Optimal Display Positions for Heads-Up Surgery to Minimize Crosstalk

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Purpose: To determine optimal display positions during heads-up surgery (HUS) to minimize crosstalk.

Methods: Three three-dimensional (3D) displays were analyzed to evaluate the relationship between display position and amount of crosstalk. First, the 3D displays were calibrated to show a completely white image in the right eye and completely black image in the left eye. Images were captured through the polarized filter, which corresponded to the left-eye image. The amount of crosstalk in the left eye was measured as white areas on the black background that originated from the right-eye image. The amount of crosstalk was measured at different display distances and heights to estimate the non-crosstalk display positions for each display.

Results: Varying amounts of crosstalk (0%–70.3%) were observed for different display distances and heights. The crosstalk almost always started from the corner of the display, although the starting area varied according to the type of display. The minimum distance of non-crosstalk position was 1.26 meters away from display 1, 1.24 meters away from display 2, and 1.8 meters away from display 3. With regard to display height, the optimal center-of-display heights for displays 1, 2, and 3 were 72 mm below, 18 mm above, and 101 mm above eye level, respectively.

Conclusions: The amount of crosstalk differed according to display positions and displays.

Translational Relevance: The optimal HUS display settings differ among displays; therefore, each surgeon should carefully evaluate individual display characteristics before using HUS in practice.

Introduction

Three-dimensional (3D) displays for heads-up surgery (HUS) are now commercially available.1–5 Eckardt and Paulo1 reported that HUS offers better ergonomics and digital image processing, as well as a large display, thus allowing surgeons to view all regions of the surgical field in comfort and serving as a valuable teaching tool. However, some surgeons hesitate to use HUS due to its disadvantages, including low resolution, display latency, and the time required to adjust the settings.

We previously conducted a clinical trial of HUS in ophthalmology.6 The results suggest that HUS is a sufficiently practical method, even in the field of ophthalmology; however, that clinical trial identified several issues related to viewing stereoscopic images on 3D displays. Most surgeons reported that their sense of depth differed from that when using a conventional microscope. Additionally, in some cases, crosstalk was evident on the screen during the surgery in the form of ghost vision. Crosstalk is the incomplete isolation of the left and right images, which impairs 3D image quality (Fig. 1).7 It can directly obstruct the surgical field or may affect stereoscopic vision, with increases...
in the crosstalk ratio causing decreases in the fusion limit and protruding distance. Therefore, suppressing crosstalk is essential during HUS.

Stereoscopic images are strongly affected by 3D display positions. The display distance and height affect the image resolution, sense of three-dimensionality, and crosstalk, which are related to 3D image quality. However, the optimal display settings for HUS have been unclear. In this study, we aimed to determine the optimal display settings, and we focused on the relationship between display position and crosstalk.

**Methods**

**Instrumentation**

All examinations were performed in the Department of Ophthalmology at Aichi Medical University Hospital. HUS systems were evaluated using the NGENUITY 3D Visualization System (Alcon, Fort Worth, TX). We evaluated three 3D displays; two of the displays were the 55EF9500-UA model (LG Electronics, Seoul, South Korea), and the third display was the OLED55E6P-U model (LG Electronics). All three displays were 55-inch, polarization-based 3D organic light-emitting diode (OLED) displays with a resolution of 3840 × 2160 pixels. The basic specifications of the three displays were identical based on their specification sheets. We used the default settings for all displays.

**Evaluation of the Amount of Crosstalk**

To evaluate the 3D image quality, we focused on the amount of crosstalk. We evaluated the relationship between the amount of crosstalk and the display distance and height. The amount of crosstalk was estimated in the following manner: The 3D display showed an image that was completely white in the right eye and completely black in the left eye (Fig. 1A); the image was generated using Final Cut Pro X (Apple, Inc., Cupertino, CA).

The amount of crosstalk was evaluated at distances of 1.5, 1.75, and 2.0 meters from the display. At each distance, the amount of crosstalk was also evaluated at every 2.5-cm increment from 30 cm below the center of the display to 30 cm above the center of the display. At each distance and height, the display was captured in a dark room using a digital camera (α6000 E-mount camera; Sony Imaging Products & Solutions, Tokyo, Japan) with a Sony lens (SELP1650) through a passive polarized filter, which corresponded to the left eye. We used a fixed camera setting of 16-mm focal length, 1/8-second shutter speed, f/7.1, ISO 1000, and image size of 6000 × 4000 pixels. Under normal conditions, we obtained one image at each distance and height.
The obtained images were analyzed using ImageJ 1.51 (National Institutes of Health, Bethesda, MD). All images were cropped to include only the area of the 3D display. The images were binarized, and the white area was measured because all obtained images corresponded to the left eye, implying that all images were completely black if the amount of crosstalk was zero. We then calculated the amount of crosstalk, which was defined as the crosstalk area divided by the display area.

Assessment of the Non-Crosstalk Display Positions

It is known that crosstalk reduces with an increase in display distance from the observer and increases when the eye level of the observer is not correct (i.e., too high or too low) (Fig. 2). To estimate the non-crosstalk display positions, we calculated the area of non-crosstalk regions as follows: First, the amount of crosstalk was calculated at each distance and height. Second, points with crosstalk area ratios of less than 1% were plotted on a grid (Fig. 3). Third, fit lines were calculated based on the maximum and minimum height points and the upper and lower ends of the displays; in this study, all three displays had the same height of 68.5 cm. Fourth, an intersection point was calculated from the two fit lines. Finally, the non-crosstalk display area was defined far from the intersection point between the two fit lines.

Results

Varying amounts of crosstalk (0%–70.3%) were observed according to the display distance and height. The amount of crosstalk decreased with increasing display distance from the observer and increased when the eye level of the observer was too high or too low (Fig. 4). The crosstalk almost always started from the corner of the display, although the starting area varied according to the type of display (Fig. 2). Each display exhibited a different amount of crosstalk at a certain distance and height. The maximum and minimum heights of the non-crosstalk area in each display are summarized in the Table. Non-crosstalk areas were observed at distances of 1.5, 1.75, and 2.00 meters on displays 1 and 2; however, on display 3, non-crosstalk areas were observed only at a distance of 2.00 meters. On display 3, for example, at a distance of 1.5 meters, crosstalk (the presence of white areas on a black background) was observed at all heights of the camera; however, displays 1 and 2 at a distance of 1.5 meters showed a white area at either the top or bottom only when observed from a camera position that was too high or too low.

The fit lines can be calculated from these data and are shown in the Table. From the maximum and minimum heights of the non-crosstalk area at each display distance and height, intersection points and approximate fit lines were calculated for all three displays (Fig. 3). The intersection point of display 1 was 1259 mm away from the display and 72 mm below the center-of-display height. The intersection points of displays 2 and 3 were 1236 mm away/18 mm above and 1802 mm away/101 mm above, respectively. When the camera was placed closer beyond the intersection point at the level of each height, crosstalk was always observed.

Discussion

In this study, we evaluated the relationship between crosstalk and display position. Our results suggest that the optimal position to reduce crosstalk varies among displays, especially different models. Therefore, we should carefully evaluate the display characteristics before using HUS in practice.

Crosstalk originates during the manufacturing of commercial micropolarized 3D displays used in HUS. The 3D display consists of an OLED panel and a micropolarizer film, which converts light into polarized light depending on the rows of display pixels (Fig. 5). As shown in Figure 1, 3D displays show right-eye images in odd-numbered rows of pixels using micropolarizer films on the display surface and passive polarized 3D glasses. If the observer is positioned correctly, the micropolarizer rows coincide with the rows of display pixels. However, if the observer views...
the display from a different distance or vertical viewing position, a parallax error could be introduced, leading to crosstalk (Fig. 5). This may explain why crosstalk almost always starts from the corners of the display, which offer a larger viewing angle to the observer. Because the larger viewing angle causes light to deviate from the desired micropolarizer rows, the corners of the display are most likely to exhibit crosstalk.

In this study, we showed that the optimal distances were at least 1.26 meters for display 1 and 1.25 meters for display 2. Display 3 required a greater distance, at least 1.8 meters, to suppress crosstalk. The center-of-display height in all three displays should be kept at almost eye level; more precisely, the heights should be 72 mm above eye level in display 1, 18 mm below eye level in display 2, and 101 mm below eye level in display 3. These results suggest that the greater the distance, the greater the permission range of non-crosstalk areas. The display height should be adjusted according to the height of the surgeon using the 3D system; if the display is set at a lower than ideal position, the display should be tilted such that it is viewed at a right angle to reduce crosstalk.

In this study, the three 3D displays had different optimal settings for the minimization of crosstalk. With regard to observing differences between the two displays that were the same model, the accuracy of the alignment of the micropolarizer strips with the rows of pixels on the display may explain this difference. For example, one manufacturer that produces 3D displays...
Figure 4. Average amount of crosstalk at each display distance and height.

has indicated that their manufacturing variability is ±15 μm.9 This may explain why the two displays that were the same model had different crosstalk results, as well as why the crosstalk was more exaggerated on one side than on the other side.

Interestingly, the differences were greater when we compared two displays of different models versus comparing the two displays of the same model. A possible reason could be differences in the manufacturing processes for the 3D displays. For example, the accuracy of alignment differs between micropolarizer films fabricated from glass and those from film. The manufacturing variability between glass and the panel is smaller than that between film and the panel (±15 μm vs. ±1000 μm).9,10 Thus, changes in material may result in such differences.

Three-dimensional image quality is also affected by the sense of three-dimensionality and resolution. The sense of three-dimensionality strongly depends on the observer; thus, it is difficult to define a standard distance. A basic rule, which was previously stated,6 is that, theoretically, the greater the display distance, the greater the sense of depth. If the 3D effect seems too exaggerated, the display should be positioned closer to the viewer.

Another factor is resolution, and determining it for 3D image systems is complicated. For a two-dimensional system, display resolution and size
Table. Summary of Non-Crosstalk Positions in Each Display and at Each Display Distance

| Display | Camera Position (mm) | Distance from the Observer (mm) | Fit Line |
|---------|----------------------|---------------------------------|----------|
|         |                      | 1500   | 1750   | 2000   |       |
| 1       | Maximum height       | 0      | 25     | 75     | $y = 0.2114x - 338.11$ |
|         | Minimum height       | -175   | -250   | -275   | $y = -0.3295x + 336.82$ |
| 2       | Maximum height       | 125    | 175    | 200    | $y = 0.2837x - 332.95$ |
|         | Minimum height       | -75    | -125   | -150   | $y = -0.2566x + 334.89$ |
| 3       | Maximum height       | None   | None   | 150    | $y = 0.2463x - 342.5$ |
|         | Minimum height       | None   | None   | 75     | $y = -0.1338x + 342.5$ |

Figure 5. Principle of polarization-based 3D display and mechanism of crosstalk. (A) The OLED panel displays a black image (which indicates no light) in the rows corresponding to the left eye and a white image in the rows corresponding to the right eye. The micropolarizer film converts light into polarized light depending on the row of display pixels. Under ideal conditions, the right-eye image is completely white and the left-eye image is completely black. (B) Due to a large viewing angle or misalignment of the micropolarizer film, light deviates from the desired micropolarizer rows. This causes crosstalk, which is the display of a black and white image in the left eye.

decide the minimum distance from the human retina for the differentiation of pixels at which the resolution becomes maximum. If the observer has 20/20 visual acuity and the 55-inch display has a resolution of 4K ($3840 \times 2160$ pixels), the minimum distance at which an observer would not detect any pixels could be calculated as 1.09 meters. However, 3D systems are slightly different, because the passive glasses deliver only half the vertical resolution, as shown in Figure 1. Thus, for a 55-inch 3D display with a resolution of 4K ($3840 \times 2160$ pixels), the minimum distance could be calculated as 2.18 meters, due to halving the vertical resolution. We speculate that the minimum distance for 4K, 55-inch 3D displays is between 1.09 and 2.18 meters. González-Saldivar and Chow reported that the lateral resolution in HUS significantly increased as the 3D display distance decreased, and they found the minimum distance to be primarily between 1.2 and 1.5 meters.

When one considers crosstalk, a sense of three-dimensionality, and display resolution, the optimal display distance is approximately 1.2 meters and the optimal center-of-display height is 0 to 100 mm above eye level for displays 1 and 2. For display 3, the distance should be at least 1.8 meters to suppress crosstalk; however, the resolution would decrease and the sense of three-dimensionality would be emphasized. Theoretically, crosstalk always starts from the corners of the display (Fig. 2). Thus, if a surgeon focuses on the central portion of the display, a small amount of crosstalk may not disturb the surgical procedure, but it might become a concern if the surgeon utilizes the entire area of the display. Hence, the rules of three-dimensionality should be well understood,
and several settings should be tried when adjusting for HUS.

In this study, we focused on the relationship between display position and crosstalk and also evaluated the sense of three-dimensionality and display resolution. Our results show that the amount of crosstalk differed among the three displays, with distinct effects of display distance and height. Although other factors may affect what is viewed on 3D displays during HUS, our results identified initial, standard settings for HUS. No single position can correspond to all cases and situations. The most important factor to be considered is the relationship between display position and 3D images to determine the optimal settings for each case.

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