Solution for Nonuniformities and Spatial Noise in Medical LCD Displays by Using Pixel-Based Correction

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Liquid crystal displays (LCD) are rapidly replacing cathode ray tube displays (CRT) for medical imaging. LCD technology has improved significantly in the last few years and has important advantages over CRT. However, there are still some aspects of LCD that raise questions as to the usefulness of liquid crystal displays for very subtle clinical diagnosis such as mammography. One drawback of modern LCD displays is the existence of spatial noise expressed as measurable stationary differences in the behavior of individual pixels. This type of noise can be described as a random stationary image superposed on top of the medical image being displayed. It is obvious that this noise image can make subtle structures invisible or add nonexistent patterns to the medical image. In the first case, subtle abnormalities in the medical image could remain undetected, whereas in the second case, it could result into a false positive. This paper describes a method to characterize the spatial noise present in high-resolution medical displays and a technique to solve the problem. A medical display with built-in compensation for the spatial noise at pixel level was developed and improved image quality is demonstrated.

KEY WORDS: LCD, medical, uniformity, noise, pixel, compensation, mammography

A general definition of noise could be: "A disturbance that affects a signal and that may distort the information carried by the signal." If we talk about a medical display, then the signal is the medical image displayed. Noise in this case means differences between the image we want to display and what is actually perceived by the user.

In medical LCD displays, there are mainly two kinds of noise: temporal noise and spatial noise. Temporal noise can be described as fluctuations

over time, whereas spatial noise is a distortion over the display area that is stable in time. An example of temporal noise is the well-known phenomenon of flicker on a CRT display. Research has demonstrated that in LCD displays, the temporal noise plays a minor role and that spatial noise can cause significant problems.^{1,2}

A very easy method to visualize spatial noise on LCD is to look at a uniform image of a low gray level. In case of a perfect display, we would perceive this image as being perfectly uniform and all of the display pixels would have the same luminance value. However, because of the spatial noise, a typical luminance fall-off near to the corners of the display is visible, but, more important also, high-frequency noise can be perceived. This high-frequency noise can have many different shapes: a few examples are small darker and brighter spots in the image, faint lines horizontal or vertical, and circle or ellipse such as shapes of graining structures. Very often, these spatial noise patterns are much more noticeable than the smallest difference in gray scales that can be displayed on the LCD, and therefore, they can interfere with the image being displayed.

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There are strong indications that this spatial noise, in particular, the high-frequency part of it, can have a negative influence on the accuracy of medical diagnosis.^{3,4,6}

MATERIALS AND METHODS

A 5-megapixel monochrome LCD panel with 1,024 levels of gray was used for our research. In a first step, we characterized the spatial noise present in the display by measuring the luminance value of each individual display pixel. A digital high-resolution (several megapixels) cooled CCD camera was used for this purpose. The pixel luminance values were obtained by displaying a specific video level over the complete area of the LCD display and taking detailed images of all 5 million display pixels. To avoid problems with aliasing, a magnification ratio of at least 12x12 CCD pixels for one LCD pixel is required. For each display pixel, a corresponding luminance value was obtained from the images resulting in a map of 2,560x2,048 pixel luminance values. In the case of a noise-free display, those luminance values should all be the same. The spatial noise map for that video level was then generated by subtracting the mean luminance value from the luminance map. We used 14-bit quantization of the camera luminance values to guarantee sufficient precision of the noise map. When comparing the spatial noise patterns for several video levels, we noticed significant variations, and therefore, the characterization process was repeated for multiple video levels.

A second step comprised of calculating appropriate correction values for each of the display pixels and this for all video levels. These correction values are added to the actual pixel data during the correction phase and are selected so that all display pixels show the same luminance value when driven with the same video level. The final output luminance of all pixels after correction is equal to the mean luminance value over all display pixels before correction, or, in other words, the average luminance calculated over the complete display area will be the same before and after correction. Note that a simple normalization of the highest pixel luminance value is not a valid solution. This is because the spatial noise pattern is video level dependent, and therefore it is required to normalize for all video levels. The correction is performed on a pixel-by-pixel basis so there is no spreading of noise to neighboring pixels and the full resolution of the display is retained. After calculation of the correction values, the pre-corrected uniform images are displayed on the LCD and the accuracy of the correction is verified with the CCD camera. Note that the noise compensation technology does not interfere with other technologies such as peak luminance stabilization and DICOM calibration. The display system will, for instance, still be calibrated to a 600-cd/m² white point by means of a sensor system and a backlight stabilization circuit.

The correction concept is illustrated in Figure 1. The image to be displayed is a square, but before sending these pixel data to the LCD panel, a digital precorrection is applied. The

per pixel uniformity (PPU) correction data are chosen so that they will compensate at pixel level for the spatial noise of the LCD panel. This can be observed in Figure 1: the correction data that are applied are the inverse of the spatial noise of the LCD. When the image is displayed, the stationary spatial noise of the LCD and the precorrection cancel out, and therefore, the overall perceived image is spatial noise-free.

Of course, this technique can only remove stationary spatial noise patterns because the noise map is measured once. Therefore, we performed extensive tests on a number of display systems to verify how stable the spatial noise patterns are. These tests included temperature stress tests, vibration and shock tests, and highly accelerated life time (HALT) tests over a period of several months. Discussing all results is outside the scope of this article, but we can conclude that even in those worst-case situations, the spatial noise patterns only changed with less than 5% over several months time.

Specialized hardware (PPU or per pixel uniformity) in the display performs real-time and user-transparent reduction of the LCD spatial noise based on the calculated correction map. Each pixel value that is sent to the LCD panel is first precorrected as described above to obtain a uniform output and to remove the spatial noise between the individual LCD pixels. The correction algorithm is implemented in a gate array because of the large computational requirements and fast processing requirements.

To measure the effect of our noise compensation objectively, we used several image quality metrics. A first metric is the RMS noise before and after compensation; this was carried out for multiple video levels. The RMS noise expresses how strong the average noise is compared with the image signal. Another metric we used is luminance uniformity. The luminance uniformity is calculated as L_{dark} divided by L_{bright} , where L_{bright} is the luminance of the brightest part of the area and L_{dark} is the luminance of the darkest part of the area. In data sheets of medical LCD panels, one usually distinguishes between luminance uniformity of adjacent areas (uniformity within a circular area of 10 mm placed anywhere on the screen) and screen total luminance uniformity (uniformity over the entire screen area). Finally, we also examined the NPS or noise power spectrum of the display. The noise power spectrum is obtained by applying a Fourier transform to the map of pixel luminance values. The NPS is very important because it clearly indicates how strong the image noise is at different frequencies and this both for horizontal and vertical directions. The NPS was measured for the LCD display with and without the uniformity correction and also for a high-quality CRT display that designed specifically for mammography.

Note that all measurements are performed on the native display panel. This means that the lookup table was set to linear. However, DICOM calibration has no effect on the results (this was verified) because the PPU correction is performed transparent in the display itself. Indeed, applying DICOM calibration is, in principle, just adding a lookup table between image data and the display system.

A secondary effect of applying PPU technology is that the display will be much better calibrated to the DICOM standard. Indeed, if we have a normal LCD display with up to 30% of uniformity, then it is easy to understand that there will be areas on the display where the calibration is far from optimal because the nonuniformity makes the local luminance values

Fig 1. General concept of PPU.

deviate from the intended calibrated display response. When PPU is used, the luminance is uniform over the complete display area. Therefore, if a display is calibrated to the DICOM standard in the center of the display (as is common practice at this moment), then this calibration will also be valid for the complete display area.

RESULTS

In a first step, the spatial noise pattern of the LCD was measured and characterized. Figure 2 shows the measured luminance values for the complete

Fig 2. Luminance uniformity of the complete display.

area of the display and this, as an example, for video level 32 (in Fig 2, the x - and y -axes have an arbitrary distance scale with origin the upper left display corner). The luminance values have been expressed as a percentage compared with the mean luminance value of the complete display. In other words, the 100% luminance level equals the mean luminance value. The plot shows that the peak-to-peak luminance varies over more than 60%, whereas the typical values are located between 80% and 110%. This corresponds to a large area uniformity of around 70% (80 divided by 110).

Figure 2 only represents the low-frequency spatial noise; therefore, a more detailed plot of the spatial noise pattern is shown in Figure 3. This graph represents an area of 256x256 LCD pixels (approximately 4x4 cm²) so each point in the plot visualizes a luminance value of an individual pixel. Figure 3 shows that there is a significant variation in pixel luminance (noise with frequency up to the Nyquist frequency of LCD) even in such a small display area. The luminance typically varies between 95% and 105%, but there are also larger distortions present.

Figure 4 shows detailed images of two areas each having 256x256 display pixels. In both images, a uniform gray level was displayed. These images indicate that apart from the traditional Gaussian noise, there is also a strong non-Gaussian noise component present. Statistical analysis (tests for normality) based on Kolmogorov–Smirnov and Shapiro–Wilk tests confirms that the distribution indeed has an important non-Gaussian component. This non-Gaussian noise component results in systematic errors in the medical image. In other words, phantom artifacts of varying size and shape are introduced because of the spatial noise. These artifacts are easily visible for the user of the LCD because the human eye is very good at detecting systematic structures even in noisy backgrounds.

All results shown above are for a normal LCD display without spatial noise compensation. We now compare the image quality of one and the same display where the PPU technology is activated or deactivated. By comparing results from the same display, we avoid variation in noise characteristics that exist between different display devices.

Fig 3. Luminance uniformity of a 256x256 LCD pixel area.

Figure 5 compares luminance values for the complete display area and this without and with the PPU technology. The measurements were performed for uniform images of video levels 32, 128, 768, and 1,000.

When we visually analyze a detailed area of the display, we then see that, indeed, also the high-frequency noise is reduced. With high-frequency noise, we mean the noise with frequencies up to the Nyquist frequency of the LCD (for instance,

256x256 pixels

256x256 pixels

Fig 4. Typical spatial noise patterns in a 256x256 LCD pixel area.

Fig 5. Effect of PPU on luminance uniformity for the complete display area.

between 0.1x and 1x the Nyquist frequency of the display). This is shown in Figure 6 where the same 256x256 LCD pixel area is shown without and with PPU.

To have an idea of the magnitude of the noise, a statistical analysis was performed. Figure 7 shows

this analysis for the complete display area (top) and also for a 256x256 pixel area (bottom). On the left-hand side is the analysis with PPU technology deactivated, whereas the right-hand side shows the same analysis for the PPU technology activated. “Count” is the number of pixels that was analyzed,

Fig 6. Effect of PPU for a detailed 256x256 LCD pixel area.

so on the left-hand side, this is 5 million (complete display), whereas on the right-hand side, this is 256x256 pixels. The values for “Mean,” “StdDev,” “Min,” and “Max” are expressed in video levels.

As example, we explain this for the situation 256x256 pixels without correction. The “Mean” value is 11.18; this means that the mean luminance value for that area is 11.18 video levels above the

Fig 7. Statistical analysis of PPU performance (top: complete display, bottom: 256x256 LCD pixel area).

Fig 8. Effect of PPU on the NPS and comparison with CRT.

mean luminance value of the complete display. The “Min” is -4.12 , so the darkest pixel in the 256×256 pixel area is 4.12 video levels below the mean luminance value of the complete display. The “StdDev” is 3.36 video levels so the typical distortion of an individual pixel compared with the mean luminance value of the 256×256 pixel area is over 3 video levels.

Figure 8 shows the noise power spectrum (NPS) both in horizontal (left) and vertical directions (right) and this for three different system configurations: LCD without PPU, LCD with PPU, and a “MGD521M” 5-megapixel mammography CRT. The horizontal axis of the plots shows the frequency relative to the Nyquist frequency of the LCD display system. The Nyquist frequency of a display system is the highest frequency that the display system is capable of displaying (6.3 lines/mm), and this corresponds to a dot-on-dot-off pattern. For example, relative frequency 0.25 corresponds to a pattern with period equal to four LCD pixels (approximately 0.6 mm on the LCD system). The ordinate shows the noise energy that is present at these frequencies: the higher the value, the more noise there is at that particular frequency. Note that in practice, the NPS depends on the video level, in this case full white. For simplicity and because the results are similar, we limited ourselves to this one example video level.

DISCUSSION

A large difference in spatial noise behavior exists between conventional CRT displays and LCD. With CRT devices, the spatial noise patterns are

mostly limited to the typical and well-known luminance fall-off near to the borders of the display. There is very little high-frequency noise present in traditional CRT displays. The spatial noise patterns with CRT are also rather stable over the complete video range, which means that a noise structure that is visible at one video level will most likely also be visible at another video level. Therefore, with CRT displays, an easy way to distinct the noise from the image is to look at a uniform image of any video level because the structures that are visible on a uniform background are noise.

LCD, on the other hand, has both low- and high-frequency components in the spatial noise map. This can be observed in Figures 2 and 3. The low-frequency part not only consists of the typical luminance fall-off, but also of other structures and patterns of more irregular shape. The high-frequency components can have almost any shape (see Fig 4) including structures that normally indicate diseases. In addition, these noise patterns on LCD are heavily video level dependent, which makes it really hard, even almost impossible for the user to distinguish between the actual video signal and the spatial noise of the display. Figure 5 shows the spatial noise map of an LCD and this for multiple video levels. At very low video levels, there are several brighter zones visible, and all of them are absent at higher video levels where other noise structures can be noticed. A medical image of course consists of multiple video levels so the actual spatial noise structures are image-dependent with LCD.

To verify whether or not this spatial noise can interfere with medical diagnosis, we analyzed the noise strength compared with the signal strength. Figure 8 indicates that in small areas of 256×256

pixels (approximately $4 \times 4 \text{ cm}^2$), the peak-to-peak noise is 28 video levels. In addition, the typical noise (StdDev) is 3.36 video levels. This means that for a typical LCD pixel, the noise is 3.36 times stronger than the smallest difference in gray scale that can be displayed on that LCD (this is 1 video level out of 1,024). These measurements therefore demonstrate that small and subtle features in medical images can easily be hidden because of the spatial noise.

Because of this noise strength, the following question arises: is there any reason to show 1,024 shades of gray on a display system that has a typical noise level (variance or standard deviation) of over 3 shades of gray? Recently, some manufacturers of medical displays even introduced medical LCD displays with 2,048 (11 bit) or even 4,096 (12 bit) shades of gray. It is very important to understand that by further increasing the number of gray shades at the same time, the difference between the shades of gray is reduced equally. Because the spatial noise strength of the display does not change, the noise proportionally becomes two (11 bit) or even four (12 bit) times stronger compared with the image signal. In our situation, this would mean that on a system with 2,048 shades of gray, the noise level (standard deviation or variance) would be as high as 6.72 video levels. Therefore, it is necessary to reduce the spatial noise of LCD as the number of gray scales is increased. In other words, although increasing the number of gray shades can reduce the magnitude of quantization errors, this is not a solution because without noise reduction, the variance (standard deviation) between individual pixels expressed as video levels increases with the same factor.

We now analyze the performance of the PPU noise compensation technology. A first metric we observe is the luminance uniformity at different video levels and this without and with PPU. Figure 5 shows that with PPU, we are able to increase luminance uniformity from typically 70% to over 95%. The performance at the very low video levels is slightly lower than at higher video levels. This is caused by the difficulty to accurately measure luminance at very low light levels ($<1 \text{ cd/m}^2$). But even at the lowest video levels, luminance uniformity is always above 95%. Note that the European EUREF standard for digital mammography requires a display uniformity of at least 90% over the complete display.⁵

To verify if also the high-frequency noise components are removed, we again analyzed a detailed area of 256×256 LCD pixels. Figure 6 shows the uncorrected luminance values at the left-hand side and the corrected luminance values at the right-hand side. The images show that by using the PPU technology, all systematic noise structures have been removed. Remember that especially those systematic noise patterns can easily interfere with subtle details in the medical images. Even in the compensated images, there is still some purely Gaussian noise left. The reason is that any measurement device has a noise floor of its own: every measurement that is performed has a certain degree of inaccuracy in it. This noise floor of the measurement equipment results in a remaining Gaussian noise component after compensation.

To estimate the degree of noise reduction, Figure 7 shows the RMS noise before and after compensation. We see that there is improvement of a factor of 6 if we do the analysis on the complete LCD area and a factor of 2 if we analyze that particular 256×256 pixel area on its own. In addition, the histogram visually shows that the individual pixel luminance values are much more concentrated around the correct value with PPU activated.

A final but very important metric is the noise power spectrum shown in Figure 8. The left-hand side shows the horizontal noise components, and the right-hand side shows the vertical noise components. The higher the values are on the noise power spectrum, the more noise is present in the display system. The original LCD panel without noise compensation shows a rather equal distribution of the noise power for frequencies above 0.05 times the Nyquist frequency (structures smaller than 20 LCD pixels or 3.16 mm). For larger structures, the noise is somewhat stronger. These larger noise structures include, among others, the luminance fall-off near to the display borders. There is no significant difference in noise strength between horizontal and vertical directions. The plots show that the PPU technology results in a significant reduction of the spatial noise and this over the complete frequency spectrum (measurements up to 0.25 times the Nyquist frequency). Indeed, the curve for PPU on is located below the "PPU off" curve and this for all frequencies. The difference is particularly very large at lower frequencies (up to 0.1 times Nyquist frequency or about 1.5 mm in size). In addition, at

very high frequencies (up to 0.25 times Nyquist frequency or structures of size 0.632 mm), there is still some improvement because of the PPU technology. If we compare the compensated LCD with a high-quality mammography CRT device, then we see that the compensated LCD has lower noise when compared with the CRT. This can be observed from Figure 8: the NPS for LCD with PPU is located below the NPS for CRT (especially at frequencies up to 0.1 times Nyquist frequency, the difference is very clear), and lower values mean less noise strength. The same LCD display with PPU deactivated has larger noise when compared with the CRT display.

CONCLUSIONS

This paper described a method to characterize the spatial noise present in high-resolution medical displays and provided a true solution for the problem. A medical display with built-in compensation for the spatial noise at pixel level was described, and improved image quality was demonstrated.

Our methods have proven to significantly increase uniformity and decrease spatial noise of medical LCD displays to a level superior to noncompensated LCDs and even better than special mammography CRT devices. The technology works for all video levels of the display, and the correction is applied completely transparent for the user in real time.

Especially for very subtle clinical diagnosis such as mammography, these methods could be an important step forward because the noise compen-

sation almost completely removes all systematic static noise patterns from the display and therefore reduces the risk of false positives and increases the probability of detection of subtle true structures in the image.

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REFERENCES

1. Roehrig H, Krupinski EA, Chawla AS, Fan JH, Gandhi K: Spatial noise and threshold contrasts in LCD displays. *SPIE Medical Imaging* (San Diego, CA), February 2003, pp. 15–20
2. Fan J, Dallas WJ, Roehrig H, Gandhi K, Krupinski E: Spatial noise of high-resolution liquid-crystal displays for medical imaging: quantitative analysis, estimation and compensation. In: *SPIE Medical Imaging Conference Workshop*, San Diego, CA, pp. 14–19, February 2004
3. Badano A, Hipper SJ, Jennings RJ: Luminance effect on display resolution and noise. *Proc SPIE Int Soc Opt Eng* 4681:305–313, 2002
4. Krupinski E, Roehrig H: Pulmonary nodule detection and visual search: P45 and P104 monochrome versus color monitor displays. *Acad Radiol* 9(6):638–645, 2002
5. van Engen R, Young K, Bosmans H, Thijssen M, Visser R, Oostveen L, Geertse T, Bijkerk R, Heid P: Addendum on digital mammography to chapter three of the European Protocol for the quality control of the physical and technical aspects of mammography screening, November 2003
6. Roehrig H, Krupinski EA, Fan J, Chawla A, Gandhi K: Physical and psychophysical evaluation of LCD noise. *18th International Computer Assisted Radiology and Surgery Conference*, Chicago, IL, pp. 23–26, June 2004