A Pilot Study of Eye Movement During Mammography Interpretation: Eyetracker Results and Workstation Design Implications

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Digital mammography can potentially improve mammography image and interpretation quality. On-line interpretation from a workstation may improve interpretation logistics and increase availability of comparison images. Interpretation of eight 4k- × 5k-pixel mammograms on two to four 2k- × 2.5k-pixel monitors is problematic because of the time spent in choosing which images to display on which monitors, and zooming and roaming on individual images that are too large to display completely at full resolution. The authors used an eyetracker to measure radiologists viewing behavior during mammography interpretation with film on a viewbox. It was observed that a significant portion of the mammographers' time is spent viewing "comparison pairs" (typically two or more comparisons per case), such as the left mediolateral and craniocaudal images or old and new images. From the eyetracker measurements, we estimated that the number of image display, roam, and zoom operations decreases from an average of 64 for one monitor to 31 for four monitors, with the largest change going from one to two monitors. We also show that fewer monitors with a faster response time is superior to more monitors with a slower response time. Finally, the authors demonstrate the applicability of time-motion analysis to mammographic workstation design.

KEY WORDS: eyetracking, digital mammography, image display.

SCREENING MAMMOGRAPHY is an effective procedure for early identification of breast cancer.[1-10] Mammography imaging technology has improved significantly in the last 20 years including the development of dedicated mammography equipment with appropriate x-ray beam quality, grid capability, adequate breast compression, automatic exposure control, better film screen systems, and appropriate film processing.[11,12] Nevertheless, roughly 10% of clinically obvious breast cancers are not visible with mammography,[4] most frequently in patients with large amounts of breast glandular tissue.[4,13] Further, near-optimal film processing is critical,[14] and film-based mammography is often inaccessible in rural locations with insufficient population to justify a proximity-located mammographer.

Digital mammography has the potential to alleviate some of these problems.[15] Typically, such systems generate a 4,000- × 5,000- 12-bit/pixel matrix for each image in the mammography study. Preliminary evaluation indicates enhanced gray-scale resolution over film-screen mammography,[16] which may improve detection under conditions of large amounts of breast glandular tissue. Digital mammography would also allow filmless interpretation and teleradiology to remote locations.

However, display of digital mammography is problematic. There is a new generation of film printers becoming available that can print 4,000 × 5,000 pixels on an 8- × 10-inch format at 50 μm/pixel, and 10 to 12 bits of gray scale. However, it is possible that even with these printers, intensity windowing, or some other gray-scale manipulation approach may be needed to best present the dynamic range of the acquired data. Finally, film development and handling are logistically troublesome. A mammography workstation that facilitates fast and accurate on-line interpretations would be of immense value to mammography clinics.

Monitor quality has improved significantly over the last several years with the current best-quality 70-Hz monitors generating 150 fl of luminance and displaying a 2,000- × 2,500-pixel image in as little as 0.11 seconds. Although some further increases in luminance can be expected, monitors are not likely to produce the high brightness of a film light box nor have sufficient gray-scale dynamic range to allow interpretation without intensity windowing or other gray-scale filtering.

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Simply using eight or more of these monitors is not likely to produce a viable workstation. At this time, the high-resolution, high-brightness monitors are physically large, resulting in a workstation that would be prohibitive in many space conscious clinics. They would also add the overhead of considerable time for the mammographer to move physically back and forth while trying to compare various images. For these reasons, as well as the cost, we did not consider a workstation of more than four monitors.

Two significant ergonomic obstacles remain. First, because only two or four monitors can be realistically used in a viable workstation, the radiologist needs to choose constantly which images are to be displayed on which monitor. Second, the mammographer must roam and zoom over a 4,000- × 5,000-pixel image to see it at full resolution on a 2,000- × 2,500-pixel monitor. Both roam and zoom, and image-display selection are cognitively complex tasks, disrupting the mammographer's concentration during interpretation. These tasks will require many time-consuming hand motions and button presses as well as time to wait for the system to display images, all of which can add up to an additional 2 to 4 minutes of radiologist time, whereas an interpretation on film would require less than 1 minute.

Thus, answers are needed to several critical questions that can significantly affect the viability of the mammography workstation concept. How often do mammographers need to roam around the full-resolution image, and how often can they manage with a lower-resolution image? How often will mammographers want to change which images are being displayed? Which sequence of images will they choose to display next? How fast must a monitor display an image for the resulting workstation to be clinically viable for the radiologists who are used to working with film and alternator? A preliminary experiment[17] suggested that eyetracking of mammographers reading films could yield useful information to help answer these questions.

We used an eyetracker to study four experienced mammographers interpreting a variety of cases. An eyetracker is a device that records where someone is looking and allows researchers to determine when the subject is viewing which portions of various images.

MATERIALS AND METHODS

Subjects

Two male and two female board-certified radiologists who are experts in breast imaging and faculty members at the authors' institution served as subjects. As a group, they are responsible for all mammograms read at this institution, approximately 15,000 per year, as well as the instruction of residents. Subjects ranged in age from 34 to 72 years.

Equipment

The subjects wore an eyetracker, a device that records eye movements superimposed on a television signal (NTSC) showing the field of view (Eye Mark Recorder Model V EMR-V NAC, Instrumentation Marketing Corp, Burbank, CA). The eyetracker system consists of a head-goggle unit and a camera controller unit. The goggle unit is mounted on the head using straps and contains the eyetracking optics and electronics. To record eye movement, an infrared light-emitting diode (950-nm wavelength), which is below the sensory level of the eye, projects a dot of light onto the wearer's cornea. This dot is reflected from the cornea and detected by a video camera (metal-oxide-semiconductor), and finally sent to the camera controller for processing. In addition to the camera for each eye, there is a third "Cyclops" video camera mounted at the center of the forehead that observes the central portion of the subject's field of view. In real time, as the head and eyes move, the camera controller electronically superimposes two eye-position indicator spots (eg, a square) onto the video signal from the Cyclops camera. These spots denote the instantaneous location of each eye. This combined video signal is available for display on a video monitor or recording with a video recorder. The unit has an accuracy of 0.6 degrees, which is less than a centimeter at the viewing distances used. The eyetracker output video signal was recorded onto a VHS recorder. In addition, the gross body movements were recorded using a separate camera and recorder. Because the sensory portion of the eyetracker device is mounted completely on the subject's head, subjects are free to move their heads, resulting in less interference in the user's behavior.

Cases

To simplify this study, only eight complete cases were viewed by each mammographer. Each case contained a current and comparison study, and each study contained left and right craniocaudal and mediolateral images. These cases were selected to provide a cross section of representative mammographic findings. The cases viewed included (1) normal, fatty; (2) normal, dense; (3) dominant mass, changing; (4) dominant mass, stable; (5) cluster of calcifications, changing; (6) cluster of calcifications, stable; (7) multiple bilateral masses; (8) Multiple bilateral calcifications. Patients in each of the categories were identified using computer records from the years 1993 to 1994. For the cases chosen, the patient had to have two consecutive studies done at our institution, separated by at least 12 months; the patient had identifiable mammographic findings; and the films had to be of diagnostic quality. The cases were presented in varying order to each of the four subjects.

Procedure

To provide as realistic an environment as possible, every effort was made to reproduce normal working conditions for the radiologists. The experiment was carried out in the usual clinical setting, the breast imaging reading room at approximately the same time in the afternoon. The most notable difference between this experiment and regular mammogram reading was the presence of the eyetracking device. Other than adapting to the presence of the eyetracker, no additional training was needed. All films were prehung on a dedicated mammography film viewer/alternator (RADX Technology, Houston, TX). The cases were hung according to the standard practice at the authors' institution (Fig 1). A magnifying glass was available that provided two levels of magnification. Subjects were instructed to generate a clinically acceptable standard mammography report, and were allowed to use the magnifying glass and move images on the board as needed to generate the report. No time limits were imposed. They were given the option to stop the study at any time if they desired. The eyetracker was calibrated before each case and rechecked after each case using methods supplied by the manufacturer.

Data Collection

The standard mammography report form at the institution was used to record findings. This form provides information to the radiologist on patient demographics (hospital number, age, race), focused history, and current symptoms. It also provided information on menstrual status and hormonal therapy. The mammographer was required to fill out the section regarding pertinent findings, if there was a significant change noted since the previous study, if the breast parenchyma was dense or fatty, and a list of findings for each breast rated on the American College of Radiology 1 to 5 scale for mammography.[14] Each of the mammographers was skilled at using this form before the study.

Data Analysis

NTSC video generated from the eyetracker was electronically time-coded with a resolution of 30 frames per second. A video cassette recorder capable of shuttling frame by frame was used to analyze the video (Panasonic SVHS MTS AG-1960, Matsushita Electronic Co Ltd, Osaka Japan) and a high-resolution gray-scale monitor was used to view the video. The tape for each trial was analyzed frame by frame at a $\frac{1}{30}$-second resolution; for each frame, the position of the dominant eye was recorded on paper using a grid pattern indicating the position of all the images in a dual-study case. From these data points, frequency of operations, duration, and excursion patterns were determined.

The eyetracker device occasionally would slip somewhat on the subjects' heads during a trial, resulting in varying amounts of eye movement inaccuracy for a given trial. This was determined by the calibration sequences performed before and after each case. Thus, for analysis purposes, two levels of eye-movement accuracy were used. *Full-image resolution* noted only which image the eye was viewing in a video frame, whereas *$\frac{1}{16}$-image resolution* noted, for a given video frame, not only which image the eye was viewing but also which segment of a 4 × 4 grid imposed on that image the eye was viewing. If the posttrial calibration indicated more than a 3-cm variation in eye position from the pretrial calibration, the trial was deemed to have insufficient accuracy for the $\frac{1}{16}$-image resolution and was thus only used for full-image resolution. $\frac{1}{16}$-image resolution provides a measure of how many roaming operations will be needed to view a 4,000- × 5,000-pixel mammogram using a 2,000- × 2,500-pixel monitor. The full-image resolution data provide essential information as to the number, order, and type of image display operations needed to view 8 or more images on the display device. From these data, the authors can predict the time for and number of operations required when using two video monitors.

We define three types of operations that can be measured. They are as follows:

Average "image display" operations indicates the estimated number of times a particular image would be needed for viewing while not already displayed, thus requiring that image to be called up for display. Average image display operations were derived by counting the number of times mammographers moved their eyes from one image to another. As the number of monitors in a workstation is increased, it is increasingly likely that the desired image to be viewed is already displayed on a monitor. Thus, the number of image display operations decreases as the number of monitors in a workstation is increased from one to four.

Average "zoom-in" operations indicates the estimated number of times mammographers either would need to zoom in on an image that was already displayed or display a new image

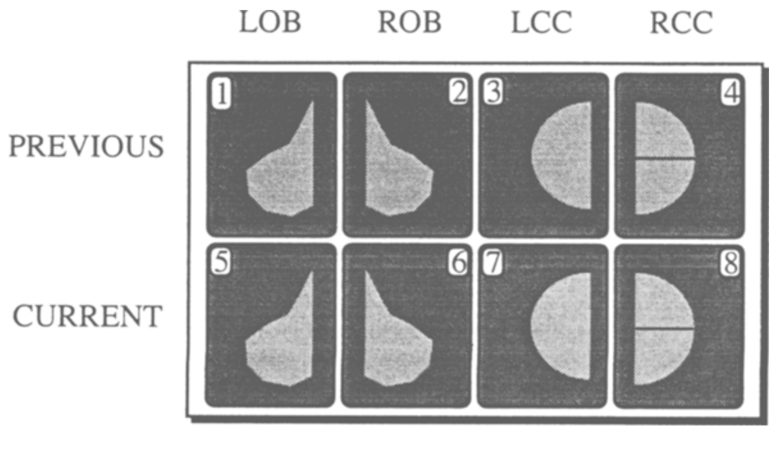

Fig 1. Arrangement of mammograms for each study. The numbers are used only for indicating comparison pairs. L, left; R, right; OB, Oblique view; CC, craniocaudal view.

(requiring an image display operation) and zoom into that image. Average "zoom-in" operations were derived by counting the number of times a mammographer picked up a magnifying glass and started looking at an image or moved to a new image holding the magnifying glass. Note that we are making an assumption that if the magnifying glass is not being used, mammographers could manage with only 2,000 × 2,500 (100 μm/pixel) resolution while they would require a full 4,000 × 5,000 (50 μm/pixel) resolution when the magnifying glass was being used. A mammographer may want to zoom into a new image that is already displayed on a monitor and has already been "zoomed." In this case, no zoom operation would be needed. Thus, the number of zoom operations decreases as the number of monitors increases.

Average "roam" operations indicates the estimated number of times that mammographers would need to move a 2,000 × 2,500 pixel viewport on the 4,000- × 5,000-pixel mammogram in 1,000-pixel increments. The authors have assumed the 1,000-pixel increment, as this would allow mammographers to be able to always view any portion of the image with all of its surroundings; a 2,000-pixel increment would not allow border pixels to be viewed with pixels just across the border. A mammographer may want to roam to a portion of a new image that is already displayed on another monitor and has already been zoomed and roamed to the required area. In this case, no roam operation would be needed. Thus, the number of roam operations decreases as the number of monitors increases. Average "Roam" operations were derived by counting the number of times a mammographer looked at a different 16th of an image with the magnifying glass in hand. The first time an image was viewed with the magnifying glass was counted as a zoom-in operation, whether the same image that had just been viewed without the magnifying glass was then viewed with the magnifying glass, or if a new image was viewed with the magnifying glass in hand.

Workstation users zoom into an image by pressing a button or moving a mouse. To be able to predict workstation zoom behavior, the author had to infer from alternator behavior when the user might zoom with a workstation. Given the roughly 4,000- × 5,000-pixel images and 2,000- × 2,500-pixel monitors, only a 2× zoom would be needed. Thus, the user is either at full resolution or at 2,000- × 2,500-pixel resolution. Receiver-operating characteristic analysis of digitized film[18] indicates that 2,000- × 2,500-pixel images are almost, but not quite, sufficient for mammography interpretation, so mammographers only occasionally need the higher resolution. The authors thus assumed that the 2,000- × 2,500-pixel resolution would be sufficient for all viewing except when the magnification glass was used with film and alternator. When the user is not using the magnification glass, the authors assumed they were viewing the entire mammogram at 2,000- × 2,500-pixel resolution and thus do not need to roam within the image. The authors had no way of verifying or testing this assumption, so the number of roam and zoom operations are of limited accuracy. Nevertheless, they provide us with a basis for some preliminary conclusions about mammography workstation design.

RESULTS

Data

Table 1 indicates the interpretation times for all 32 trials in the experiment. All trials were successfully completed and allowed for interimage analysis. However, only 6 cases of the 32 were analyzed at the 1/16-image resolution: subject B, cases 4 and 7; subject C, case 2; and subject D, cases 1, 2, and 7.

Table 2 contains eyetracker-derived estimates—based on the 1/16 image resolution of several workstation operations as the number of workstation monitors varies from one to four. Six cases may seem to be too limited of a sample for a time-motion analysis of roam behavior. However, these cases provide for a total of more than 40 roam data points, or more than 80 roam and zoom data points across four subjects, and are more than sufficient for the level of accuracy needed for the simple time-motion workstation-design decision-making purposes to which this data might be applied. The information in Table 2 was derived from several thousand experimentally gathered data points that denoted for each subject and case every 30th of a second, in which 4- × 4-inch grid or which image the radiologist was viewing. The three types of operations, as previously defined, are image display, zoom-in, and roam.

Comparison Pairs

The mammographers often went back and forth between two images presumably looking for differences, similarities, and changes. Table 3 shows the per-case average frequency of viewing for the six most common comparison pairs. A comparison pair is considered to have been viewed when the

Table 1. Interpretation Times (minutes) with Eyetracker

Subject	Case No. 1	2	3	4	5	6	7	8	Subject Average
A	3.04	1.93	1.73	3.01	2.34	1.12	1.97	3.60	2.34
B	4.32	2.37	5.33	2.97	2.42	2.98	2.98	4.47	3.48
C	2.54	3.41	1.28	1.48	3.09	2.82	0.87	2.36	2.23
D	1.86	1.34	1.23	1.47	1.01	1.00	0.53	1.54	1.25
Case average	2.94	2.26	2.39	2.23	2.22	1.98	1.59	2.99	2.32

Table 2. Estimated Workstation Operations for Equivalent Interpretation

	No. of Monitors*			
	1	2	3	4
Average† "image display" operations	49 (14-68)†	29 (10-43)	23 (10-33)	19 (6-30)
Average "zoom-in" operations	9 (4-17)	7 (4-11)	7 (4-10)	6 (4-10)
Average "roam" operations	6 (3-9)	6 (3-10)	6 (3-10)	6 (3-10)

*Numbers in parentheses show the range for the six cases.
†Average number of operations required as a function of the number of monitors.

radiologist views the first image, then views the second, and finally goes back and views the first image. A viewing of an image, followed by a second image, and then viewing the first with no intervening viewing of other images would be considered a single viewing of that comparison pair. If the radiologist returned to view the second image for a second time, that would be considered two viewings of the comparison pair. A third viewing of the first image would be considered a third viewing of the pair.

From the six cases analyzed at $\frac{1}{16}$ resolution, there were many instances of comparisons; only the six most frequently viewed comparison pairs are included in Table 3. All other pairs averaged well below one viewing per case. As can be seen from Tables 2 and 3, display of comparison pairs represents a significant portion of the total image display operations.

Observations

Although they were given the option, none of these subjects decided to halt the experiment because of discomfort. All of the subjects noted that although the eyetracker device was unwieldy and restrictive at first, it became tolerable and unnoticed as the experiment progressed. Only one subject complained of any side effects—namely, a headache that went away soon after the experiment. Nevertheless, it is possible that the device affected mammographer behavior.

Table 3. Number of Times Comparison Pairs Displayed per Case

		No. of Times Pair Viewed per Case
Medial lateral oblique, left	Old and new	4 (0-20)
Medial lateral oblique, left	Old and new	3 (0-12)
Craniocaudal, left	Old and new	1 (0-3)
Craniocaudal, right	Old and new	6 (0-24)
Medial lateral oblique, left and right	New	2 (0-9)
Craniocaudal, left and right	New	2 (0-3)

DISCUSSION

Number of Monitors

Table 2 clearly indicates that increasing the number of monitors will allow a decrease in the total duration of the interpretation. To illustrate this with an example, suppose an *image display* operation (including both hand motions and system response time) requires 3 seconds, and a *zoom* operation or *roam* operation requires 1 second. From Table 2, we can determine that a one-monitor system would have an average of $49*3 + 9*1 + 6*1 = 162$ seconds or about 2.7 minutes of *image manipulation time.* Using these same operation durations, the two-monitor system would have $29*3 + 7*1 + 6*1 = 100$ seconds or about 1.7 minutes of image manipulation time for a 40% reduction over the one monitor system. Moving to a four-monitor system would require $19*3 + 6*1 + 6*1 = 69$ seconds or about 1.2 minutes of image manipulation, for a 30% reduction from the two-monitor system. Note that even with reduced duration of the various operations, more monitors will result in a faster interpretation, though the advantage is less with faster operations.

Four monitors would greatly increase the expense of a mammography workstation and also the amount of space occupied in the clinic. Further, modern 2,000- × 2,500-pixel monitors tend to be large so that viewing and comparing images on four monitors might require mammographers to move their chairs back and forth between the monitors, increasing the duration of the interpretation in ways not accounted for in the preceding analysis. More than four monitors would exacerbate these problems and, therefore, were not considered in this evaluation. Ideally, the mammography workstation would use smaller monitors tailored to mammography and packaged to minimize the non-screen area between active screens.

System Response Time

Image display operations, zoom operations, and roam operations all require the mammography workstation to move a portion of a mammogram onto a particular monitor from a framebuffer, from the workstation's fast random access memory, or from disk. System response time for image display can range from 0.1 to 2 or even 5 seconds with many current medical image workstations. To take an example, suppose a two-monitor system has 42 operations (29 image display, 7 zoom, and 6 roam), then a 5-second system response time would result in a 210-second overhead, a 2-second system response time would result in a 84-second overhead, and a 0.1-second system response time would result in a 4.2-second overhead. Clearly, system response times of a few 10ths of seconds are essential if construction of a mammography workstation that can compete with a light box is to occur.

Table 4, derived from Table 2, shows the benefits as the number of monitors is increased and as the system response time is decreased. Two monitors with a 0.1-second response time are much faster than a four-monitor system with a 2-second response time. Note that response time is only a portion of the overhead for an image display, zoom, or roam operation. The time for the mammographer to move a mouse or press a button can be significant, and would likely add from 0.1 to 2 seconds to each operation and thus would tend to increase the importance of having a larger number of monitors with the corresponding fewer number of interaction operations.

Comparison Pairs

Displaying a mammogram on a particular monitor normally requires the mammographer to select the image, select the destination monitor, and wait for the system to display the image; these three steps are ergonomically complex and can easily take 3 to 5 seconds for one image and from 6 to 10 seconds for a pair of images, depending on required hand motions and system image display time. However, display of a comparison pair takes considerably less time not only because one operation will display both images but also because (presumably) the workstation designer can a priori determine which image should go on which monitors for comparison of a particular pair of images, eliminating the need for the radiologist to select monitors every time the pair is to be displayed. Thus, the authors roughly estimate that display of a comparison pair can take from 0.5 to 2.5 seconds, depending on the workstation's image display time. Table 3 indicates that considerable ergonomic savings can be achieved by a mammography workstation providing *one-button* function for display of each of the listed comparison pairs. Note that the comparison pair data does not account for all the image display operations, so a conventional mechanism for displaying a particular image on a particular monitor will still be required. The cost of a comparison-pair display function is the increase in complexity and thus the learning time for a mammography workstation.

Table 4. "Interpretation Overhead" Results of Various System Response Times and Monitor Configurations

	No. of Monitors*			
Response Time (sec)	1 (64) (sec)	2 (42) (sec)	3 (36) (sec)	4 (31) (sec)
5	320	210	180	155
4	256	168	144	124
3	192	126	108	93
2	128	84	72	62
1	64	42	36	31
0.5	32	21	18	15
0.1	6.4	4.2	3.6	3.1

*Numbers in parentheses show the number of image operations (image display, zoom, and roam) from Table 2.

Workstation Viability

Can we construct a viable mammography workstation using 2,000- × 2,500-pixel monitors to interpret eight 4,000- × 5,000-pixel mammograms? A reasonable initial goal would be to have the difference between the workstation interpretation time and prehung film/alternator time to be no more than the average time to load the images onto the alternator and to return them back into the folder, say 20 seconds or so. Table 3 indicates that with a 0.1-second image display time and minimum of two monitors, a reduction of the time for the computer to display the various images onto the monitors to less than 5 seconds of the 20-second limit may occur. If the hand motions to initiate a roam, zoom, or comparison-pair operation were limited to two-button presses or about 0.4 seconds, for a total of 0.5 seconds per operation, including the 0.1 second image display time, the total workstation overhead for a four-monitor workstation with its estimated 31 operations (Table 4) would be 16 seconds, which might just produce a viable mammographic interpretation environment given the improved logistics of the filmless environment.

CAVEATS

There are several circumstances that somewhat limit the applicability of this study. First, the authors have ignored the effect of gray-scale manipulations on the ergonomics of workstation in general and on its viability for mammography in particular. If workstation display of digital mammography requires intensity windowing while film display does not, then there is a further burden on the workstation to present more images per case. Second, wearing the eyetracker device and knowing they were being observed almost certainly affected the behavior and speed of the mammographers. Third, only 6 of the 32 trials were analyzed at the $\frac{1}{16}$-image level of detail, though the authors believe that the number of data points analyzed were sufficient to make our limited inferences. There were eight images each on those 6 trials, and together these represent more than 80 roaming and zooming operations. Further, these 6 trials represented varying subjects and cases. It is possible that an increase in the number of trials analyzed at the $\frac{1}{16}$-image resolution would have resulted in somewhat different numbers. However, given the inherent inaccuracies and limitations of time-motion analysis to which these numbers will be applied, the 6 trials should be more than sufficient for comparison of various "roam" design alternatives.

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