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Defective Pixels in Medical LCD Displays: Problem Analysis and Fundamental Solution

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Over the past few years, traditional CRT displays have gradually been replaced by active matrix LCD displays. Each pixel in an LCD display has its own individual transistor that controls the transmittance of that pixel. Occasionally, these individual transistors will short or malfunction, resulting in a defective pixel that always shows the same brightness. This article shows how defective LCD pixels can interfere with subtle features in medical images. A defective pixel affects a broad area around it therefore possibly reducing the quality of diagnosis specifically for highly demanding applications such as mammography. A specialized image processing algorithm provides an innovative solution making these defects completely invisible and recovers information from the defect so the radiologist perceives the medical image correctly.

KEY WORDS: Medical imaging, LCD, defective pixels, mammography, human visual system

INTRODUCTION

Active matrix LCD displays have replaced traditional CRT displays over the past few years. In these types of displays, each pixel has its own individual transistor that controls the transmittance of that pixel (Fig 1). Occasionally, these individual transistors will short or otherwise malfunction, resulting in a defective pixel.[1] These transistor defects are a deficiency of the production process, therefore the number of defects is fixed at production time and does not increase over time (except for situations such as dropping or putting extreme pressure on the panel). Two phenomena characterize a defective LCD pixel: a "lit" pixel appearing as one or several randomly placed red, blue, and/or green pixel elements on an all-black background; or a "missing" or "dead" pixel, which appears as a black dot on all-white backgrounds. With the ever-increasing resolution of displays the number of defect pixels per display increases accordingly. State-of-the-art processes are capable of producing displays with no more than one faulty transistor part per 3 million. Fixing the transistor itself after assembly is usually not technically possible or economically infeasible. Some specific (often low-resolution) panels provide the possibility of disconnecting a defective transistor from an LCD cell and reconnecting this cell to transistors or capacitors of neighboring cells by means of a selective wire-melting process.[2,3] Although this method reduces the visual impact of defective pixels, it also locally reduces the resolution of the LCD panel. Moreover, this type of technology is currently not available for the high-resolution LCD panels typically used in medical imaging.

In applications such as medical imaging, the defect ratio could cause problems. A 5-Megapixel LCD panel for instance contains 15 million individual subpixels (3 subpixels per pixel) each with an individual driving transistor. This means that a 5-Megapixel display on average would have around 5 failing pixels. These "lit" pixels are extremely visible and often very annoying for the user of the display. A corrective measures exists for "killing" a defective transistor using a laser;[4,5] however, this is not really a solution as it only transforms a "lit" pixel into a less visible "dead" pixel. For some

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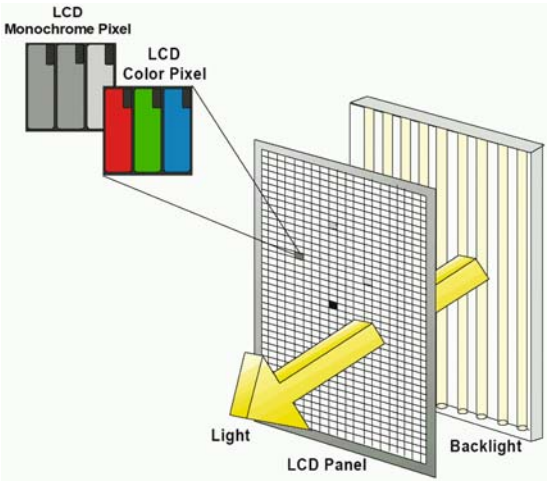

Fig 1. Working principle of transmissive active matrix LCDs.

applications such as medical imaging, all "lit" pixels therefore are often transformed into "dead" pixels using this laser technique.

A first goal of this work is to determine whether or not defective pixels can actually have any clinical relevance. This paper analyzes whether or not a defective pixel can influence the visibility of subtle clinical features. From the best of our knowledge, these questions have never been answered.

As a second contribution, this article describes an innovative solution for the defective pixel problem. By using a pixel-data-processing algorithm based on characteristics of the human vision system, we are able to visually mask "missing" pixels. Although this method cannot repair the pixel defects itself, it makes "dead" pixels (almost) invisible, and recovers the information of the defect so that the radiologist perceives the medical image correctly.

MATERIAL AND METHODS

To model the effect of defective display pixels, we use mammogram images containing microcalcifications. Pairs of images are created where the only difference between these intrapair images is the presence or absence of a defective pixel. As defective pixels are fixed at production time of the LCD, we cannot control their existence or location and therefore we simulate defective pixels by inserting completely black pixels in the mammogram images. This approach results in the exact same visual effect, because a true "dead" display pixel is always in the black state. To analyze the actual visibility of these defects for the human observer, we use JNDmetrix[6] to generate a JND map. This JND map describes the perceptual difference for a human observer between the pairs of images and therefore the perceptual effect of defective pixels because this was the only difference between the intrapair images. We simulated a 5-Megapixel grayscale display with a luminance f 500 cd/m^2. The viewing distance was set to 50 cm and the room ambient light level was set to 1.0 cd/m^2, the display was calibrated to the DICOM standard.

Figure 2 shows an example of a mammogram that was used in this study. The mammogram contains a cluster of calcifications with subtle spiculation and also isolated calcification in innocuous background as marked in the image. Figure 3 shows a detailed area of an example pair of images that was used as input for JNDmetrix. Note that the only difference between the images is the presence of a defective pixel near to the cluster of calcifications.

The second goal of this work is to provide a fundamental solution for the problem of defective pixels in medical LCD displays. This innovative solution is based on characteristics of the human visual system. The optical system of the human eye comprises three main components: the cornea, the iris, and the lens. The cornea is the transparent outer surface of the eye. The pupil limits the amount of light that reaches the retina and it

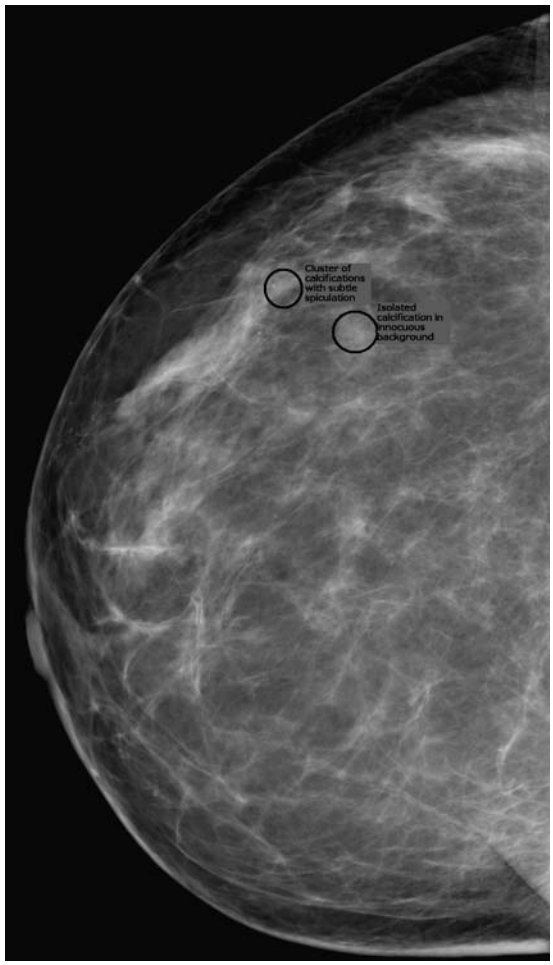

Fig 2. Example mammogram image.

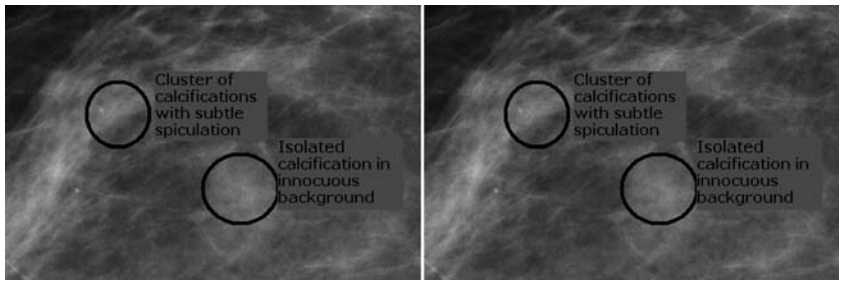

Fig 3. Example pair of images used as input for JND analysis.

changes the numerical aperture of the optical system of the eye. By applying tension to the lens, the eye is able to focus on both nearby and faraway objects. Figure 4 shows a schematic overview of the human eye.

The optical system of the eye is very complex but the process of image formation can be simplified by using a "black-box" approach. The behavior of the black box can be described by the complex pupil function:[7] $P(x,y) \cdot \exp[-i(2\Pi / \lambda) \cdot W(x,y)]$. In this formula, i stands for $\sqrt{-1}$ and λ is the wavelength of the light. The pupil function consists of two parts: the amplitude component $P(x,y)$, which defines the shape, size, and transmission of the black box, and the wave aberration[8] $W(x,y)$, which defines how the phase of the light has changed after passing through the black box.

Once the nature of the light that passed through the black box (in this case the eye) is known, the image formation process can be described by the point spread function (PSF). The PSF describes the image of a point source formed by the black box. Most lenses, including the human lens, are not perfect optical systems. As a result the visual stimuli passed through the cornea and lens undergo a certain degree of degradation or distortion. This degradation or distortion can be represented by projecting an exceedingly small dot of light, a point, through a lens. The image of this point will not be the same as the original because the lens will introduce a small amount of blur. The PSF of the eye can be calculated using the

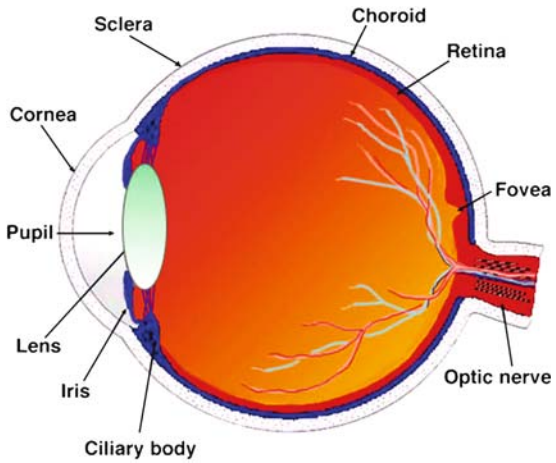

Fig 4. Schematic structure of the human eye.

Fraunhofer approximation: $\mathrm{PSF}(x',y') = K \cdot \left|\mathrm{FT}\{P(x,y) \cdot \exp[-i(2\Pi / \lambda)W(x,y)]\}\right|^2$, where FT stands for the two-dimensional Fourier transform, usually denoted as $F(x',y') = \mathrm{FT}\{f(x,y)\}$, and K is a constant. The $|\ |$ represents the modulus operator. In case of the human eye, the PSF describes the image of a point source on the retina. Figure 5 shows some examples of typical PSF for small pupil size (1 mm) and for multiple degrees of defocus of the eye. The right-hand side of Figure 5 shows another example of a measured PSF of a human eye this time in an older subject with more aberrations. This last example shows that very often the PSF is not point-symmetric and therefore difficult to model analytically.

Based on the PSF of the optical system, the response or expected response of the eye to a defective pixel can be mathematically described. Therefore the defective pixel is treated as a point source with an "error luminance" value dependent on the defect itself and the image data that should be displayed at the defect location at that time. For instance, if the defective pixel is driven to have luminance value 23 but due to the defect it outputs luminance value 3, then this defect is treated as a point source with error luminance value −20. It should be noted that this error luminance value can have both a positive and a negative value. Suppose that sometime later, this same defective pixel is driven to show luminance value 1 but due to the defect it still shows luminance value 3, then this same defective pixel will be treated as a point source with error luminance value +2.

As described above, this point source with a specific error luminance value will result in a response of the eye as described by the PSF. Figure 6 shows an example of the image projected onto the retina of 3 × 3 equally driven LCD pixels. The sizes of these projections of LCD pixels depend on the LCD pixel size and the observer distance. Because this eye response is not a single point, it is possible to use pixels and/or subpixels in the neighborhood of the defective pixel to provide image improvement. These neighboring pixels, called masking pixels, can be driven in such a way as to minimize the response of the eye to the defective pixel. This is achieved by changing the drive signal of the masking pixels such that the superposition of the image of the masking pixels and the image of the defective pixel results in a lower or minimal response of the human eye. In other words, if there was no defective pixel then a certain image would be projected onto the retina of the eye. In a situation where defective pixels are introduced, the masking pixels are driven in such a way that the projection onto the retina resembles that certain image without defects as closely as possible. Note that the image projected onto the

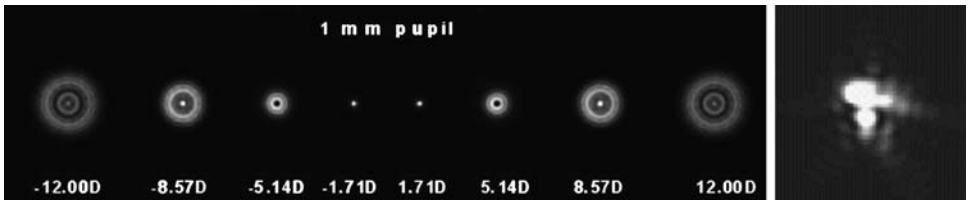

Fig 5. Examples of some typical PSF of normal human eye (left) and eye with aberrations (right).

retina is a superposition of the individual projections of the individual LCD pixels. Although we cannot change the projection of the defective pixel itself, we can change the projection of the masking pixels and therefore influence the projected image. For this article, we used 3×3 and 5×5 masking pixels to evaluate the performance of our algorithm. The defect pixel is located in the center of this area and the 24 pixels around the defect are used to mask it. To evaluate the visual performance of our algorithms, we always drive the defect pixel with value zero (completely off) and use the masking pixels to make this defect invisible.

RESULTS

Figure 7 shows a JND map describing how a defective pixel is actually perceived by the human observer. The JND map (left-hand side) corresponds pixelwise to the original image (right-hand side). A very important and rather unexpected conclusion from the JND map is that the defective pixel has a significant effect on a very broad area around the defect. In an 11 × 11 LCD pixel area around the defective pixel the perception of the display image is clearly influenced by the defect. In this area, the JND analysis suggests that the effect is clearly perceivable by the human observer. In a broader area of up to 32×32 LCD pixels, the defective pixel influences image perception; however, in this case, the JND values are smaller and will require a more trained observer to see the difference.

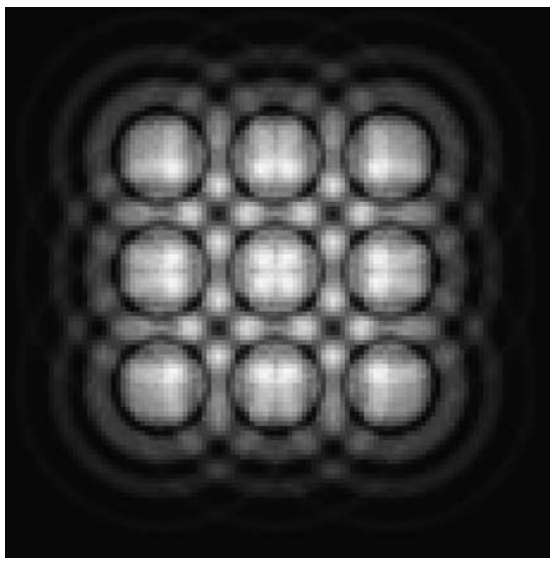

Fig 6. Image of 3×3 LCD pixels as projected onto the retina of the eye.

These results have important consequences. The generally accepted idea until now was that defective pixels are not that harmful because it is very unlikely that a clinically relevant feature coincides exactly with the defective pixel. However, the results presented here suggest that each defective pixel has significant impact on at least 121 (11×11) LCD pixels in the area around the defect. An average of 5 defective pixels would therefore result in over 600 LCD pixels that are perceived incorrectly by the human observer. In an even broader 32×32 LCD pixel area around a defect, the JND differences exceed 1 JND, influencing the perception of those LCD pixels to a lesser extent. Therefore, more than 5,000 LCD pixels show changed perception because of a relatively small number of defective pixels. Although the present results do not prove that the changed perception of the area around a defective pixel can actually change the outcome of clinical diagnosis, it would not be wise to ignore this possibility. Especially in mammography, radiologists look for subtle features of often only a few pixels in size. These types of tasks are very sensitive to even small changes in image perception. Further research is required to actually determine the possible effect of defective pixels on reliability of clinical diagnosis.

There are several underlying reasons why a defective pixel influences such a wide area around the defect. A first obvious reason is that the im-

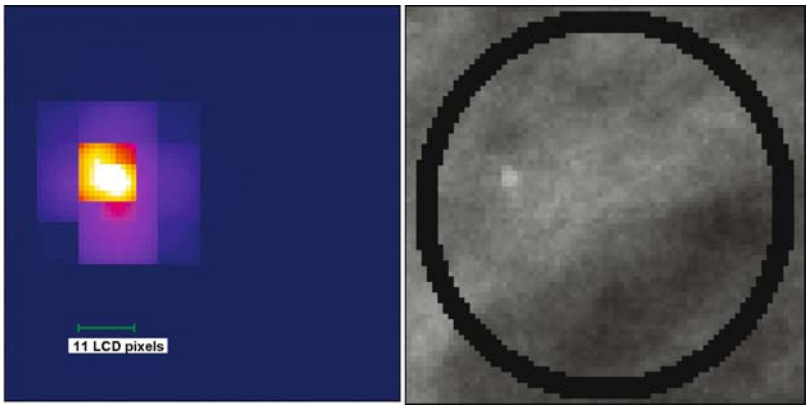

Fig 7. JND map describing the perceived effect of a defective pixel (left) and the pixelwise corresponding original image.

ages of neighboring LCD pixels projected onto the retina overlap. Therefore, a defective pixel will influence the perception of neighboring LCD pixels because the image on the retina of those pixels will also show decreased luminance value. However, this effect can only explain the changed perception of pixels at a limited distance of the defect. A second and more important reason is to be found in the preprocessing in the eye itself. The signals resulting from light falling on the photoreceptors of the eye are not sent directly to the brain, but are instead first processed in a number of ways by a variety of interactions among neurons within the retina. Each output neuron receives excitatory input from an overlying photoreceptor as well as inhibitory input from adjacent photoreceptors. It is this laterally spread inhibition that gives "lateral inhibition" networks their name. Because of this lateral inhibition,[9] the strong signal resulting from the defective pixel can influence several neurons in a broad area around the central location of the defect.

The observation that a defective pixel influences the perception of other pixels in a broad area around the defect also suggests that it is possible to use those neighboring pixels to influence the perception of the defect itself and therefore to compensate for the defect. To evaluate the performance of the described correction algorithm, we performed a JND analysis. Figure 8 shows the results when a defective pixel on a uniform gray background of video level 128 was studied both with and without our compensation applied. In this figure, each square represents an LCD pixel and the luminance of the square indicates how large the perceived difference for that particular pixel will be compared to a defect-free situation. The left-hand side shows the perceived effect of the uncompensated defective pixel, whereas the right-hand side shows the same defect but with our compensation algorithm applied. In this situation, we used a 5×5 LCD pixel neighborhood to compensate for the defective pixel. The left and right JND map have the same scale (both in dimensions and gray levels) so they can be directly compared to each other. It is obvious from the results that the correction algorithm was able to significantly reduce the area influenced by the defect and also clearly reduce its visibility. The largest remaining perceivable differences are located exactly on the defective pixel itself. Also note that the compensation pixels themselves do not introduce any artifacts of their own. These simulations were done for a 5-Megapixel display, 500 cd/m^2 luminance, and 1 cd/m^2 room ambient light.

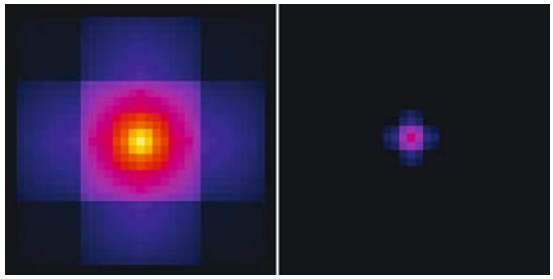

Fig 8. JND map of a defective pixel in uniform background (left) and the same defect with compensation applied (right).

As an example, Figure 9 shows the correction values that were applied to the pixels in the neighborhood of the defective pixel. The defective pixel is shown in the center and it is not possible to change the luminance value of this pixel. The other correction values represent the relative correction that is required for each individual pixel. For example, the neighboring pixel left of the defective pixel requires a correction factor of 0.4846 – meaning that the luminance of that pixel should be increased by 48.46% (relative to the original luminance error that was introduced by the defective pixel) to compensate for the defective pixel. The neighboring pixel upper left of the defective pixel requires a correction value of −0.252, meaning that its luminance output should be decreased by 25.2% to compensate for the defective pixel.

Another more direct method to evaluate the performance of our correction algorithm is to analyze the image as projected onto the retina of the eye by means of the PSF. Figure 10 shows this projected image for a number of viewing distances both with and without correction applied. In this case, a correction of only a neighborhood of 3×3 LCD pixels was used. Observations showed increasing the distance between the user and display also increased the area or number of pixels impacted by a defective pixel. This can be explained intuitively; as the distance between user and display increases, the separation between individual display pixels perceived by the eye decreases. In other words, by increasing the viewing distance a larger number of pixels are mapped to the same unit area on the retina as compared to a shorter viewing distance. A second observation is that for all viewing distances the correction is able to significantly reduce the luminance distortion due the defective pixel. The scale of the vertical axis represents the relative error luminance due to the defective pixel compared to the maximum error luminance value in the uncorrected situation. For example, in the case of viewing distance 40 cm, the correction algorithm is able to reduce the maximum remaining error luminance due to the defective pixel to about 15% compared to the uncorrected situation. Note that enlarging the correction kernel to 5×5 LCD pixels or even 7×7 LCD pixels will further increase the performance of the correction algorithm.

In addition to the mathematical performance analysis, a limited user test was done. Sample images where displayed on a 5-Megapixel monochrome medical display. Users were asked whether or not defective pixels were visible, and then asked to point these defects out. The viewing distance was 50 cm in this experiment. The sample images included a uniform background of different video levels and also a number of medical images such as mammograms and chest images. In each of the images a pixel was set to value zero, to simulate a defective pixel. On half of the images our correction algorithm was performed. Preliminary results of the user test indicate that defective pixels are more visible in areas with uniform backgrounds. In such situations, almost everyone was able to locate the defects. When our correction algorithm was applied, majority of the subjects were unable to locate the defective pixels. Those viewers that could still locate the defects required significantly longer time to find the defective pixels. A more extensive user test is required, and will be done in the future.

DISCUSSION

Until now, the generally accepted idea was that negative effects of defective pixels can be ignored

-0,041	0,0892	-0,1719	0,0892	-0,041
0,0892	-0,252	0,4846	-0,252	0,0892
-0,1719	0,4846	-1	0,4846	-0,1719
0,0892	-0,252	0,4846	-0,252	0,0892
-0,041	0,0892	-0,1719	0,0892	-0,041

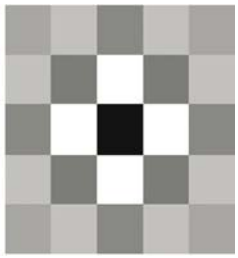

Fig 9. Example of required correction values for a 5×5 neighborhood around a defective pixel.

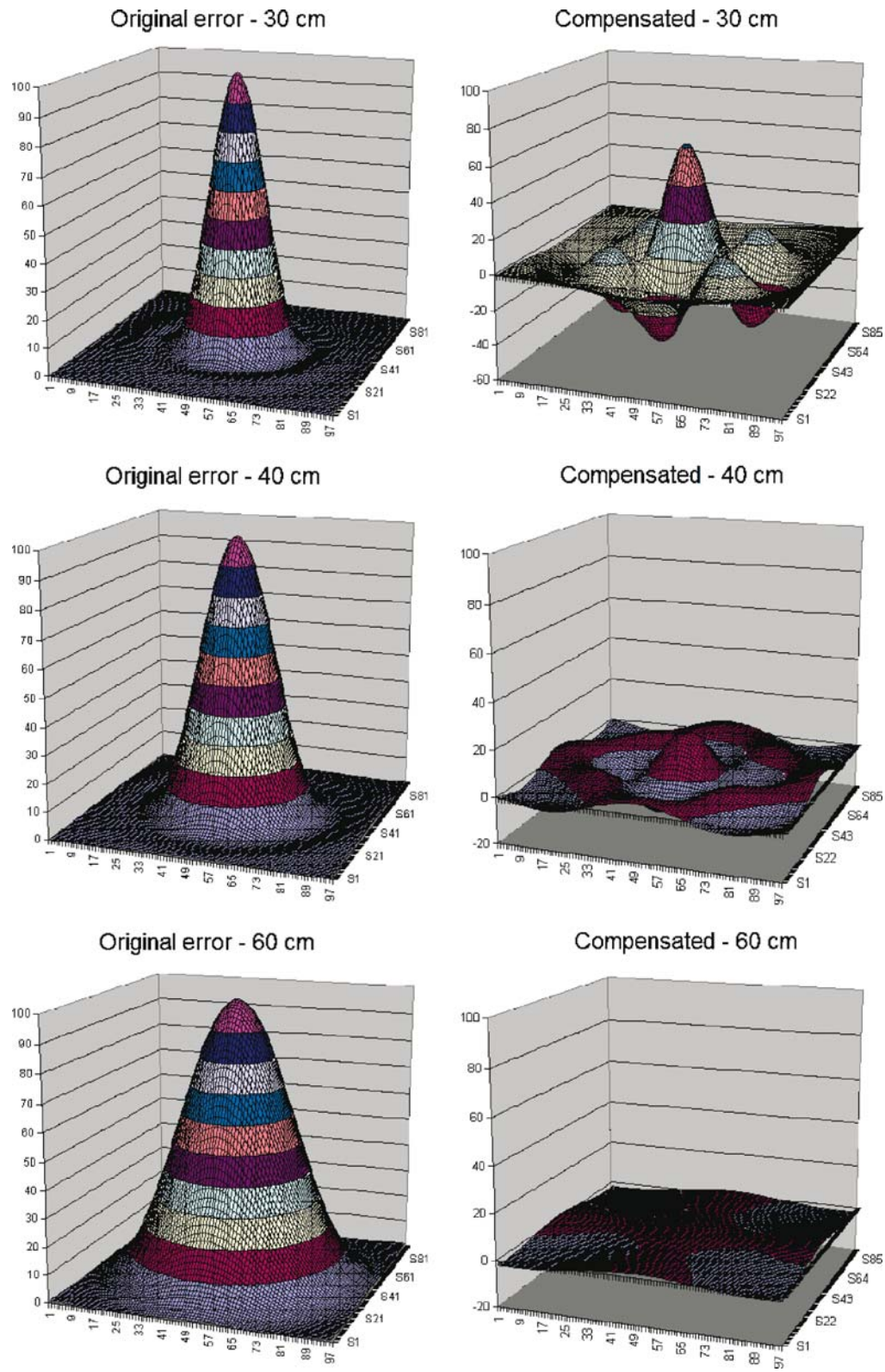

Fig 10. Image projected onto the retina of the eye with and without correction applied and this for multiple viewing distances.

or at least minimized because of the low probability that a clinically relevant feature coincides exactly with a defective pixel. This work, however, shows that the defective pixel influences the image perception in a broad area containing at least several hundreds of pixels around the defect. The likelihood that a clinically relevant feature is in such a neighborhood of a defective pixel is several magnitudes higher than the likelihood that the clinically relevant feature is exactly on top of a defective display pixel. Therefore the impact of such a defect pixel should no longer be ignored. This is especially true for specific tasks such as mammography where defective pixels can actually mask clinically relevant features. This is because in mammography radiologists search for subtle features often only a few pixels in size, making this task very sensitive to even small changes in image perception.[10] Further study is needed to describe the actual impact of defective pixels on accuracy of clinical diagnosis.

A possible solution to overcome this problem is proposed. The solution is based on using neighboring pixels of the defective LCD pixel to minimize the visibility of the defect for the user of the display. The method used to calculate the correction values of the neighboring pixels is based on characteristics of the human visual system. More specifically, the correction algorithm minimizes the image of the defective pixel as projected image on the retina of the eye. It is very important to note that masking the defect pixel in this way not only reduces the visibility of the defect itself, but also recovers lost information of the defective pixel. The pixel information from the defective pixel is recovered, because it is used to provide input to the algorithm that calculates the correction values of the masking pixels. Indeed, the error luminance of the defective pixel is based on both the actual defective luminance output of the pixel and the actual luminance output that it should be displaying in the image. This is the theoretical reason why the pixel information of the defective pixel is recovered. Practical tests were also done to verify that information from a defective pixel could be recovered. A uniform background was shown on a display with a defective pixel, and specifically that defective pixel was then driven to a pixel value differing (fort instance slightly higher) from the background pixel values. Without any correction, of course, this different value was not perceived by the users, but only the defect itself was perceived. After correction, the users were able to actually perceive the defective pixel correctly: the defect was not visible anymore, but the pixel was perceived as having a correct luminance value differing from the background. This recovery of information of a defective pixel could be very important in highly demanding applications such as mammography. If, for instance, a defective pixel is located exactly on or in the neighborhood of a microcalcification, then this microcalcification will not or will only be partially displayed and this could result in failure to detect the microcalcification. If, however, our algorithms are applied, then the radiologist will perceive the image as though no defective pixel were present: even if a defective pixel is driven to generate a very subtle image feature, this feature will still be visualized by means of the masking pixels and therefore can be detected by the radiologist.

The performance of the correction algorithm was validated using three methods. The first method was based on a JND analysis, a second method was based on the actual image as projected onto the retina of the eye, and the third method was a limited user test. All three methods showed significant reduction in visibility and impact of defective pixels. Further research will include more extensive user tests to validate the proposed algorithms and will also focus on modeling the postprocessing of the image after the retina.

CONCLUSIONS

This work has shown that defective LCD pixels may interfere with subtle features in medical images in a broad area around the defect, and may therefore reduce the quality of diagnosis for specific and highly demanding applications such as mammography. As a second contribution, an innovative solution was proposed – a specialized image processing algorithm that makes these defects completely invisible and recovers the information of the defect so that the radiologist perceives the medical image correctly.

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REFERENCES

1. Understanding bright and dark pixel defects in flat-panel monitors. Dell Whitepaper, http://www.dell.com/downloads/global/vectors/2004_pixels.pdf

2. Wu Biing-Seng: Liquid crystal display member having defect repairing function. US patent US2001028429, Chi Mei Electronics Corporation

3. Whetten Nathan: Liquid crystal display with redundant FETS and redundant crossovers connected by laser-fusible links. US patent US5062690, General Electric

4. Defective pixels in liquid crystal displays. NEC whitepaper, http://www.necdisplay.com/support/css/Techlibrary/whitepaper_dead_pixel_wp.pdf

5. Kim Kyung-Wook, Kim Dong-Gyu: Thin film transistor array panel and method for repairing liquid crystal display including the same. US patent US2004263724, Samsung Electronics Co Ltd

6. JNDmetrix technology. Sarnoff Corporation, Evaluation version available: http://www.sarnoff.com/products_services/video_vision/jndmetrix/downloads.asp

7. Chao C, Iskander DR, Collins MJ, Davis B, Bennamoun M: Dynamic retinal image reconstruction of the human eye. In: 5th International Symposium on Signal Processing and Its Applications, Brisbane, Australia, 23rd–25th August 1999.

8. Walsh G, Charman WN: Measurement of the axial wavefront aberrations of the human eye. Opthal Physiol Opt 5(1):23–31, 1985

9. Course EE368b Image and Video Compression, Human Visual Perception. Bernd Girod, Stanford University, p. 12. http://www.stanford.edu/class/ee368b/Handouts/09-HumanPerception.pdf

10. Kotre CJ: The effect of background structure on the detection of low contrast objects in mammography. Br J Radiol 71(851), 1162–1167