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FULL PAPER

The effect of time in use on the display performance of the iPad

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Objective: The aim of this study was to evaluate changes to the luminance, luminance uniformity and conformance to the digital imaging and communication in medicine greyscale standard display function (GSDF) as a function of time in use for the iPad.

Methods: Luminance measurements of the American Association of Physicists in Medicine (AAPM) Group 18 task group (TG18) luminance uniformity and luminance test patterns (TG18-UNL and TG18-LN8) were performed using a calibrated near-range luminance meter. Nine sets of measurements were taken, where the time in use of the iPad ranged from 0 to 2500 h.

Results: The maximum luminance ($L_{\max}$) of the display decreased ($367\text{--}338\text{ cdm}^{-2}$) as a function of time. The minimum luminance remained constant. The maximum non-uniformity coefficient was 11%. Luminance uniformity decreased slightly as a function of time in use. The conformance of the iPad deviated from the GSDF curve at commencement of use. Deviation did not increase as a function of time in use.

Conclusion: This study has demonstrated that the iPad display exhibits luminance degradation typical of liquid crystal displays. The $L_{\max}$ of the iPad fell below the American College of Radiology–AAPM–Society of Imaging Informatics in Medicine recommendations for primary displays ($>350\text{ cdm}^{-2}$) at approximately 1000 h in use. The $L_{\max}$ recommendation for secondary displays ($>250\text{ cdm}^{-2}$) was exceeded during the entire study. The maximum non-uniformity coefficient did not exceed the recommendations for either primary or secondary displays. The deviation from the GSDF exceeded the recommendations of the TG18 for use as either a primary or secondary display.

Advances in knowledge: The brightness, uniformity and contrast response are reasonably stable over the useful lifetime of the device; however, the device fails to meet the contrast response standard for either a primary or secondary display.

INTRODUCTION

There is increasing interest in using the Apple iPad® (Apple, Cupertino, CA) for displaying and interpreting radiographic images particularly for on-call and emergency radiology.^{1–5} A recent review found that there were no significant differences in the diagnostic accuracy between the iPad and digital imaging and communication in medicine (DICOM)-calibrated control displays.⁶ The US Food and Drug Administration have cleared the use of the iPad for primary radiological diagnosis.⁷ However, the clearance is limited to small-matrix images and situations where there is no access to a primary diagnostic display. Furthermore, there is a requirement for the observer to successfully complete an interactive contrast test before radiological images are displayed. Most major picture archiving and communication system vendors offer mobile viewing support through applications integrated with their picture archiving and communication system offerings.

There are well-established guidelines on the display characteristics of monitors used in diagnostic radiology.⁸ It is also well recognized that display performance will degrade with increasing time in use, which in turn may degrade diagnostic performance.⁹ The display characteristics of the iPad have been previously reported.¹⁰ However, there has been no evaluation of the effect of time in use on the display performance of the iPad. The aim of this study was to evaluate changes to the display characteristic of the luminance, luminance uniformity and conformance to the DICOM greyscale display function (GSDF) as a function of time in use for the iPad.

METHODS AND MATERIALS

A case study approach was used to perform a quantitative evaluation of the Apple iPad Air® (Apple, Cupertino, CA) using the testing guidelines described by the American Association of Physicists in Medicine (AAPM) Group 18 task group (TG18) report.¹¹

Test patterns

For this study, we generated 8-bit test patterns according to the instructions of the AAPM.¹² The generated patterns were based on the TG18-UNL and TG-LN8 patterns and were scaled to provide a one-to-one relationship between the image pixel and the display pixel of the iPad and therefore had a resolution 2048×1536 pixels. The generated test patterns were stored in tagged image file format and were displayed using the iPad's photo application.

Equipment

Luminance measurements were taken using a calibrated Unfors Luxi® (Unfors Instruments AB, Billdal, Sweden) near-range luminance meter. Contact luminance measurements of the iPad were made through a luminance tube attached to photometer's detector. The tube was used to shield the iPad from ambient lighting, thereby reducing the ambient luminance to zero. All measurements were taken with the iPad in the same orientation (landscape with the home button to the right), with auto-brightness turned off and the display brightness set to maximum.

Between measurements, the iPad remained powered on. During this time, the device was set to auto-brightness, displayed a homogeneous white image covering the full screen and was not used for any other purpose. The auto-brightness feature adjusts the brightness of the iPad display by dimming the display in low ambient lighting and increasing the brightness of the display in high ambient lighting. The iPad was stored in an office with sensor-controlled lighting. Resultantly, changes in ambient lighting would have changed the brightness levels of the iPad display. Various brightness levels over time in use correspond to normal usage patterns. The time the device was powered on (time in use) was recorded manually. For the present study, nine sets of measurements were taken over a period ranging from 0 to 2500-h time in use. This range was chosen as it equated to realistic usage rates for the usable life of the device (15 h per week for 3 years).

A Hagner universal photometer® (Hagner Photometric Instruments, Solna, Sweden) was used to measure levels of reflected

light (reflectance) from the screen under simulated viewing conditions at ambient light levels typical of an internal office environment (light level in the range of 40–60 lux).

Data collection

To evaluate luminance uniformity as a function of time in use, five luminance measurements (centre and four corners) were taken of both the TG18-UNL10 and TG18-UNL80 test patterns (Figure 1). The maximum non-uniformity coefficient for each display pattern was calculated as the percent difference between the maximum luminance ($L_{\max}$) and minimum luminance ($L_{\min}$) values relative to their average values.¹¹

Luminance measurements of the TG18-LN8 test patterns were performed to evaluate the $L_{\min}$, $L_{\max}$ and conformance to the DICOM GSDF as a function of time. The luminance measurement of TG18-LN8-01 corresponds to $L_{\min}$ and the luminance measurement of TG18-LN8-18 (Figure 2) corresponds to $L_{\max}$. Whereas, measurements of the 18 distinct luminance levels of test patterns TG18-LN8-01 to TG18-LN8-18 were used to construct the luminance response curve for the iPad. The luminance response curve for the iPad was compared with the GSDF to determine the degree of conformance. This was performed according to the recommendations of TG18, using the measured luminance response data corrected for reflected ambient light—to better evaluate the response as seen by a human observer. The contrast response curves were also constructed according to the recommendations of TG18 to provide a quantitative evaluation of the device for use as a primary display.

RESULTS

Luminance uniformity

The non-uniformity coefficient calculated for the TG18-UNL10 test pattern ranged from 7.6 to 11.3% and for the TG18-UNL80, the range was 6.6–11.1%. For both test patterns, the non-uniformity coefficient increased slightly as a function of time in use (Figure 3).

Figure 1. Generated test patterns based on the TG18-UNL10 and TG18-UNL80 test images.

Figure 2. Generated test patterns based on the TG18-LN8-01 and TG18-LN8-18 test images.

Luminance decay

The $L_{\max}$ of the iPad display decreased as a function of time in use. The highest $L_{\max}$ of the iPad display (367 cdm^{-2}) was measured at 0-h time in use (Figure 4). After approximately 1800 h of time in use, $L_{\max}$ had decreased by 8% to 338 cdm^{-2} . This was the lowest $L_{\max}$ measurement in the present study.

$L_{\min}$ remained constant as a function of time in use. The mean $L_{\min}$ was $0.37 \pm 0.07 \text{ cdm}^{-2}$.

Reflectance

The mean value of luminance due to diffuse reflection from the screen of ambient illuminance at a level of 40 lux with the device turned off was 2.2 cdm^{-2} .

Digital imaging and communication in medicine greyscale standard display function conformance

The DICOM GSDF conformance curves for the iPad device were constructed (including the reflected ambient illuminance) and are shown in Figure 5. Inspection of the conformance curves

demonstrates a considerable deviation from the Barten model across the range of luminance and particularly in the lower range of just noticeable difference (JND) indices.

The calculated contrast responses for the iPad device are shown in Figure 6. Conformance with the Barten model exceeds the $\pm 20\%$ range and is particularly notable at the lower range of JND indices. This latter effect is increased by the ambient illuminance. The recommendation of TG18 is that the contrast response for primary class devices should fall within 10% of the expected value at any measured point.

DISCUSSION

This study has demonstrated that the iPad display exhibits luminance degradation as a function of time typical of liquid crystal displays.¹³ $L_{\max}$ reduction from 367 to 340 cdm^{-2} was observed over 2500 h of time in use. The rate of decay was highest initially, with $L_{\max}$ falling below the recommended level for primary display at around 1000 h in use. Subsequently, the $L_{\max}$ value plateaued (>1800 -h time in use). $L_{\min}$ did not vary significantly with time in use.

Luminance is important in radiological diagnosis because an appropriate luminance level allows a reader to distinguish one shade of grey from the next. This ability is lost if the display is too dim.¹⁴ Recommended luminance levels are published in the American College of Radiology (ACR)–AAPM–Society of Imaging Informatics in Medicine (SIIM) technical standard guidelines.⁸ Recommendations are more stringent for primary displays than for secondary displays. By way of background, display devices are categorized by their function as either primary or secondary. Primary displays are used when reading images for the purpose of diagnosis, whereas secondary displays are used for reviewing images for purposes other than diagnosis—for example, the review of images by a referring clinician when a radiologist report has been provided.⁹ Primary displays are often dedicated medical display devices, whereas secondary displays are often consumer-grade computer displays. An $L_{\max}$ of $>350 \text{ cdm}^{-2}$ is recommended for primary displays with the

Figure 3. Luminance uniformity.

Figure 4. Maximum luminance.

exception of mammography, where $>420 \text{ cdm}^{-2}$ is suggested. In the present study, the L_{max} of the iPad was below the recommendation for mammography reporting. It did, however, continue to exceed the recommendation for primary displays until 1000 h in use. Beyond 1000-h time in use, the L_{max} fell below the recommendations for primary displays. The recommendation for secondary displays ($>250 \text{ cdm}^{-2}$) was exceeded during the entire study. In this study, the minimum measured luminance was 0.37 cdm^{-2} . Reflected ambient light was measured as 2.2 cdm^{-2} . The presence of a reflected ambient light constrains

the ability of the iPad to deliver an effective contrast resolution in the ambient light range, as there is no mechanism to set the L_{min} above the level of reflected light. This could prevent an observer from resolving a dark radiographic structure against a dark background.

The present study has also demonstrated a considerable deviation ($>\pm 20\%$) of the iPad's luminance response from the DICOM GSDF and an associated deviation from the expected contrast response of a GSDF conformant device; this (without

Figure 5. Digital imaging and communication in medicine (DICOM) greyscale standard display function conformance curves at 2 h in use and 2500 h in use. cdm^{-2} , candela per square metre (luminance); JND, just noticeable difference.

Figure 6. Contrast responses at 2 h in use and at 2500 h in use. DICOM, digital imaging and communication in medicine; dL/L, difference in luminance between sequential grey levels; JND, just noticeable difference.

correction) will preclude its use as a primary display. Deviation from the DICOM GSDF has been previously reported in tablet displays.¹⁰ The contrast response is particularly notable at the lower range of JND indices.

GSDF conformance of image-viewing devices aims to establish perceptual linearization of the display. A perceptually linearized display will demonstrate the same difference in image contrast equally across the full range of background luminance values. A second goal or perceptual linearization is to establish consistent presentation of images, whereby the same image will demonstrate similar contrast characteristics on different devices that are conformed to the GSDF. The results for the iPad tested in this study indicate that its contrast performance will be compromised across the luminance range as indicated in Figure 6, resulting in the same difference in image contrast being displayed (and perceived by the user) differently depending on the background luminance in which the contrast difference is located. The contrast performance of this device will also be different to that of other viewing devices that have been conformed to the GSDF.

Limitations

The lowest $L_{\max}$ we measured was 338 cdm^{-2} —which is $<4\%$ below the ACR–AAPM–SIIM recommendations for primary displays. Hence, some tolerance needs to be applied to the 1000-h time in use we reported, where the iPad display fell below this recommendation in our study. This study did not measure the interdevice variability of the iPad display characteristics. Variability has been previously reported¹⁰ and emphasizes the need to undertake conformance checks on devices used to display medical images.

CONCLUSION

This study has demonstrated that the iPad display exhibits luminance degradation typical of liquid crystal displays. The $L_{\max}$ of the iPad fell below the ACR–AAPM–SIIM recommendation for primary displays ($>350 \text{ cdm}^{-2}$) at approximately 1000 h in use. The $L_{\max}$ recommendation for secondary displays ($>250 \text{ cdm}^{-2}$) was exceeded during the entire study. The iPad luminance value was below the recommendation for mammography reporting ($>420 \text{ cdm}^{-2}$) at the commencement of the study. The $L_{\min}$ of the iPad is below reflectance in typical ambient light conditions and cannot be adjusted. The maximum non-uniformity coefficient did not exceed the recommendations of $<30\%$ for either primary or secondary displays.

The conformance of the iPad device in this study deviated from the GSDF curve at commencement of use and this deviation varied only marginally for the duration of the study. A similar effect was noted with the contrast response curve. The deviation of the calculated contrast response exceeded the recommendations of the TG18 report for use as a primary or secondary display.

Furthermore, iPads should not be used for mammography reporting. When using an iPad for image interpretation, the auto-brightness function should be disabled and the brightness should be manually set to maximum brightness. This is to ensure that the ambient light compensation does not reduce the maximum display luminance below the recommended levels. The iPad requires routine conformance checks to ensure that the $L_{\max}$ has not decayed below established recommendations. Caution should be exercised if attempting to use an iPad for image display, particularly in a moderate-to-high ambient illuminance.

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