2-AFC observer study of digital stereomammography

Predrag R. Bakic, Michael Albert, and Andrew D. A. Maidment
University of Pennsylvania, Philadelphia, PA 19104

ABSTRACT

A two-alternative forced choice (2-AFC) observer study has been performed to estimate the dose needed for detection of small cancers by digital stereomammography compared to projection mammography. Monoscopic and stereoscopic images simulating 4 different values of signal-to-noise ratio (SNR) were interleaved and repeated for 3 different object diameters. Five hundred images per condition were read by 4 observers and the fraction of correct answers and the corresponding d' as a function of condition were calculated. Preliminary results indicate that stereoscopy could be performed at 1.5±0.2 times the dose of monoscopic viewing. In our previous contrast-detail (C-d) study, we observed a factor of 1.1±0.1. The two experiments differ in target properties and decision tasks. In the C-d experiment, the viewer was asked to determine whether suprathreshold objects with an SNR of 5-6 were visualized in terms of a well defined edge and shape. In the 2-AFC experiment, the viewer was asked to detect an object at the limits of visibility (SNR range of 1 to 3). Experiments to elucidate the differences in observer performance are planned.

Keywords: Radiography, mammography, digital, stereoscopy, dose, radiographic technique, observer study, human perception.

1. INTRODUCTION

Stereoscopic analysis of radiographic images has the well-known advantage of separating overlapped anatomic structures, therefore reducing ambiguity due to anatomic noise. Optimization of the dose used during stereoradiography has not been addressed specifically in the literature. This work is a continuation of our study of the effects of quantum noise on dose and contrast sensitivity in stereoradiography.[1] Previously, we performed a contrast-detail (C-d) observer study using radiographic projections of a mammographic C-d phantom acquired with a flat-panel digital x-ray detector. In that study, we concentrated on the issue of quantum noise, separating it from the effects of angular disparity by acquiring both left and right stereoscopic images using the same geometry (no depth information was encoded). The images differed only in the given realizations of the background quantum noise. The results of the study, involving seven observers, suggested the potential for reducing the dose needed to acquire both images of a stereo pair to about 1.1 times the dose for a single radiographic projection, due to combining quantum noise from the two stereo images by the human visual system.

Our current study reevaluates these previous results using a two-alternative forced choice (2-AFC) approach. Our 2-AFC study is based upon computer generated images. In comparison with repetitive acquisition of x-ray projections of a physical phantom, use of synthetic images is advantageous in several aspects, as follows. Dimensions of phantom object(s) are not fixed and allow finer rendering of the perception dependence on the object size and thickness (i.e., contrast). A large number of synthetic images can be generated under the controlled conditions, therefor separating the effects of phantom and noise on the perception from systematic influences, as e.g., the time variations in x-ray tube kV and mAs or variations in detector properties. Interpretation of the obtained results, however, depends on how nearly the simulation approximates physical experiments, which is not always a trivial task.

Further author information: (Send correspondence to A.D.A.M.) P.R.B.: E-mail: bakic@rad.upenn.edu, M.A.: E-mail: albert@rad.upenn.edu, A.D.A.M.: E-mail: maidment@rad.upenn.edu, Telephone: (1 215) 662 6225, Fax: (1 215) 349 5115, Address: Hospital of the University of Pennsylvania, Department of Radiology, 1 Silverstein, 3400 Spruce Street, Philadelphia, PA 19104

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Table 1. Object contrast computed for disks of three different diameters (D) and four SNR values. The contrast values are expressed in the number of JNDs and as a multiple of the standard deviation of the background noise (σ_N).

D(pixels) / SNR	20	28	40
1.19	1.87 JNDs (0.034 σ_N)	2.58 JNDs (0.047 σ_N)	3.68 JNDs (0.067 σ_N)
1.68	2.58 JNDs (0.047 σ_N)	3.68 JNDs (0.067 σ_N)	5.22 JNDs (0.095 σ_N)
2.38	3.68 JNDs (0.067 σ_N)	5.22 JNDs (0.095 σ_N)	7.37 JNDs (0.134 σ_N)
3.36	5.22 JNDs (0.095 σ_N)	7.37 JNDs (0.134 σ_N)	10.45 JNDs (0.190 σ_N)

2. MATERIALS AND METHODS

The 2-AFC study consisted of a series of observations. In each observation, a pair of simulated noisy images were displayed, with only one image containing an object (a disk) of known shape, size, and position. The observers were asked to indicate the image containing the object. The probability of correct selection was computed separately for monoscopic observations (each eye was presented the same simulated image pair) and for stereoscopic observations (left and right eye were presented separately simulated image pairs). Four observers participated in the study.

2.1. Image Simulation

The simulated images were generated in real time before each observation. A random Gaussian background was generated separately for each image in the 2-AFC pair. One of the images in the pair was selected randomly and a bright disk, positioned in the center, was added. The variations of pixel values in the background region were kept constant. Three sizes of disks have been used, with diameters, D=20, 28, or 40 pixels. The dimension of the images was 256×256 pixels. The left and right stereo images were generated with objects of the same size and contrast within two random realizations of the background noise. Since we are analyzing the effects of stereoscopy on suppression of the quantum noise, the same geometry was used for simulating the left and right stereo images; no angular separation was included.

Contrasts of the disks have been selected so that, for each disk size, the corresponding signal-to-noise ratio, SNR, took one of four values: 1.19, 1.68, 2.38, or 3.36. The SNR value of a disk of diameter D and contrast C, within the background noise of standard deviation σ_N, is equal to:

$$\mathrm{SNR} = \sqrt{\pi}\frac{D}{2}\frac{C}{\sigma_N}. \quad (1)$$

These SNR values were selected in a preliminary experiment, in order to achieve a probability of correct detection approximately in the range of 0.55 to 0.95 (see Section 2.2).

Simulation of images was followed by perceptual linearization, a nonlinear image transformation based upon Barten's model of human visual contrast sensitivity.[2] The goal of perceptual linearization is to ensure that equal changes in the displayed image brightness are equally perceived. Barten's model was derived experimentally using a standard target – a 2 deg × 2 deg square filled with a horizontal or vertical sinusoidal modulation of 4 cycles/deg – placed in a uniform background of the mean target luminance. The threshold modulation at which the target becomes just visible to the average observer defines the just-noticeable difference (JND) at the luminance value of the background. We have used a version of the Barten model from the DICOM standard,[3] and an interpolation of photometric measurements of the monitor characteristics,[1] to derive a nonlinear transformation of the simulated image intensity values. Application of this transformation provides for a linear relationship between the simulated image intensities and the JND index value. Based on that relationship, σ_N of the simulated background noise corresponds to 55 JNDs, relative to a base level of a JND index of 350, corresponding to an 8-bit digital driver level of 90. Disk contrast values corresponding to the four selected SNR values are given for each disk size in Table 1, both in units of background noise sigma and JNDs.

2.2. Preliminary Experiments

We performed several preliminary experiments in order to optimize parameters and protocol for the 2-AFC observer study. First, a staircase 2-AFC technique was used for estimating the optimal object contrast in noisy images. Staircase techniques[4,5] consist of reducing or increasing the object contrast during a series of 2-AFC observations, after registering a certain number of succesive correct or incorrect selections. Such a series of observations is expected to converge to an object contrast value, which corresponds to the probability of correct detection value selected by the experiment design. Our aim was to identify an approximate range of object contrasts corresponding to probabilities of correct detection of between 0.55 and 0.95. Probability values below 0.55 are hard to distinguish from pure guessing. To achieve a probability higher than 0.95 would require only a small number of incorrect detections among long series of correct ones, and thus random and mechanical errors start to have significant effect on the observer's performance. Based on these preliminary estimates, we have selected four values of object contrast for each of the three simulated disk sizes. For a given object size, the selected contrast values are ordered with the ratio of two successive values equal to $\sqrt{2}$.

Second, during a flyer experiment, it was noticed that the initial separation between the stereoscopic and monoscopic performances would gradually decrease during repeated sessions, for all observers. The 2-AFC images used in these preliminary experiments did not contain fiducial markers, and we believe that the observed drop in stereoscopic performance was due to fatigue from attempts to fuse different portions of noisy images with object contrasts close to the perception threshold. After including eight white radial fiducial lines per image, stability of the stereoscopic performance improved significantly. Use of fiducial markers, e.g., Toto circles,[6] in 2-AFC experiments has been reported in the literature for ensuring the conditions of signal-known-exactly, SKE, detection in monoscopic 2-AFC experiments. All the observations in our 2-AFC study were performed using the fiducial lines. In our previous C-d experiment[1] no additional fiducial markers were used; their role was instead played by the large, clearly visible disks in the structured array of the mammographic C-d phantom.

Third, during the preliminary experiments several observers reported making incorrect detections caused by "ghosting," the virtual appearance of increased residual brightness from the previous "truth" image, due to the persistence of the eyes. Long sequences of incorrect detections can occur because of this effect. In order to reduce the ghosting effect, before displaying each new image pair the monitor screen was flashed for 0.2 s with a constant gray level image.

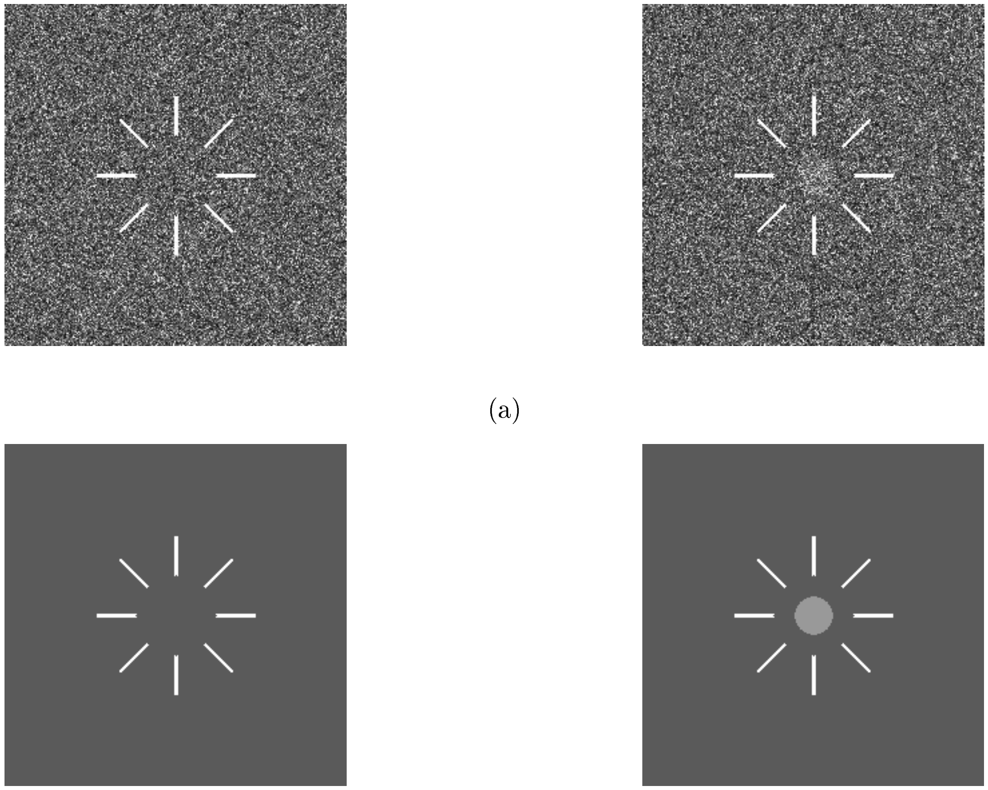
2.3. Observer Study

Four observers, three medical physicists and a medical student, performed the 2-AFC experiments. Three out of the four observers had also participated in the contrast-detail, C-d, study.[1] The stereoscopic acuity of the observers was tested using the RANDOT Stereotest (Stereo Optical Company, Chicago, IL), a standard clinical test roughly covering the range of 20-500 seconds of arc of stereoscopic angular separation. Minimum observable angle of stereo disparity, for the four observers, was equal to 30, 70, 30, and 25 seconds of arc.

The observations were performed in a darkened room with a grey monitor background, approximately matching the average pixel values of the image backgrounds. The distance between the observer eyes and the monitor was kept constant at approximately 1 m. From that distance, the three disk sizes used in the study correspond to viewing angles of 0.49°, 0.68°, and 0.96°, for disk diameters of 20, 28, and 40 pixels, respectively.

Both stereo and mono observations with all three sizes of disks were performed using stereoscopic Crystal Eyes goggles (StereoGraphics, San Rafael, CA). In addition, observations with the medium sized disks (28 pixel diameter) were repeated without stereoscopic goggles. As an illustration, Figure 1 (a) shows a 2-AFC image pair. After making a selection by pressing the left or right mouse button to indicate the choice between the corresponding images from the pair, the truth image, Figure 1 (b), was shown accompanied with an appropriate sound signal; a pleasant tone for a correct selection or a buzzer for an incorrect selection.

Forty sessions were performed by each observer, with 400 observations (200 monoscopic and 200 stereoscopic) per session. During each session, the size of the disks was kept constant and there was an equal number of randomly interleaved images (100) for each of the four different contrast values. Each observer performed a total of 16,000 observations and the probability of correct detection was computed by averaging over 500 observations for each viewing condition. Summarizing, there were 32 conditions testing three disk sizes with and one size



(a)

(b)

Figure 1. An example of synthetic 2-AFC images shown to the observer. (a) A 2-AFC pair of noisy images is shown to the observer, who is asked to identify the image with an object. (The object contrast is exaggerated for the purpose of illustration.) (b) Ground truth noiseless image, displayed after the observer's decision has been made, accompanied with an appropriate audio signal.

without the stereoscopic goggles, four disk contrasts for each size, and mono or stereo viewing of all disk sizes and contrasts.

In each sequence of forty sessions for each observer, the order of the disk size and use of stereo goggles was randomized and balanced. Similarly, the order of the 400 observations in each session was randomized and balanced for different disk contrasts, and monoscopic and stereoscopic presentation. A timesheet for each observer contained a checklist for each session with the given viewing condition (disk size and with or without goggles). The observers were instructed to take at most two sessions a day, but not back-to-back, in order to prevent fatigue. In addition, a short break about half a way through each session was suggested, also to reduce fatigue. For each observation, the software recorded a time stamp, the contrast of the disk, random seeds used for simulation of the noisy background, and the observer's selection.

In our previous C-d experiments the observers were asked to identify the smallest visible object (disk) from radiographic images of an array of similar objects, satisfying requirements with regard to the object shape and position. Images, acquired with constant kVp and mAs values varying between 2 and 100, were postprocessed in order to keep constant either the contrast of the largest disk or the variance of the background noise for images with different mAs. Analyzing the identified objects, the computed SNR values were in the range of 5 to 6, which is comparable with the Rose detection criterion.[7]

In the 2-AFC experiments reported here, the observers selected between two simulated noisy images, one of which contained a simulated object (a disk) of predefined shape and position, with the SNR of the object being set between 1 and 3 during simulation. If we have tried to match the SNR values of the simulated objects in the 2-AFC study with the previously computed SNR values from the C-d study, it would essentially give completely predictable detection of the image with the disk in a 2-AFC pair, and would not allow comparison between monoscopic and stereoscopic performance.

3. RESULTS

The observers spent on average 16.7 minutes per session (st. dev. 6.5). All sessions were completed in the course of three months (from June to September 2002). Comparison between the observer's monoscopic and stereoscopic performance has been analyzed in terms of the (i) probability of correct detection, P_{corr}, as a function of the object contrast, and (ii) the detectability, d', as a function of the image SNR. The detectability, represents a separation between two Gaussian distributions which would yield the same P_{corr} as the analyzed experiment. In the case of an ideal observer, the object visibility and detection would be determined only by the SNR, yielding a linear relationship:

$$d' = k \text{ SNR}, \tag{2}$$

There is a nonlinear relationship between P_{corr} and d' given by:

$$d' = 2 \text{ erf}^{-1}(2P_{corr} - 1). \tag{3}$$

For radiographic projection images of a disk of thickness t and radius r, the SNR is given by:[1]

$$\text{SNR} = t \; D \; K \sqrt{\text{mAs}}, \tag{4}$$

where K is a proportionality constant. From Equations 1 and 4, for constant disk size and background noise variance, the contrast and the SNR are proportional to the square root of the equivalent mAs values that would be used to produce an x-ray image with the same SNR. Assuming a linear relationship between the mAs values and the radiation dose, the dose needed to acquire a stereo image pair, X_{2S}, relative to the dose for a single radiographic projection, X_{1M}, can be computed using the following equations:

$$\frac{X_{2S}}{X_{1M}} = 2 \left(\frac{C_{0.75,S}}{C_{0.75,M}}\right)^2, \tag{5}$$

where $C_{0.75,M}$ and $C_{0.75,S}$ are the values of object contrast corresponding to $P_{corr} = 0.75$, averaged for monoscopic and stereoscopic observations, respectively, or

$$\frac{X_{2S}}{X_{1M}} = 2/\left(\frac{k_S}{k_M}\right)^2, \tag{6}$$

where k_M and k_S are the slopes of the linear fits to $d'(\text{SNR})$ averaged for monoscopic and stereoscopic observations, respectively.

The intercept value of P_{corr}=0.75 in Equation 5 has been used in previously reported studies on comparing the contrast threshold values in monoscopic and stereoscopic detection and discrimination of sinusoidal gratings.[8] P_{corr}=0.75 represents the mid-value between completely random (P_{corr}=0.5) and completely predictable (P_{corr}=1.0) selection, and corresponds approximately to a detectability of $d' = 1$ (see Equation 3). It should be noted, however, that Equation 5 would yield a different value of the dose ratio for another selection of P_{corr} intercept values. On the other hand, assuming an approximately linear relationship between d' and SNR, the dose ratio computed using Equation 6 would remain constant for any given value of d'.

3.1. Observer Performance in Terms of P_{corr}

Figure 2 (a) shows linear fits through the P_{corr} values as a function of disk contrast, computed separately for monoscopic and stereoscopic observations averaged over all the disks of the same size. The corresponding values

Table 2. Values of the ratio between the radiation dose needed for 2 images from a stereoscopic pair and the dose for a single monoscopic image, estimated from P_{Corr}(Contrast) graphs, and averaged over all experiments done by the same observer and using disks of the same size.

Observer	$D = 20$ pixels	$D = 28$ pixels	$D = 40$ pixels
1	1.39	1.33	1.33
2	0.73	1.22	1.36
3	1.20	1.37	1.46
4	1.36	1.52	2.94

Table 3. Values of the ratio between the radiation dose needed for 2 images from a stereoscopic pair and the dose for a single monoscopic image, estimated from d'(SNR) graphs, and averaged over all experiments done by the same observer and using disks of the same size.

Observer	$D = 20$ pixels	$D = 28$ pixels	$D = 40$ pixels
1	1.60	1.40	1.24
2	1.38	1.67	1.48
3	1.48	1.77	1.37
4	1.45	1.43	1.88

of the dose ratio (Equation 5) are equal to:

$$\begin{aligned} \frac{X_{2S}}{X_{1M}} &= 1.21 \quad (D = 20 \text{ pixels}), \\ \frac{X_{2S}}{X_{1M}} &= 1.37 \quad (D = 28 \text{ pixels}), \\ \frac{X_{2S}}{X_{1M}} &= 1.50 \quad (D = 40 \text{ pixels}). \end{aligned} \tag{7}$$

Dose ratios computed separately for each observer and each disk size are given in Table 2.

3.2. Observer Performance in Terms of d'

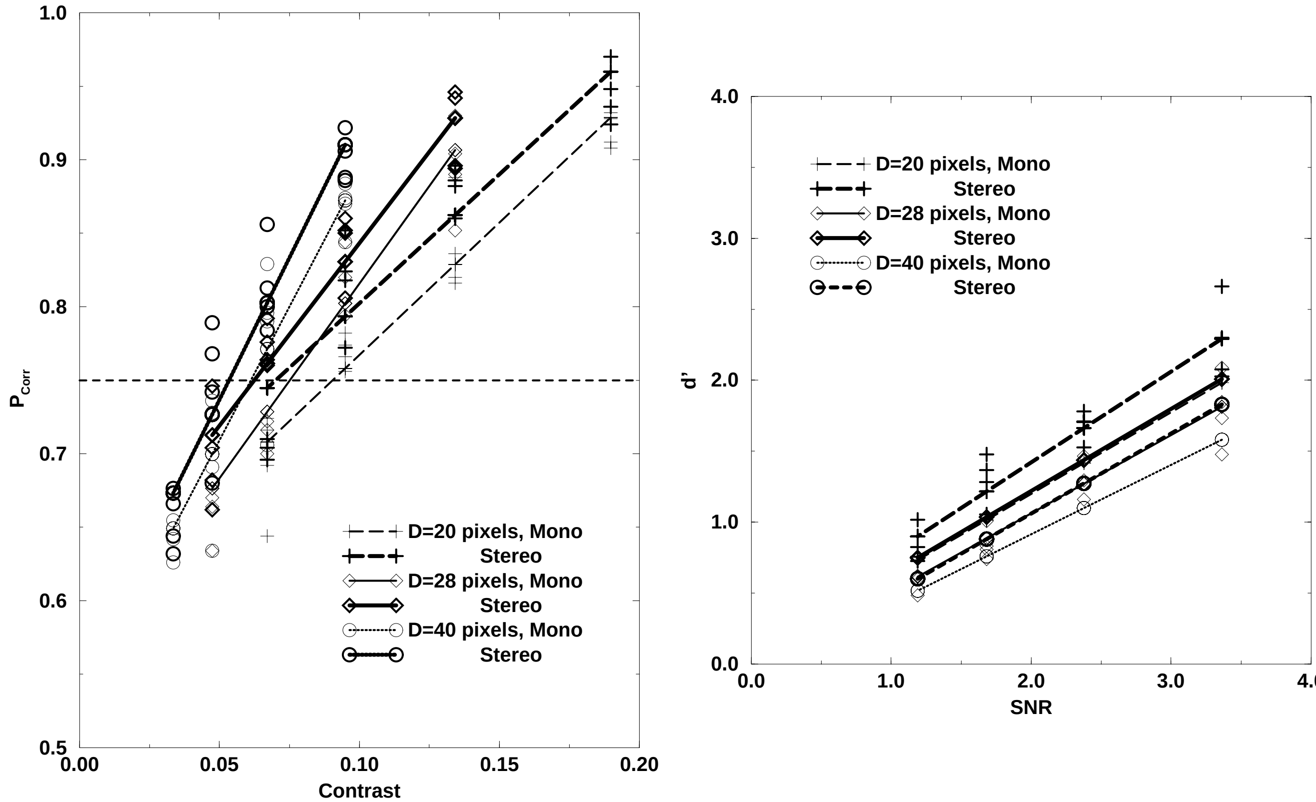
Figure 2 (b) shows linear fits constrained to pass through the origin (see Equation 2) for d' values as a function of disk SNR, computed separately for monoscopic and stereoscopic observations averaged over all the disks of the same size. The corresponding values of the dose ratio (Equation 6) are equal to:

$$\begin{aligned} \frac{X_{2S}}{X_{1M}} &= 1.47 \quad (D = 20 \text{ pixels}), \\ \frac{X_{2S}}{X_{1M}} &= 1.57 \quad (D = 28 \text{ pixels}), \\ \frac{X_{2S}}{X_{1M}} &= 1.48 \quad (D = 40 \text{ pixels}). \end{aligned} \tag{8}$$

Dose ratios computed separately for each observer and each disk size, using linear fits constrained through the origin, are given in Table 3.

4. DISCUSSION

Stereomammography presents the prospect of using the stereoscopic capabilities of the human visual system to reduce superposition effects. Traditionally, stereoradiography has been implemented by doubling the dose required for a single projection image. In part, this was due to limited dynamic range of screen–film systems.



(a) (b)

Figure 2. Graphs of (a) P_{Corr}(Contrast) and (b) d'(SNR), used for estimation of the dose ratio, by Equations 5 and 6, respectively.

With the introduction of digital devices, which have a large dynamic range, comes the oppportunity to evaluate this situation in terms of fundamental limits of detectability.

From the perspective of signal detection theory, for an ideal observer working in the context of an exactly known signal limited only by quantum noise, that ideal observer should be able to perform equally well whether one projection is acquired at a given exposure or two projections are each acquired at one–half the given exposure. Experience in many contexts has shown that human observers can use stereoscopically acquired images to great advantage and detect what would otherwise be overlooked. The experimental program discussed in this paper is aimed at determining if the advantages of stereoscopy can be achieved without either increasing dose or sacrificing the detection of objects which are at the lower limits of detectability.

The question of how well a human can combine information from both eyes when performing tasks under these limiting conditions is generally referred to by the psychophysical community as the problem of "binocular summation". The problem of binocular summation must be distinguished from the problem of "binocular fusion". As in similar experiments reported in the psychophysical literature, our experiments to date were arranged so as to faciliate fusion in order that matters of summation could be tested independently. Of course, fusion must occur before summation can take place.

To the best of our knowledge, there is no conclusive work in the literature which addresses the problem of binocular summation under the conditions of stereoradiography. One research note[9] based on one observer presented a comparison of detectability at threshold of sine-wave patterns when noise was generated independently for each eye (corresponding to the conditions of stereoradiography) with the case of the same noise pattern being presented to both eyes (corresponding to the conditions of single–projection radiography). This research note suggested that the threshold under the former conditions was reduced from that of the latter conditions by a factor of $\sqrt{2}$ over a broad range of frequencies, which would agree with the expectations of a simple signal–detection model. The conditions of this test differed from those of stereoradiography in that the detection of sinusoidal patterns differs from the detection of discrete objects.

In much of the other work in the psychophysical literature, measurements were performed under conditions not directly relavent to the comparison of single–projection and stereoscopic radiography. In particular, we have used "monoscopic" to refer to viewing a single exposure–the subject was imaged with one "eye" at the x-ray focus. The viewer, however, uses both eyes when viewing this image acquired from a single vantage point with a single x-ray focus serving as a virtual "eye". In the psychophysical literature, most comparisons involve the simultaneous viewing with both eyes and viewing with one eye while the view from the other eye has been obscured or suppressed. Nevertheless, one might still look at such work as suggesting the ability of the human visual system to use information from both eyes to suppress noise, whether that noise is internal or external, dynamic or frozen into the images. The classic work of Campbell and Green[10] found that the threshold for binocular detection of sine–wave patterns was a factor of $\sqrt{2}$ less than monocular viewing, again in agreement with a simple signal–detection model. In general, binocular viewing is found to improve detectability, but this improvement can vary, apparently depending upon the precise experimental setup and the method by which the data is analyzed.

In an earlier contrast-detail experiment, we reported evidence that binocular summation under stereoradiography conditions has an efficiency nearly that of the value suggested by signal–detection theory, and thus only a 10% increase in total exposure to the patient would be required to avoid losing details at the limit of detectability. The 2AFC experiment we report here indicates that, in order to avoid the loss of objects at the limits of detectability, the total exposure must be increased by a factor of 1.5, still less than a factor of two but a possibly significant increase in dose which would need to be weighed against the possible benefits of stereomammography. It must be noted that both of the experiments involve tasks which more or less approximate the task of a radiologist reading a mammogram, but neither task is precisely equivalent to the task of a radiologist nor are the tasks equivalent to each other. In particular, the limiting objects in the C-d experiment had signal–to–noise ratios on the order of five, as C-d phantoms are conventionally scored not by the faintest objects detectable but by the faintest objects which can be considered to have been well imaged. In the 2AFC experiment reported here, the objects used had SNRs on the order of 1–3, and were barely detectable. This might be related to the apparently greater ability of humans to discriminate between the contrast of two objects, both of which are above the threshold of detectability, than to detect objects at the limits of detectability.[11] This interpretation, however, is not completely clear. For example, Legge[8] worked on monocular and binocular tests of detection and discrimination of sinusoidal patterns and interpreted the data in terms of a threshold contrast and an exponent related to the slope of the psychometric function. Legge reports a factor of approximately 1.5 in the ratio of the monoscopic to stereoscopic threshold, but (in Figure 7 of that paper[8]) shows a ratio of d' for binocular versus monocular viewing of greater than 3, with the advantages of binocular viewing decreasing as one passes from the detection task to discrimination between patterns above the detectability threshold.

While precise quantification is difficult, our results in conjunction with the literature and reasonable expectations based on signal–detection theory strongly suggest that it is possible to perform stereomammography without doubling the dose to the patient and without sacrificing the detectability of small, faint objects. An increase of 50% in dose would not be negligible, but would need to be weighed against possible benefits. An increase of 10% would, of course, be far more acceptable. It is possible that the actual increase in dose would lie somewhere between these two figures. This can be clarified only by clinical studies or experiments which mimic clinical tasks more closely than the experiments we have performed. The experience to date suggest that these more complicated and expensive investigations might be profitably pursued. For the next step, our intention is to refine synthetic images by adding simulated anatomic noise, based upon our recently developed 3-D software breast phantom.[12]

5. CONCLUSIONS

A series of 2-AFC experiments was performed in order to reevaluate findings from a previous C-d experiment that stereomammography can be performed without doubling the radiation dose to the patient. Hypothetically, the total dose for a stereo image pair should be equal to the dose for a single conventional monoscopic projection, due to combining quantum noise from two images by the human visual system. In the 2-AFC study we have observed, on average, a ratio between the dose for a stereo image pair and the dose for a single mono projection of 1.5±0.2, compared to previously observed dose ratio of 1.1±0.1 for the C-d experiments. The main difference between the two experiments is in the range of object SNR values: 5-6, for the C-d study vs. 1-3 for the 2-AFC study. Further clarification is planned using images with simulated anatomic noise.

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