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Optimum Shadow-Casting Illumination for Endoscopic Task Performance FREE

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ABSTRACT

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Hypotheses Task performance improves with the use of a balanced degree of shadow and illumination compared with no or maximum shadow contrast; and overhead shadow-casting illumination is better than side illumination.

Design The standard task entailed touching target points on an undulating surface by using a surgical hook. Each run consisted of 13 target points in a random sequence. Five settings were investigated: no shadow; 22%, 42%, and 65% shadow contrast created by overhead illumination; and 22% shadow contrast produced by side illumination. Each surgeon completed 3 runs with each setting in a random order.

Setting Research laboratory at the Surgical Skills Unit, Ninewells Hospital, Dundee, Scotland.

Participants Ten surgical trainees.

Main Outcome Measures Number of errors and execution time.

Results Shadow contrast settings had fewer errors than shadowless imaging ($P<.001$). Work with overhead 22% shadow contrast had a lower error rate than side illumination ($P<.001$). With overhead illumination, 22% and 42% shadow contrast were accompanied by a lower error rate than maximum shadow contrast of 65% ($P<.001$ and $P = .005$, respectively). No significant difference was found in the execution time.

Conclusion Optimum endoscopic task performance is obtained with overhead shadow-casting illumination and a balanced degree of illumination and shadow contrast.

Restrictions in videoendoscopic imaging contribute to degradation of task performance compared with direct vision.[1] Standard videoendoscopic imaging systems provide 2-dimensional depth (pictorial) cues of the operative field and, thus, the surgeon has to reconstruct a 3-dimensional picture from a 2-dimensional image. Several 3-dimensional videoendoscopic systems have been introduced to improve depth perception of the operative field, but without significant improvement in surgical endoscopic task performance.[1-4] The current videoendoscopic systems have a single disparity, which yields different magnitudes of depth depending on the viewing distance. By

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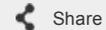
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contrast, the human visual system perceptually rescales disparity information for different distances to produce valid depth, a process called *stereoscopic depth constancy*.[5] The depth perceived by the current 3-dimensional systems is valid if it corresponds to the predicted depth by geometry.[6] As a result, there is a limited operational distance in which 3-dimensional effect is obtained, but outside this range, the surgeon operates from false depth information.

An alternative approach for improving depth perception is to enhance monocular depth cues available in the current 2-dimensional endoscopic image. The coaxial alignment of the lens system and optical light fibers in rigid endoscopes produces a shadowless operative field.[7] Our group's earlier research showed that endoscopic task performance significantly improves when a shadow-producing system (separate ports for imaging and illumination) is used.[8] The use of various illumination sources produces different degrees of shadow. The aim of this study was to optimize shadow production in terms of the degree of shadow contrast and the location of shadow-casting illumination.

METHODS

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ERGONOMICS OF THE SETUP

Experiments were conducted in a wooden trainer box (480 × 360 × 250 mm) with the use of a 2-dimensional videoendoscopic system (Karl Storz, Tuttlingen, Germany). Two illumination sources were used; the primary endoscope provided both illumination and imaging, while a second endoscope provided shadow-casting illumination. Figure 1 shows the experimental apparatus. The primary endoscope (10-mm diameter, forward-viewing direction) was introduced with an optical axis–to–target angle of 60° and at a distance of 100 mm from a fixed point on the trainer base (setup reference point). The primary endoscope was attached to a video camera (Telecam; Karl Storz, Tuttlingen, Germany) to display the endoscopic field on a monitor (model PVM-1443MD; Sony Corp, Tokyo, Japan). The shadow-casting illumination was provided by a 10-mm forward-viewing endoscope at a distance of 100 mm from the setup reference point. The shadow-casting illumination was positioned with light direction either perpendicular or at an angle of 60° to the horizontal plane at the reference point to provide either overhead or lateral light. Two 450-W halogen light sources were connected to the endoscopes by means of fiberoptic light cables of 8.6-mm diameter. The light sources were adjusted independently to change the level of illumination. An endoscopic instrument was introduced with an elevation angle of 60° between the instrument axis and the horizontal plane. The angle between the instrument and the center of shadow-casting illumination was 30°, whereas the angle between the instrument and the optical axis of the primary endoscope was 40°.

Figure 1.

Schematic representation showing the ergonomics of the setup.
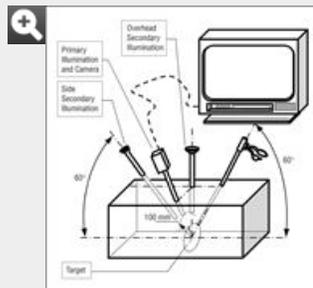
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MEASUREMENT OF SHADOW CONTRAST

Illumination was measured at the reference point by means of a calibrated light meter (DX200; INS Enterprise, Taipei, Taiwan). The shadow contrast was measured by taking a snapshot of the operative field, as shown in Figure 2, with a high-resolution video capture card (Trust Corp, Dordrecht, the Netherlands) attached to the endoscopic camera. The captured images were subsequently converted to gray scale images by means of a computer graphics program (Corel Photo-Paint; Corel Corp, Ottawa, Ontario) to render the images in 256 separate shades of gray, with zero representing the blackest and 255 the whitest point. A gray scale plot along the A-B line (Figure 2) was made with other software (Scion Image; Scion Corp, Frederick, Md). The A-B line was placed close to the instrument tip in the illuminated area and crossing the shadow area. The shadow

contrast measure is called the *Michaelson contrast ratio* and was calculated by the following formula[5]: Shadow Contrast = {[(Highest Gray Scale Value on the A-B Line) – (Lowest Gray Scale Value on the A-B Line)]/256} × 100.

Figure 2.

Illumination of the operative field to produce 22% shadow contrast from above (A) or the side (B). A gray scale plot was created along the A-B line in each setup.
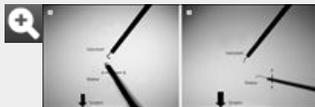
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SETTINGS OF ILLUMINATION AND SHADOW PRODUCTION

There was no shadow with illumination from the primary endoscope as the only source for illuminating the operative field. Shadow was produced by overhead and side illumination, with the maximum shadow contrast obtained by using the primary endoscope for imaging and another light source for illumination (Table 1). Figure 2 shows the shadow produced by overhead and side illumination. With the overhead light (Figure 2A), the shadow of the instrument came from the same side of the monitor frame as the surgeon (actual side of the instrument entry), whereas the instrument's shadow appeared from the side of the monitor frame with side illumination (apparent instrument's side on the monitor) (Figure 2B).

**Table 1.** Different Settings of Illumination and Shadow Production

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INFLUENCE OF SHADOW CONTRAST ON TASK PERFORMANCE

The standard task entailed touching target points on an undulating surface (Figure 3) with the use of a surgical hook. The target points were electrodes connected to a light-emitting diode on a control panel. Illumination of the light-emitting diode indicated successful task execution at the corresponding target point. Each run consisted of 13 target points in a random sequence. Each error was identified by a red light in the control panel. An error was defined as touching the wrong electrode or the surface of the target object instead of the electrode. The end points for each run were the execution time and number of errors. Ten surgical trainees participated in the study. Each subject performed 3 runs with each of the 5 shadow-illumination settings in a random order. All subjects had 20/20 corrected visual acuity, and each used his or her dominant hand to perform the task. Experiments were carried out in the research laboratory with the same background illumination.

Figure 3.

Target object.

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STATISTICAL ANALYSIS

The data were not normally distributed, and therefore Kruskal-Wallis 1-way analysis of variance and Mann-Whitney test were used for analysis. Significance level was set at $P<.05$.

RESULTS

Table 2 shows the median and magnitude of the interquartile range of the execution time and errors committed by the participants. No significant difference in the execution time was found between different settings of shadow contrast. The "no-shadow" setting had a higher error rate than shadow contrast settings of 22% (P<.001), 42% (P<.001), and 65% (P = .009) for overhead illumination and the shadow contrast setting of 22% (P = .01) for side illumination. With overhead shadow-casting illumination, 22% and 42% shadow contrast were associated with a lower error rate than the maximum shadow contrast (65%) (P<.001 and P = .005, respectively). Twenty-two percent shadow contrast produced by overhead illumination was accompanied by a lower number of committed errors than the same contrast shadow intensity produced by side illumination (P<.001).

Table 2. Execution Time and Committed Errors on Different Settings Using Overhead or Side Shadow-Casting Illumination

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COMMENT

The study confirmed the findings of our group's earlier research that shadow depth cues enhance endoscopic task performance.[8] The present study has, however, shown that a balanced degree of shadow and illumination is necessary for maximum gain in task performance. Thus, excessive shadowing (shadow contrast of 65%) is accompanied by a higher error rate than lower shadow intensity levels (22% and 42%). We postulate that a low level of illumination at a shaded area may account for poor performance with maximum shadow contrast. The present investigation has also shown that the best performance is obtained with overhead shadow-casting illumination as opposed to side illumination. This observation is not unexpected, as several studies in visual psychology have confirmed that the human visual system prefers overhead illumination,[9-12] as it is accustomed to overhead lighting by the sun and other sources of artificial light. This dependence on overhead illumination for appreciation of valid shadow cues develops very early, as 7-month-old infants have been observed to select convex shapes on the basis of shading information.[13]

In addition to depth enhancement, shadow may have a role in the orientation of endoscopic instruments in the operative field. In the setup of our study, the instrument was introduced into the trainer box from the same side of the surgeon, but the instrument appeared to enter the operative field toward the surgeon from the upper part of the monitor frame. The difference between real instrument location and apparent display on the monitor is due to viewing of the instrument by the endoscope from below.[14] Nevertheless, with overhead shadow-casting illumination, the instrument's shadow appeared on the monitor in the same direction as the real location of the instrument. With side illumination, the shadow appeared on the monitor from the same side as the shadow-casting illumination, ie, quite different from real instrument direction. This may explain the superiority of overhead illumination as the source for the shadow.

Currently, there are 2 endoscopic systems that generate shadow in the operative field: the illuminating port and the shadow-producing endoscope (MGB Endoscopy Co Ltd, Seoul, Korea).[15,16] The shadow produced by both systems is not optimum, as the shadow-casting illumination comes from the side by the illuminating cannula and from below by the shadow-producing endoscope. There is a need to develop a system that provides overhead illumination of the operative field to create true shadow cues for endoscopic surgery. We have previously suggested that fiberoptic light bundles can be deployed inside superelastic diverging shape-memory alloy tubes to provide ceiling shadow-casting illumination. Such a system has the potential for creating a balance between illumination and degree of shadow contrast.

We believe that an overhead shadow-casting illumination system will improve depth perception in endoscopic surgery. However, the degree of such improvement in the clinical setup depends on the available depth cues, such as familiar size, interposition, and proximity-luminance covariance. Shadow depth perception is likely to be more beneficial when monocular cues are sparse in the 2-

dimensional display systems. Nevertheless, the results of our laboratory experiment on optimum shadow contrast need to be validated in clinical surgery to ensure that the effect of shadow will improve depth perception without compromising detailed anatomy and tissue planes. Experimental psychological research showed that recognition of natural objects is highly invariant to the complex luminance patterns caused by shadows.[17] Further research is required to develop the ideal shadow-producing videoendoscopic system.

ARTICLE INFORMATION

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