Optimization of a Contrast-Detail-Based Method for Electronic Image Display Quality Evaluation

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The authors previously reported a general technique based on contrast-detail methods to provide an overall quantitative evaluation of electronic image display quality. The figure-of-merit reflecting overall display quality is called maximum threshold contrast or MTC. In this work we have optimized the MTC technique through improvements in both the test images and the figure-of-merit computation. The test images were altered to match the average luminance with that observed for clinical computed radiographic images. The figure-of-merit calculation was altered to allow for contrast-detail data with slopes not equal to −1. Preliminary experiments also were conducted to demonstrate the response of the MTC measurements to increased noise in the displayed image. MTC measurements were obtained from five observers using the improved test images displayed with maximum monitor luminance settings of 30-, 50-, and 70-ft-Lamberts. Similar measurements were obtained from two observers using test images altered by the addition of a low level of image noise. The noise-free MTC and MTC difference measurements exhibited standard deviations of 0.77 and 1.55, respectively. This indicates good measurement precision, comparable or superior to that observed using the earlier MTC technique. No statistically significant image quality differences versus maximum monitor luminance were seen. The noise-added MTC measurements were greater than the noise-free values by an average of 4.08 pixel values, and this difference was statistically significant. This response is qualitatively correct, and is judged to indicate good sensitivity of the MTC measurement to increased noise levels.

KEY WORDS: contrast-detail experiments, electronic image display, image quality evaluation.

THROUGH THE CONTINUED use of ultrasonography, computed tomography, and magnetic resonance imaging, and the increasing use of digital radiography and picture archive and communications systems (PACS), the utilization of electronic display devices for primary diagnostic interpretation of digital images in diagnostic radiology is becoming commonplace. For all equipment involved in image acquisition or display, it is typical practice that quantitative measurements of physical parameters affecting image quality be made for the purposes of new equipment selection, acceptance testing, and quality control (QC). Electronic displays are problematic in that routine measurements of display parameters other than luminance require specialized equipment, and may be difficult to obtain especially in the field.[1,2] Also, it is helpful to obtain visual perception-based evaluation data along with physical measurements to provide a complete evaluation of imaging systems.[3] To address these considerations, we are investigating a perceptual technique based on traditional contrast-detail (CD) methods[4-6] to measure overall display quality, and have previously reported our initial results.[7] Our technique allows calculation of a single figure-of-merit dubbed Maximum Threshold Contrast (MTC), which reflects the overall display quality, including the effects of display contrast, noise, sharpness, and glare. The purpose of the current work is to optimize the design of the original MTC test pattern and the figure-of-merit in preparation for future, more extensive validation experiments. We also provide a preliminary demonstration of the assertion that the MTC metric will be sensitive to the effects of known factors such as noise, which affect the overall quality of the displayed image but which may be difficult to measure physically.

MATERIALS AND METHODS

Our test images and protocol for data collection are similar to those of traditional contrast-detail techniques,[4-6] with the incorporation of a forced-choice element to provide proof that the target actually is visualized.[8] Three test sets of 8-bit-per-pixel test images were created using a common PC paint application (PaintShop Pro, Version 4; JASC Inc, Eden Prairie, MN). Each test set consisted of eight images, each image corresponding to one of eight possible square target sizes (1, 2, 3, 4, 7, 11, 17, and 27 pixel edge lengths). In each test image, eight rows of four test areas were present. Each row corresponded to one of eight possible target contrasts. The target contrasts were 1, 2, 3, 4, 7, 11, 17, and 27, and represent the pixel value difference between the target and the background. All targets were darker than the background to enhance sensitivity to cathode ray tube (CRT) glare. Each test area presents the target in one of four randomly selected quadrants, and the test areas are defined by low-contrast

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0897-1889/99/1202-0003$10.00/0

borders. The three sets of test images were identical in overall design, but varied as to the particular quadrant location of the targets. The pixel matrix of each test image was 1,508 × 1,746, and was selected to match the video memory matrix of the workstation used to present the images to the observers (SCID 2A diagnostic workstation and PACS; General Electric Co, Mount Prospect, IL).

The test images used in our earlier experiments had uniform background pixel values equal to either 15% (pixel value = 38) or 85% (pixel value = 217) of the full video range (corresponding to a pixel range of 0 to 255). The brighter 85% patterns were judged to produce the most useful display quality measures.[7] The current test images have been optimized to approximately match the average luminance presented by a variety of computed radiographic (CR) images when displayed on our clinical PACS workstations. (Approximate clinical CR luminance levels were determined by analysis of CR display pixel values, as well as measurements of illuminance increases observed when displaying CR images.) This matching was done by dividing the background pixels into two regions consisting of target background pixels at 55% video, and a surrounding frame at 45% video. The central targets and background occupy about 40% of the full image area. This alteration in the test image design should make the quality measurements more relevant to the digital clinical radiology practice. A sample test image shown in Fig 1.

To demonstrate the sensitivity of the MTC metric to the effects of displayed image noise, we created sets of test images with known amounts of noise added to them. This approach (ie, altering the noise in the test images) is assumed to effectively model the situation where noise-free test images are used to measure MTC from a display that has increased noise, and was taken to circumvent inherent difficulties in introducing known alterations to the display monitor noise itself. Three additional test sets of images were created by adding uncorrelated Gaussian noise to the optimized test images described above. The noise standard deviation was 1% of the full 8-bit display range (or 2.55), and was chosen to approximately match the pixel standard deviation observed in clinical CR images of the hand when displayed on our PACS workstations. This value was taken as the approximate best-case (minimum) noise level commonly seen in our electronic clinical practice. Our use of a Gaussian distribution with standard deviation of a few percentage points to model monitor noise is consistent with other reports in the literature.[9,10]

A group of five observers, consisting of two medical physicists and three radiology quality control technologists, was recruited to view the noise-free test images. During a viewing session, the three image test sets were displayed, and the observer was asked to inspect each test area of each image and indicate either the quadrant in which the target was observed, or that no target was seen. A score of 1 was assigned for each correct target location indicated, 0 was assigned for each incorrect response, and 0.25 was assigned for each "no target seen" response (the average score expected from guessing).

The image test sets were viewed under three display conditions on the same workstation and CRT monitor (Megascan Model UHR4212P; Raytheon E-Systems, Billerica, MA). These display conditions corresponded to nominal maximum monitor luminance settings of 30 ± 0.5, 50 ± 0.5, and 70 ± 0.5-ft-Lamberts (ft-L), which were obtained through adjustment of the

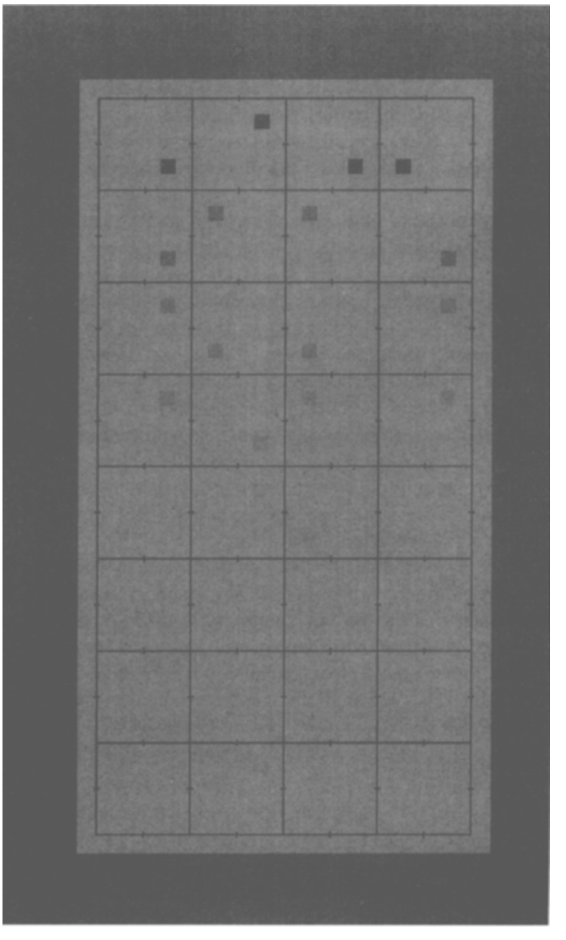

Fig 1. Sample optimized test image used for display quality evaluation. The target size (edge length) in this image is 27 pixels.

monitor brightness and contrast controls. For each luminance condition, a SMPTE test pattern was displayed, and it was verified that the 5% and 95% contrast patches were visible and that no gross image artifacts were apparent. The display was not perceptually linearized in any of the cases. Room lighting was held constant at about 5 lux, corresponding to the ambient light level found in one soft-copy reading room on our campus.[11] To characterize the luminance response of the monitor used in the experiments, display luminance was measured at 13 points between the minimum and maximum display pixel value. Luminance response was measured for all three maximum luminance conditions, before and after collection of all of the observer data. All luminance and illuminance measurements were made using a calibrated luminance head (model 265), cosine filter (model 211), and photometer (model 371; United Detector Technology, Graseby Optronics, Orlando, FL).

Threshold contrast values were determined for each image and target size. This was done by summing the scores for the four test areas in each row. Then, starting at the lowest contrast row, the row-scores were examined for the first instance in which a critical value of 2.5 was exceeded. This critical value of 2.5 corresponds to the midpoint between perfect target visualization (row-score = 4) and that obtained by guessing (average row-score = 1). Variations in this value were found not to significantly alter our results.[7] The threshold contrast was obtained via logarithmic interpolation between the target contrasts bracketing the critical value. Each test image will potentially yield a (target size, threshold contrast) ordered pair or data point, so each 8-image test set will yield a maximum of 8 data points.

The data points from each test set are graphed on a log-log (base-10) plot and are fitted to a line. In our previous work, the slope of the line was fixed at -1 (as predicted by the Rose Model[12] for the case of ideal, white noise), resulting in a best-fit y-intercept. The best-fit y-intercepts from each of the three test sets observed during the viewing session were inverse-logged, and the mean and standard deviation were computed. The mean value was used as the overall image display quality figure-of-merit, and represented the maximum threshold contrast (MTC), corresponding to observation of the smallest (1-pixel) target. MTC has the units of contrast (in our test images, the pixel value difference between the target and the background). Lower MTC values indicate superior display quality.

Contrast-detail theory[4,13] does allow for best-fit linear slopes that deviate from -1, and in this study the figure-of-merit was optimized to allow for this possibility. The data points (target size, threshold contrast) from each test set are log-transformed and fit to a line as before, but now with the slope as a free parameter. The equation for the corresponding linear-space curve of threshold contrast (C_t) versus target size (S) is

$$C_t = bS^m, \quad (1)$$

where log (b) is the best-fit intercept and m is the best-fit slope. The area (A) under this curve, between $S = 1$ and $S = S_{max}$, which is defined by the point of intersection of the curve with the line $C_t = 1$, is

$$A = b(S_{max}^{m+1} - 1)/(m + 1) \quad m \neq -1 \quad (2a)$$

$$A = b \ln (S_{max}) \quad m = -1, \quad (2b)$$

where $S_{max} = b^{-1/m}$. The area (A) is an indication of the number of possible targets defined in $C_t - S$ space that are not visualized by the display system. The b value of the equivalent "Rose display" (defined as one with a contrast-detail slope of -1) having the same value for A (ie, which would preclude or allow visualization of the same number of targets) is determined for each of the three test sets used during a viewing session. The mean of these three Rose-equivalent b values is used as the display quality figure-of-merit, and the standard deviation of this mean value also is computed. As before, this figure-of-merit parameter represents a maximum threshold contrast and thus is referred to by that name (and acronym, MTC). MTC as defined here has the desired properties of representing the overall display quality in a single parameter, and has meaningful units ("pixel value"). This method of computing MTC allows for log-log best-fit slopes not equal to -1, and should represent an unambiguous overall display quality measure as long as the measured contrast-detail curves for systems being compared do not intersect.

To investigate the sensitivity of the MTC technique to increased image noise, two observers also viewed the sets of test images containing the added noise, and MTC was computed.

RESULTS

Figure 2 shows the luminance response of the monitor, for the three maximum luminance conditions, measured before and after collection of all the observer data reported in this work. No important deviations in luminance response during the time of observer data collection are evident.

Figure 3 shows sample contrast-detail data, from which MTC is computed. These data were obtained using a 30-ft-L maximum monitor luminance, and test images with and without added 1% noise. The slopes are observed to both approximate -1.

Figure 4 shows the MTC values collected from the five observers (denoted A, B, C, D, and E) using the noise-free test images. The average uncertainty (standard deviation) of the MTC values across all three maximum luminance values and all five observers was 0.77 pixel values. The MTC differences measured between the maximum luminance pairs of 30 versus 50-ft-L, 50 versus 70-ft-L, and 30 versus 70-ft-L, averaged over all observers, were -0.10 ± 1.09, -0.30 ± 1.92, and -0.40 ± 1.64,

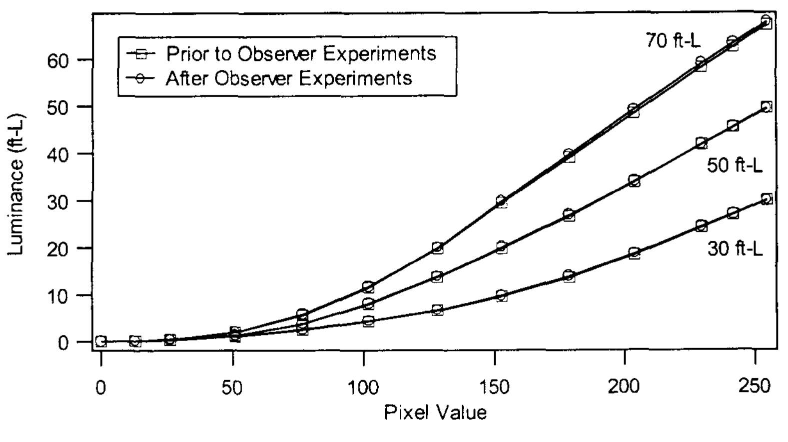

Fig 2. Luminance response data measured for the three maximum luminance conditions, both before and after collection of the observer data.

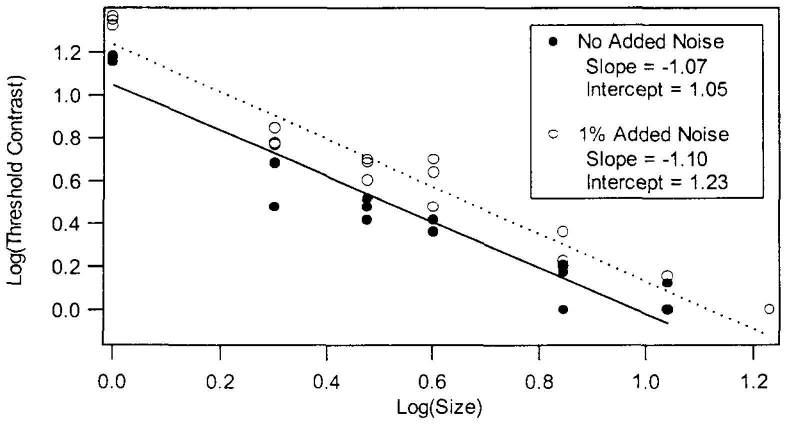

Fig 3. Sample contrast-detail data sets acquired using both noise-free test images and test images with 1% added noise. These data sets were obtained with 30-ft-L maximum monitor luminance.

respectively. The 95% confidence intervals for each of these differences include zero, so no statistically significant differences in display quality as a function of maximum display luminance are evident. The average of the three MTC difference standard deviations reported above is 1.55 pixel values.

Figure 5 shows the MTC values collected from the two observers using the noise-added test images. The uncertainty of the MTC values averaged over the three maximum luminances and the two observers was 0.85 pixel values. The MTC differences measured between the maximum luminances of 30 versus 50-ft-L, 50 versus 70-ft-L, and 30 versus 70-ft-L, averaged over the two observers, were -1.97 ± 1.01, 2.57 ± 0.97, and 0.60 ± 0.67, respectively. The 95% confidence intervals for each of these differences includes zero, so no statistically significant differences in display quality as a function of maximum display luminance are demonstrable statistically. The statistical analysis is hampered significantly by the small number of available measurements, hence the preliminary nature of these data. Subtle differences in display quality as a function of maximum display luminance are suggested, as compared to the analogous results for the noise-free case discussed earlier. No MTC difference exceeds 2.6 pixel values. The average of the three MTC difference standard deviations reported above is 0.89 pixel values.

For the two observers (A and B) who viewed both the noise-free and noise-added images, the differences in measured MTC between these two situations were computed for each maximum luminance value. The MTC differences measured between the noise-added and noise-free test image sets for maximum luminances of 30-, 50-, and 70-ft-L were 3.94 ± 1.37, 5.17 ± 1.70, and 3.13 ± 1.57, respectively. As above, the 95% confidence intervals for each of these individual differences include zero, so no statistically significant differences in display quality are demonstrable statistically. Again, the statistical analysis is hampered significantly by the small number of observers ($n = 2$). It is interesting to note that in all three comparisons, the noise-added measurement pro-

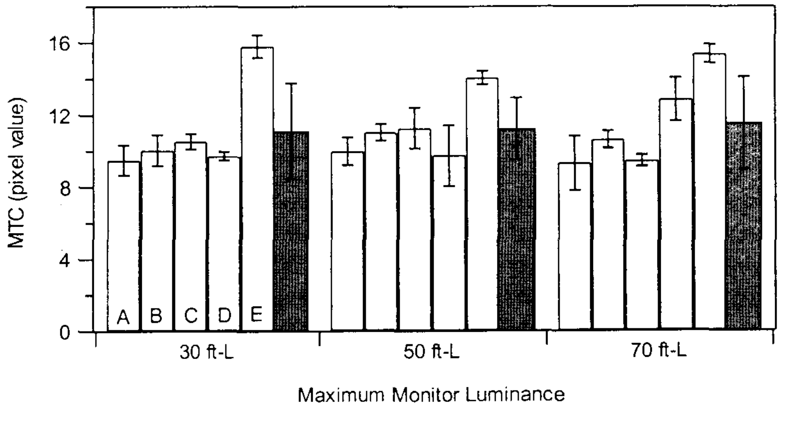

Fig 4. MTC data collected using the noise-free test images for maximum monitor luminance values of 30-, 50-, and 70-ft-L. The white bars correspond to measurements from the five individual observers (A-E). The shaded bars represent the average MTC values. The error bars represent ±1 standard deviation.

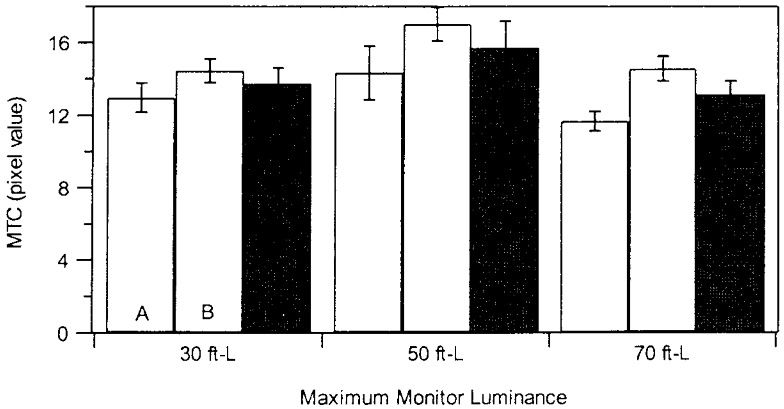

Fig 5. MTC data collected using the test image sets containing added 1% noise, for maximum monitor luminance values of 30-, 50-, and 70-ft-L. The white bars correspond to measurements from the two individual observers (A and B). The shaded bars represent the average MTC values. The error bars represent ±1 standard deviation.

duced a larger MTC value than the corresponding noise-free measurement. The average of the MTC differences across the three maximum luminance values is 4.08 pixel values, and the average of the three MTC difference standard deviations is 1.55 pixel values. This average MTC difference is found to be significantly different from zero at the 95% level ($n = 3$).

DISCUSSION

Comparing the results of the optimized MTC method with those of our initial work,[7] it is found that the absolute MTC values fall between those previously measured with the 15% and 85% background test images. This is to be expected because of the midrange average background pixel value in the new test images. The standard deviations of the optimized MTC measurements are less than 1 pixel value, and the standard deviations of the optimized MTC difference measurements are less than a pixel value of about 1.5, indicating very good absolute measurement precision. The absolute precision of the optimized MTC and MTC difference measurements is comparable to or better than the corresponding measurement precision seen in the earlier 85% background studies. The time required for image review using the new test images was found to range from 25 to 35 minutes, depending on the individual observer. These times are similar to those measured in the earlier 85% background studies. They are believed to be compatible with application of the MTC method for routine monitor QC, and certainly are short enough for other applications such as new equipment selection and acceptance testing.

The MTC measurements obtained with the noise-added test images are all larger than the noise-free measurements obtained with the same maximum monitor luminance. This behavior also is suggested by Fig 3. The MTC difference averaged across the three maximum luminance conditions was found to be statistically significant at the 95% level. This is the correct qualitative result, because larger MTC values indicate poorer display performance, and poorer display performance is expected in response to increased image noise levels. The average MTC increase caused by the added noise is 40% (an increase of 4.08 pixel values over an average MTC value of 10.08 measured by observers A and B using the noise-free images). The observers also noted that it was difficult to determine with confidence whether a noise-added or noise-free image was being viewed on the display. This large measurement change (40%) in response to the presence of a subtle amount of added noise indicates good sensitivity to this important determinant of overall image quality. This directly illustrates the utility of the MTC method for quantitatively evaluating the effects of noise, which previously have been difficult to measure in the field.

The MTC measurements obtained using the noise-free test images display no dependence on maximum monitor luminance value. MTC measurements obtained using the noise-added images do exhibit subtle variation with respect to maximum luminance; however, these differences were not statistically significant. This invariance with respect to maximum luminance is in agreement with our earlier results,[7] but counter to conventional expectations. These results may indicate that other factors that can effect low-contrast detectability using CRT displays (eg, noise, blur, and glare) are involved. A similar result has been reported in a recent study using traditional contrast-detail analysis to compare electronic and hard-copy display systems.[14]

It may be argued that test images containing a clinically relevant level of noise should be used to make the technique less sensitive to monitor noise variations that may be lower than the noise levels expected in practice when viewing clinical images. This approach would be consistent with most previously reported contrast-detail work in which the test images were acquired using image acquisition devices and clinically relevant exposure factors, and thus included a clinically relevant level of noise (for examples, see references 4-6, 8, and 14). The MTC measurements also systematically increased with added noise, thus improving the relative measurement precision. It was further observed that the average number of contrast-detail data points increased with the addition of the noise, from 5.7 to 6.7. All these factors imply that the MTC technique may be further optimized by routinely using test images containing a low level of added noise. This requires further study and assessment.

One factor that must be considered when comparing display configurations is the perceptual response of the display in terms of just noticeable differences (JNDs). Barten's model describes the perceptual response of the human visual system (HVS) to changes in luminance, and has been used in formulating the American College of Radiology (ACR) Display Function Standard.[15] This HVS model was applied to the luminance response curves for the 30-, 50-, and 70-ft-L cases shown in Fig 2 to generate the response function in terms of JNDs versus pixel value. These functions were differentiated with respect to pixel value, resulting in the curves shown in Fig 6. These graphs plot JND/pixel value versus pixel value. The quantity JND/pixel value is interpreted as the "perceived contrast" of the display in the sense that it indicates, as a function of pixel value, the number of perceptual JNDs generated for each incremental increase in pixel value. The greater the magnitude of JND/pixel value, the greater the ability of a human observer to perceive a unit change in pixel value. Also shown in Fig 6 is the range of pixel values represented by the targets and background values in the test images (with the background value occupying the upper end of this range). Figure 6 shows that there are differences in perceived contrast of the test images as a function of maximum pixel value. The 50- and 70-ft-L cases are similar in the test image region, whereas the 30-ft-L case exhibits inferior characteristics, especially at the lower end of the test image range. The 50- and 70-ft-L curves also vary over the test image range, whereas the 30-ft-L curve is relatively constant. All three curves generate at least one JND/pixel value increment except at the very high end of the display ranges.

If differences in perceived contrast were normalized out of the data presented in Figs 4 and 5 by plotting contrast measured in units of JND rather than pixel value, the 30-ft-L performance would be expected to improve relative to that of the 50- and 70-ft-L cases. Deriving MTC from such normalized contrast-detail data would tend to mask practical differences that exist between displays. Even if the monitor luminance response functions for the three maximum luminance cases were each perceptually linearized[15] (an option not available on our workstation model), each JND/pixel value function would be a horizontal line with zero slope, but differences in perceived contrast (ie, as reflected by

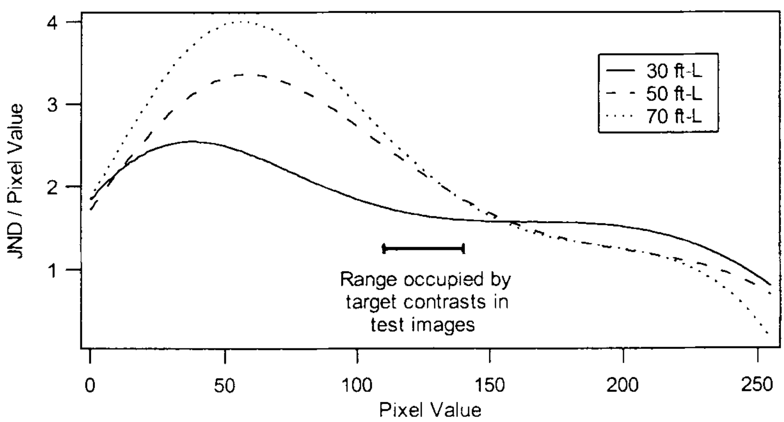

Fig 6. Graphs of JND/pixel value versus pixel value for the three maximum luminance conditions. These functions indicate the expected incremental JNDs produced by the display per unit increment in display pixel value. These functions were computed from the "Prior" luminance response data in Fig 2 by first fitting the luminance response data to a function of the form: $\log_e(y) = A + Bx + Cx^2 + Dx^3 + Ex^4 + Fx^5$, where y = luminance and x = pixel value.

the intercept of the line) would still exist. These differences would affect detail perception in the reading room. MTC measurements derived from contrast-detail data, as shown in Figs 4 and 5 (with contrast measured in pixel values), more accurately reflect the practical display situation.

Several limitations of the current MTC methodology should be noted. The test images used are similar in nature to those employed in traditional contrast-detail experiments, in that targets are presented that have different combinations of contrast and size. Traditional test patterns usually present the targets in a matrix with variations in size occurring along one axis, and variations in contrast occurring along the orthogonal axis.[4-6,14] This design offers the viewer a significant opportunity to include this a priori information regarding the pattern design in his or her assessment of whether a particular target can be visualized. Our test image sets have a similar organization in that each image contains targets of a single size, and each row contains targets of a single contrast. However, we also employ a design similar that used by Krupinski et al,[8] which divides each test region into four quadrants, only one of which (randomly determined) contains the target. The fact that observers had to "prove" that targets actually were visualized by identifying the correct quadrant should provide advantages over traditional methods, even though our target presentation is not entirely randomized. Our targets were square, unlike the circular targets most commonly seen in the contrast-detail literature. This was done as a matter of convenience because square targets of various sizes are much easier to define in a digital image. It has been shown that square and circular targets provide comparable results.[16]

A second limitation of the particular implementation of the MTC method reported in this work relates to the fact that we have chosen a particular display range (ie, our test images had 55% video backgrounds with a 45% surround) and spatial location (ie, our test targets appear in a centrally located rectangle occupying approximately 40% of the full image area) in which to present our test targets. As discussed above and shown in Fig 6, the contrast performance in terms of JND/pixel value may vary throughout the pixel value range, especially in displays that have not been perceptually linearized. Similarly, it is well known that the blur of CRT displays, as well as luminance response, can vary considerably with spatial location in the displayed image. Our test images were designed with the goal of providing a single, overall measure of display image quality that could be obtained in a reasonable period ($\sim$1 hour). To that end, we presented our targets over a spatial display region, and in a display video range that was commonly utilized in the electronic reading room. MTC measurements obtained in this manner should allow valid comparison of the overall quality of different display systems or configurations, as long as test images with the same design are used to gather data from both systems. These MTC measurements also may be used in conjunction with measurements of other parameters (eg, luminance) obtained as functions of video level and display position, to provide a more complete evaluation of display image quality. Alternatively, test images could be designed specifically to investigate variations in display video level or spatial location using the MTC approach, but at a possibly substantial increased measurement time.

It was noted in the Methods section that the possibility exists for contrast-detail data to exhibit slopes different from -1. Variations in slope are caused by deviations of the image noise from ideal white noise (for which a slope of -1 is expected).[4,13] One common example is correlated CT image noise, which is expected to exhibit a contrast-detail slope of $-3/2$. All slopes observed in the current work were found to be approximately the same, and roughly equal to -1 (for example, see Fig 3). The fact that the slopes are similar in the 30-, 50-, and 70-ft-L cases is not surprising because the same monitor (including electron gun, beam-focusing sub system, and phosphor) were used in all cases. (Also, the noise added to some of the test images in our experiment was not correlated spatially.) These factors should primarily affect the noise correlation in the displayed image. When the MTC method is used to compare overall quality of different monitors, the possibility exists that the noise correlation and contrast-detail slopes will be different. This in turn allows for the possibility that the contrast-detail curves may intersect. In this situation, the MTC overall quality metric should be used with caution as each display will be superior for observing targets in a certain size (or contrast) range.

CONCLUSION

The MTC method for overall display quality measurement has been optimized through improvements to the test images and the formula for computing the overall quality figure-of-merit, MTC. Use of the 55% background/45% surround test image, with average luminance approximately matched to that observed with clinical CR images, should make the MTC measurement more relevant to our electronic clinical practice, as compared to the 15% and 85% background patterns used in our previous work. The new MTC calculation makes the technique more versatile in that displays having contrast-detail curves with slopes different from -1 are accommodated. The new MTC measurements also have better absolute precision. Further improvements to the method may be realized through the routine use of test images with a small amount of added noise, although this requires further study. The MTC technique also exhibits good sensitivity to the presence of increased noise in the display image.

REFERENCES

1. Senol E, Muka E: Spatial-frequency characteristics of CRT soft-copy displays, in Kim Y (ed): Medical Imaging 1995: Image Display. Proc SPIE 2431:302-315, 1995

2. Weibrecht M, Spekowius G, Quadfleig P, et al: Image quality assessment of monochrome monitors for medical soft copy display, in Kim Y (ed): Medical Imaging 1997: Image Display. Proc SPIE 3031:232-244, 1997

3. Launders JH, Kengyelics SM, Cowen AR: A comprehensive physical image quality evaluation of a selenium based digital x-ray imaging system for thorax radiography. Med Phys 25:986-997, 1998

4. Cohen G, DiBianca FA: The use of contrast-detail-dose evaluation of image quality in a computed tomographic scanner. J Comput Assist Tomogr 3:189-195, 1979

5. Constable RT, Henkelman RM: Contrast, resolution and detectability in MR imaging. J Comput Assist Tomogr 15:297-303, 1991

6. Dobbins JT, Rice JJ, Beam CA, et al: Threshold perception performance with computed and screen-film radiography: Implications for chest radiography. Radiology 183:179-187, 1992

7. Hangiandreou NJ, Fetterly KA, Bernatz SN, et al: Quantitative evaluation of overall electronic display quality. J Digit Imaging 11:180-186, 1998 (suppl 1)

8. Krupinski EA, Roehrig H, Yu T: Observer performance comparison of digital radiographic systems for stereotactic breast needle biopsy. Acta Radiol 2:116-122, 1995

9. Mertelmeier T, Kocher TE: Monitor simulations for the optimization of medical soft copies, in Kim Y (ed): Medical Imaging 1996: Image Display. Proc SPIE 2707:322-333, 1996

10. Muka E, Mertelmeier T, Slone RM, et al: Impact of phosphor luminance noise on the specification of high-resolution CRT displays for medical imaging, in Kim Y (ed): Medical Imaging 1997: Image Display. Proc SPIE 3031:210-221, 1997

11. Hangiandreou NJ, King BF, Swensen AR, et al: Picture archive and communication system implementation in a community medicine practice. J Digit Imaging 10:36-37, 1997 (suppl 1)

12. Rose A: The sensitivity performance of the human eye on an absolute scale. J Soc Opt Am 38:196-208, 1948

13. Wagner RF, Brown DG: Unified SNR analysis of medical imaging systems. Phys Med Biol 30:489-518, 1985

14. Cook LT, Cox GG, Insana MF, et al: Comparison of a cathode-ray-tube and film for display of medical images. Med Phys 25:1132-1138, 1998

15. Blume H, Members of the ACR/NEMA Working Group XI: The ACR/NEMA proposal for a gray-scale display function standard, in Kim Y (ed): Medical Imaging 1996: Image Display. Proc SPIE 2707:344-360, 1996

16. Cohen G, McDaniel DL, Wagner LK: Analysis of variations in contrast-detail experiments. Med Phys 11:469-473, 1984