and case description by typing directly into the labeled fields in the Main Window.

Saving a case writes the following information about that case to the database:

- A unique ID number assigned by the system
- A patient ID field (text from the Patient data entry field on the Main Window)
- The name of the image file to present to the left eye
- The name of the image file to present to the right eye
- The current brightness setting
- The current contrast setting
- A descriptive text field (text from the Description data entry field on the Main Window)
- The X and Y offset for the left eye image
- The X and Y offset for the right eye image

The user can change the settings or descriptions for a case already in the database by first selecting the case, then changing settings or typing in the Patient or Description field on the Main window, and finally "saving" the case again. The new data replaces the old data in the database.

This command brings up a confirmation dialog that asks the user to confirm the action.

### 3.1.4 Create a Database

When you save a case, information about that case is saved to a database file. When you load a case from the database, information about that case is retrieved from the database file.

The following steps are required to create a database file.

1. Create an empty file with any name (preferably in the directory containing the stereo pair files.)
2. Identify that file to the application as the database file using the **Case->Load Case List...** menu on the GUI Main Window.
3. Use the Load Stereo Pair command to load a stereo pair.
4. Press the space bar to exit Mouse Mode and return to the GUI Main Window.
5. Click the Save button on the GUI Main Window and click OK to confirm the "save".

The steps above will write out the first case to the database file in the correct format. Subsequent cases that you save will be added to this file.

You can use the **Select Case from Database...** button to see the database table created from the database file.

## 3.2 Display Mode

GUI Main window:
Display->Stereo menu
Display->Mono menu

The user can choose a stereo or a monaural view of a case. In the stereo display, the perception of a three-dimensional image is achieved by presenting one image to the left eye, while presenting a different image, acquired from a slightly different point-of-view, to the right eye. The human visual system is able to fuse these two images into one containing depth.

A mono display simply presents the same image (in this case the image presented to the left eye) to both eyes. The perceived image has no depth.

## 3.3 Display Enhancements

Before they are displayed on the screen, the 8-bit data values in an image file pass through a look-up table that maps each of the input data values into an output display value between 0 (full white) and 255 (full black). By default, the table maps each input data value onto itself. The resulting picture on the display is a true representation of the image data as it exists in the file. The user can change the mapping of input-to-output values to enhance the appearance of the picture on the screen. By changing the mapping the user can change visual aspects of the display such as brightness and contrast, create a "negative" of the image, or highlight a specific data value.

Grayscale manipulation can be done in two ways:

1. By using the Brightness/Contrast controls on the GUI Main Window
2. By the mouse in Brightness/Contrast Mode.

### 3.3.1 Increase/Decrease Brightness

<u>GUI Main Window</u>:

Scrollbar attached to the "Brightness" rectangle
Rectangle labeled "Brightness"

<u>Mouse Mode (Brightness/Contrast Mode)</u>:

Move the mouse left or right.

This command increases or decreases the overall brightness level of the image from its current setting. The value of the brightness level ranges from 0 to 255. The user can change this value in large or small increments as needed. For the default linear map, the higher the value the brighter the display (if the map is inverted, the higher the value the darker the display).

The controls on the GUI Main Window allow the user to make discrete changes to the brightness value. With the scrollbar, the user can make small changes to the value by clicking the left or right arrows, or make larger changes by dragging the slider or clicking arrows. With the Brightness rectangle, the user can increase or decrease the value continuously by placing the cursor in the rectangle then holding down either the right or left mouse button respectively. Releasing the mouse button stops the change.

Mouse Mode for controlling brightness and contrast is invoked by clicking the Brightness/Contrast button in the "Mouse Controllers" area of the GUI Main Window. When the Mouse Mode window appears, the user can move the mouse to the right/left to increase/decrease brightness.

**Note**: In Mouse Mode, the ability to change brightness is available only from Brightness/Contrast Mode. If the title bar of the Mouse Mode Window reads "Cursor Mode", then press the **F12** key on the keyboard to switch to Brightness/Contrast Mode.

To exit this window and preserve the current settings, press the space bar. The current value for brightness will register on the brightness controls on the Main window.

### 3.3.2 Increase/Decrease Contrast

GUI Main Window:

Scrollbar attached to the "Contrast" rectangle
Rectangle labeled "Contrast"

Mouse Mode (Brightness/Contrast Mode):

Move the mouse up or down.

This command increases or decreases the range-of-contrast value. The contrast range value is a number between 0 and 255 that defines the width of a window about the brightness level. Data values in this window will be mapped from white (0) to black (255). All data values below this range will be mapped to white and all data values above this range will be mapped to black. Increasing the contrast range decreases the amount of contrast in the display: conversely, decreasing the contrast range increases the amount of contrast in the image.

These commands on the GUI Main Window are implemented in the same manner as the Brightness level controls and commands. (See Increase/Decrease Brightness section presented earlier more information.)

Mouse Mode to control brightness and contrast is invoked by clicking the Brightness/Contrast button in the "Mouse Controllers" area of the Main Window. When the Mouse Mode window appears, the user can move the mouse up/down to increase/decrease contrast.

When a case is first displayed, the brightness and contrast values are set to default values (either to 256 and 128 respectively, or to values that were stored with the case in the database). However, once the mouse is moved, however slightly, the system computes new brightness and contrast values based on the position of the mouse cursor in the Mouse Mode Window. You can temporarily restore the default values by either holding down the middle mouse button or by pressing the Shift key.

To exit this window and preserve the current settings, press the space bar. The current value for contrast will register on the contrast controls on the Main window.

**Note:** In Mouse Mode, the ability to change contrast is available only from Brightness/Contrast Mode. If the title bar of the Mouse Mode Window reads "Cursor Mode", then press the **F12** key on the keyboard to switch to Brightness/Contrast Mode.

### 3.3.3 Reset Grayscale

GUI Main Window:

Reset button.

Mouse Mode (Brightness/Contrast Mode):

Press and hold down the Middle Mouse button

This command resets the brightness level and contrast range to their default values of 128 and 256 respectively. If the case being viewed was read from the database, then the levels will be reset to the values stored with the case.

The Mouse Mode command temporarily restores the default values so that you can quickly view the image with the default settings. When you release the mouse button or move the mouse, new values will be computed based on the position of the mouse pointer in the Mouse Mode Window.

**Note**: In Mouse Mode, the ability to reset the grayscale is available only from Brightness/Contrast Mode. If the title bar of the Mouse Mode Window reads "Cursor Mode", then press the **F12** key on the keyboard to switch to Brightness/Contrast Mode.

### 3.3.4 Highlight a Data Value

GUI Main Window:
    Highlight check box

Mouse Mode :
    Not implemented.

This command initially sets the contrast range to one and then displays the input data value that maps to the brightness level as pure white, thus highlighting that one data value. The remainder of the data is mapped linearly into values between 0 and 126. This allows the highlighted value to be observed against a dimmed version of the image.

When highlighting is enabled, the image is set to half of its full brightness and only the data whose value equals the current brightness level is mapped into pure white. The user can highlight single data values by leaving the contrast range at one and changing the brightness level, or highlight a range of values about the brightness level by changing the contrast range. Turning highlighting off returns the image to the visual state prior to the "highlight on" command.

### 3.3.5 Invert Grayscale

GUI Main Window:
    Invert GRAYSCALE button.

Mouse Mode (Brightness/Contrast Mode):
    Click the left button.

This toggle command inverts the linear grayscale mapping. Normally, input data are mapped linearly into output values ranging from pure white (0) to pure black (255). Inverting the map causes the output values for the same input values to range from black-to-white instead. This has the effect of producing a "negative" of the image. Inverting the grayscale again returns the mapping and display to its former state.

**Note**: In Mouse Mode, the ability to invert grayscale is available only from Brightness/Contrast Mode. If the title bar of the Mouse Mode Window reads "Cursor Mode", then press the **F12** key on the keyboard to switch to Brightness/Contrast Mode.

### 3.3.6 Save Grayscale Settings

The "Save Case" command described earlier allows the user to save the current brightness and contrast settings for a case so that when the case is recalled at a later time, it will appear as it did when it was saved. (See Section 3.1.3 *Save a Case to the Database*.)

### 3.3.7 Invert Depth

GUI Main window:
Invert DEPTH button

Mouse Mode (Brightness/Contrast Mode):
Click the right button.

This toggle command switches the image presentation to each eye (i.e., the image presented to the left eye is shown to the right eye instead and vice versa). The effect is an inversion in depth; whatever appears to have been at the back of the display now appears in front and what was in front appears to have moved to the back.

**Note**: In Mouse Mode, the ability to invert depth is available only from Brightness/Contrast Mode. If the title bar of the Mouse Mode Window reads "Cursor Mode", then press the **F12** key on the keyboard to switch to Brightness/Contrast Mode.

### 3.3.8 Adjust Alignment

This command is invoked from the GUI Registration Window. To see this window, select the **Tool->Registration** menu on the GUI Main Window.

GUI Registration Window:
The alignment controls are
Scrollbar attached to a rectangle identified by eye and direction
Rectangle identified by eye and direction

This capability allows the user to move each of the images up, down, left or right independently to correct for any misalignment of the images that may have occurred when the pictures were taken.

Each combination of eye and direction (left/horizontal, left/vertical, right/horizontal, and right/vertical) has two controls, similar to the controls used for brightness and contrast. With these controls, the user can move each image independently in the horizontal (left and right) or vertical (up and down) direction.

To operate any of the four scrollbars, the user clicks the left or right arrows to move the image by small increments, or drags the slide or clicks in the track to move in larger increments. To use any of the eye/direction rectangles, the user places the cursor in the rectangle then holds down either the left or right mouse button to move the image continuously in one direction (left or up) or the opposite direction (right or down) respectively. Releasing the mouse button stops the movement.

The user can save these settings by clicking the OK/Save button when exiting the window. If the user clicks Cancel to exit the window, the display is reset to the settings in effect prior to invoking the Registration window.

### 3.3.9 Pan or Scroll Image

This command is invoked from the GUI Registration Window. To see this window, select the **Tool->Registration** menu on the GUI Main Window.

GUI Registration window:
Pan/Scroll check box

Mouse Mode (Either Mode):

Scrolling: Press the Up or Down arrows on the keyboard (not the keypad).
Panning: Not implemented.

This command allows the user to move the image on the display up or down (scrolling), or left or right (panning). In this case the left and right eye images move together.

To enable panning or scrolling from the GUI Registration Window, the user clicks the pan/scroll check box to place an "X" in the box. To disable movement, the user clicks in the check box again to remove the "X". When panning and scrolling are enabled, the images are coupled together and the alignment controls for the left eye serve to move the image on the display up, down, left, or right. The alignment controls for the right eye are disabled. When panning and scrolling are disabled, the images are uncoupled, the alignment controls for the right eye are enabled, and the user can again move each image independently.

In Mouse Mode, the images are always coupled.

### 3.3.10 Zoom Image 1X, 2X, or 4X

GUI Main window:

1X, 2X, and 4X radio buttons

Mouse Mode:

Not implemented.

The user can enlarge the image on the display by a factor of 1, 2 or 4. The image is magnified about the center of the current view.

The user selects a magnification factor by clicking one of the radio buttons.

## 3.4 Stereo Cursor Control

Sometimes the user may want to point to some interesting feature in the image. The application provides a large, crosshair cursor on the stereo display that the user can position horizontally, vertically, or in depth with the aid of the mouse. The mouse is able to control the cursor when the application is in Mouse Mode for controlling the cursor (Cursor Mode).

**Note**: In Mouse Mode, commands that control the stereo cursor are available only from Cursor Mode. If the title bar of the Mouse Mode Window reads "Brightness/Contrast Mode", then press the **F12** key on the keyboard to switch to Cursor Mode.

### 3.4.1 Display a Crosshair Cursor

After loading an image, the system enters Mouse Mode in Cursor Mode and the user will see a large crosshair cursor drawn into the stereo image. Cursor Mode can also be invoked by clicking the Stereo Cursor/Line Drawing button in the "Mouse Controllers" area of the Main Window. When the Mouse Mode window appears, the user can use the mouse to manipulate the cursor as described in the sections that follow.

### 3.4.2 Move the Crosshair Cursor within a Depth Plane

Mouse Mode (Cursor Mode):

Move the mouse left, right, up or down.

The user can move the crosshair cursor left, right, up, or down by moving the mouse. This X/Y movement takes place in whatever depth plane the cursor is.

### 3.4.3 Move the Crosshair Cursor to Different Depth Planes

Mouse Mode (Cursor Mode):

Press and hold the left mouse button to move backward.
Press and hold the right mouse button to move forward.

In addition to moving horizontally and vertically, the crosshair cursor can also move forward and backward in depth, giving the appearance of moving in and out of the image itself. Once the user positions the cursor in depth, then moving the mouse moves the cursor horizontally and vertically in that depth plane.

The cursor will continue to move in depth as long as the left or right mouse button is held down. Releasing the button stops the movement in depth. The cursor remains at that depth plane until another command to "move in depth" is executed. Any horizontal or vertical movement of the mouse now moves the cursor around in that depth plane.

### 3.4.4 Drawing using the Crosshair Cursor

Mouse Mode: (Cursor Mode)

*Draw a straight line in any depth plane:*

1. If a different depth plane is desired, press the mouse buttons to move the cursor to the desired plane then release the mouse buttons.
2. To begin the line, hold the middle mouse button down while moving the cursor around the screen.
3. To end the line, release the mouse button.

The user can use the Crosshair Cursor to draw straight lines in a plane or in depth. The middle mouse button enables "LineDraw" mode. To draw a straight line, first move the cursor to the place where the line will begin, then press and hold the middle mouse button. Now when you move the cursor horizontally, vertically, or in depth, a line will be drawn from the beginning point to the current location of the cursor, giving the appearance of a "rubber band" line. When you reach the position at which you want the line to end, release the mouse button.

Mouse Mode: (Cursor Mode)

*Delete the last straight line drawn*:

Press the DELETE KEY.

*Redraw the last straight line deleted*:

Press the DELETE KEY again.

You can delete the line last drawn, by pressing the DELETE KEY. You can bring it back by pressing the DELETE KEY again.

Mouse Mode: (Cursor Mode)
*Draw a freehand line*:
Hold the ENTER KEY down while moving the cursor.

You can also do freehand drawing. The ENTER KEY enables freehand drawing. To draw freehand, hold down the ENTER KEY while moving the cursor around the screen. You cannot delete a freehand line.

Mouse Mode: (Cursor Mode)
*Clear the screen of all lines*:
Press the CTRL and DELETE KEYS.

To clear the screen of all lines, hold the CTRL KEY down then press the DELETE KEY. This will actually reload a new image.

Mouse Mode: (Cursor Mode)
*Draw a straight line backward or forward in depth*:
Hold the middle mouse button down while simultaneously pressing the left or right mouse button to draw a line backward or forward in depth. To draw a line diagonally in depth, drag the mouse while holding the mouse buttons down.

# Stereoscopic Digital Mammography

## Improving Detection and Diagnosis of Breast Cancer

David J. Getty, Ph.D.

BBN Technologies

What can you see in a stereo view of the breast that you cannot see in two orthogonal 2D films?

## Project
# Stereoscopic Digital Mammography: Improving Diagnostic Accuracy

- BBN Technologies
  - David J. Getty, Ph.D., P.I.
  - Ronald M. Pickett, Ph.D.
  - John A. Swets, Ph.D.
- University of Massachusetts Medical Center
  - Carl J. D'Orsi, M.D.
  - Andrew Karellas, Ph.D.

Supported by funding from the Breast Cancer Research Program of the Department of Defense, managed by the U.S. Army Medical Research and Materiel Command

- Mammography Consultants/ Readers

| | |
|---|---|
| ◆ Jack E. Meyer, M.D. | Brigham and Women's Hospital |
| ◆ Norman L. Sadowsky, M.D. | Faulkner Hospital |
| ◆ Elsie Levin, M.D. | Faulkner Hospital |
| ◆ Lawrence J. Moss, M.D. | U. Mass. Medical Center |

## Goals of the Project

- Acquire stereo mammograms from about 250 women patients scheduled for biopsy of a focal breast lesion.
- Improve diagnostic accuracy using stereo mammography.
- Develop understanding of new stereo-based visual features.
- Using ROC methods, compare the diagnostic accuracy of readings attained with:
  - 1. Standard films alone
  - 2. Standard films + non-stereo viewing of digital images
  - 3. Standard films + stereo viewing of digital images

## Why Stereo Mammography?

- Digital mammography devices and better stereo display methods now make stereo mammography feasible.
- Potential to improve detection of early, subtle breast lesions.
- Potential to improve the ability to distinguish malignant from benign lesions.

## A Significant Problem with Standard Mammography

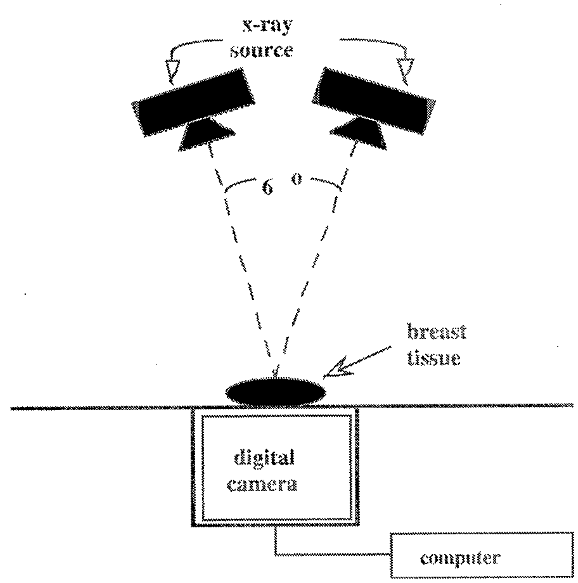
- Difficult to integrate information from a pair of orthogonal 2-D views, to mentally construct the 3-D structure of the breast.
- In stereo, one can directly see the internal 3-D structure.

## Gains in Diagnostic Accuracy from Stereo

- Calcifications
  - One can directly see the 3-D shapes of individual elements of calcium.
  - One can directly see the 3-D geometric distribution of a cluster of calcifications.
- Masses and Architectural Distortions
  - Easier to see a mass or architectural distortion because of the separation in depth of nearby overlying and underlying glandular tissue.
  - Easier to judge characteristics of the surface or border of a mass, or the structure of an architectural distortion, because it is seen directly as a volumetric shape.

Placeholder: GE digital mammography device

## Stereo Image Acquisition



## Placeholder: Stereo display system

## Stereo Mammogram Display System

- Prototype system based on a PC with a Matrox image display controller with dual image buffers and stereo circuitry.
- Stereo pair of images viewed through CrystalEyes LCD stereo eyeglasses on Hitachi 21" color monitor capable of synching to 120 Hz vertical refresh rate.
- BBN-developed software for selecting and manipulating appearance of the displayed images, with control over:
  - Brightness and contrast windowing of images
  - Inversion of grayscale
  - Inversion of depth
  - Scrolling and magnification level

Placeholder: Stereo mammogram - Left

Placeholder: Stereo mammogram - Right

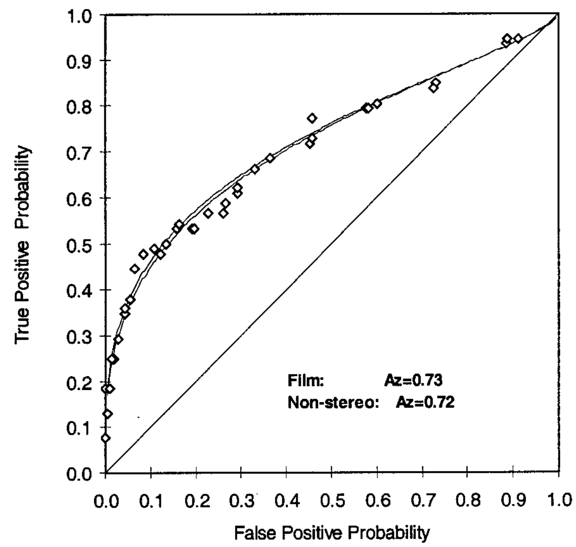
## Preliminary Reading Study

- Case set: 76 cases

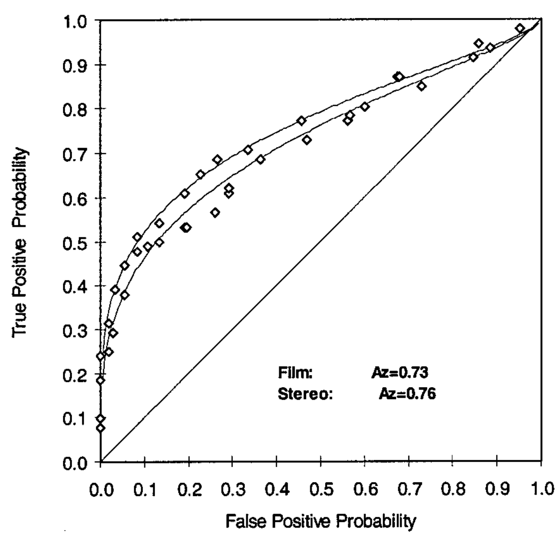
| Lesion type | Truth | | Total |
|---|---|---|---|
| | Benign | Malignant | |
| Mass | 22 | 12 | 34 |
| Calcifications | 29 | 4 | 33 |
| Architectural Distortion | 2 | 7 | 9 |
| Total | 53 | 23 | 76 |

- 4 highly-experienced mammographers as readers
- Each reader read each case in 3 stages, judging the probability of malignancy at each stage:
  - Stage 1: Films alone (using films from study leading to biopsy)
  - Stage 2: Films + non-stereo digital images
  - Stage 3: Films + stereo digital images
- Each reader was asked to log noteworthy comments about individual cases
- Accuracy of the judgment data was analyzed using ROC methods

# ROC's of Film Alone vs. Film + Non-stereo Digital Images



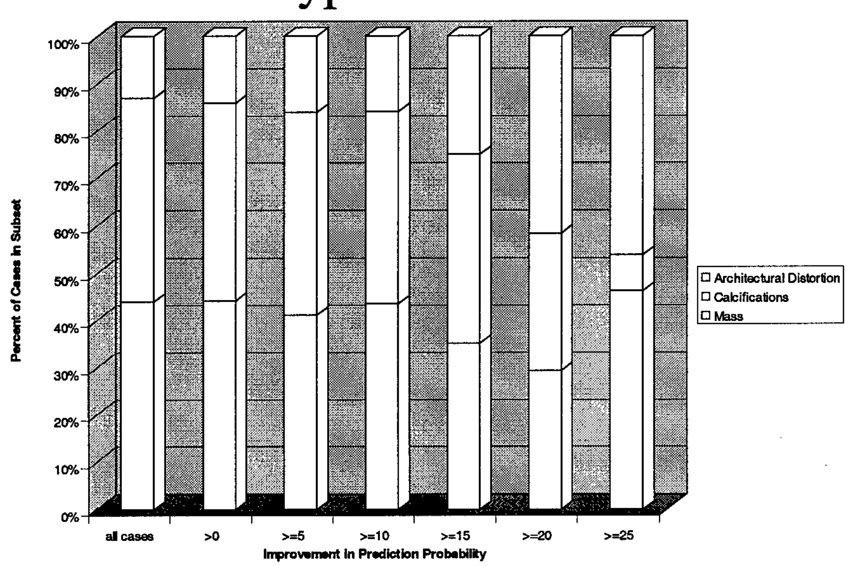

# ROC's of Film Alone vs. Film + Stereo Digital Images



## Improved Accuracy by Stereo Limited by Performance on Calcification Cases

- The net improvement in accuracy through use of stereo mammography is underestimated in these data because of the poor visibility of calcifications in the digital display.
- All 4 readers logged comments that many small, fine calcifications, which were visible in the film, were **not visible** on the digital images--affecting at least 13 of the 33 calcification cases.
- Poor visibility of small calcifications due to characteristics of the display monitor (color rather than grayscale), and possibly due also to the 100 micron spot size of the GE mammography unit.

## Improvement in Prediction Probability by Type of Lesion



## But, Volumetric Information About Calcifications Found Helpful

- Ca++ seen filling duct in stereo, which was not obvious on the film (1 case).
- Stereo shows the volumetric geometry of the calcium elements well, revealing, for example, linear or branching structure (3 cases).
- Stereo shows well that ca++ is localized within, or on the surface of, a mass (3 cases).
- Stereo shows well that ca++ is peripheral to a mass and helps determine whether the mass and calcifications are related (2 cases).

## Blank slide

## Stereo Helps in Characterizing Masses and Architectural Distortion

- By separating obscuring parenchymal tissue from a mass in depth, stereo helps define the border characteristics and shape of a mass (7 cases).
- By localizing a density in the volume, stereo helps one see that an apparent, but questionable, density or distortion on film either is, or is not, real.
  - Apparent architectural distortion on film disappears in stereo, with large (correct) change in predicted probability for 3 of 4 readers (1 benign case).
  - Architectural distortion seen more confidently in stereo (1 malignant case).

## Stereo Helps in the Detection of Masses and Architectural Distortion Not Seen On Film

- Significantly, in 6 of the 76 cases, a mass or architectural distortion was detected in the stereo images which was not visible on the films.
  - In 3 cases, a mass was detected in the stereo image which was not visible on the film.
  - In 3 cases, a region of architectural distortion was detected in the stereo image which was not visible on the film.
- The basis for this increased detection sensitivity is most likely the additional information conveyed by the volumetric display of breast tissue, permitting more sensitive direct detection of a volumetric focal density or of spherically radiating strands of tissue.

## Next Steps

- Continue accruing new stereo image cases to enlarge our sample for a final reading study.
- Acquire better stereo display monitor:
  - Grayscale, 21”
  - Capable of synching to 120 Hz vertical refresh
  - Large range of vertical size adjustment (to1/2 screen height)
  - Fast decaying phosphor (to minimize ghosting between eyes)
- Consider using stereo film display as well as digital display.
- Try to improve calcification classification by exploiting unrecognized diagnostic information carried by the volumetric geometry of the calcium elements.

## Demonstration of Stereoscopic Digital Mammography

- Stereo mammograms of several cases, illustrating stereo views of masses, architectural distortion, and micro-calcifications.
- Images presented in hand-held stereo viewers, each containing a stereo pair of 35mm slides of one case.