See-through type 3D head mounted display based surgical microscope system for microsurgery: Feasibility study

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41Abstract

42Background: The surgical microscope is used primarily for microsurgeries, which are more complicated than other surgical procedures and require delicate tasks for a long time. Therefore, during these surgical procedures, surgeons experience back and neck pain. To solve this problem, new technology, such as wearable displays, are required so that surgeons can maintain comfortable postures and enjoy advanced functionality during microsurgery.

43Objective: The purpose of this study is to develop a surgical microscope system that will work with wearable devices. It would include a head mounted display (HMD) that can offer surgical images in 3D and allow a flexible and comfortable posture instead of fixed eyepieces of surgical microscope and can also provide peripheral visual field with its optical see-through function.

44Methods: We designed and fabricated a surgical microscope system that incorporates a see-through type 3D HMD, and we developed image processing software to provide better image quality. The usability of the proposed system is confirmed by preclinical examination. Seven ENT surgical specialists and eight residents performed mock surgery: axillary lymph node dissection on a rat. They alternated between looking through the eyepieces of the surgical microscope and viewing a 3D HMD.
screen connected to the surgical microscope. The success of the surgery was examined, and the specialists and residents were asked to grade eye fatigue on a scale of 0 (none) to 6 (severe) and posture discomfort on a scale of 1 (none) to 5 (severe). A statistical comparison was performed with a t-test, and \( P = 0.00083 \) was considered significant.

**Results:** Although 3D HMD case showed a slightly better result with regard to visual discomfort \( (P = 0.097) \), the average eye fatigue was not significantly different in either case: eyepieces and 3D HMD \( (P = 0.79) \). However, when the 3D HMD was used, the average posture discomfort was lower than when the eyepieces were used, especially in neck and shoulder pain \( (P = 0.00083) \).

**Conclusions:** We developed a see-through type 3D HMD-based surgical microscope system and showed through preclinical testing that the system can help reduce posture discomfort. The proposed system, with its advanced functions, could be a promising new technique for microsurgery.

**Keywords:** head mounted display, surgical microscope, microsurgery, 3D imaging

**Introduction**

The surgical microscope is mainly used for microsurgeries, such as in neurosurgical application, ENT (ear, nose, and throat) surgeries, ophthalmic surgeries, plastic and reconstructive surgeries, and dental treatments. Microsurgery requires accurate and stable task performance with small and delicate instruments, and surgeons spend long sessions with their eyes on the eyepieces of the microscope. Therefore, due to their awkward static postures during operations, surgeons experience back and neck pain, musculoskeletal fatigue, and injuries \([1\sim4]\). In a national cross-sectional survey of 325 ENT consultants by Babar-Craig et al., 72% reported having experienced either back or neck pain or both, with most reports coming from otologists, relating their symptoms to lengthy microscopic work and prolonged sitting. Fifty-three percent of respondents attributed their symptoms directly to previously performed ENT surgeries. Other predisposing factors include static postures and bending during endoscopic procedures, similar to their general surgical colleagues \([2]\). In a survey of five different
specialists in United Kingdom—general surgery, otorhinolaryngology, plastic surgery, orthopedic and trauma surgery and neurosurgery—results indicated that the back and neck were the most common areas of pain. Posture was the most common cause of pain (46%), followed by the use of microscopes or surgical instruments (21% each), then the use of surgical loupes or head-mounted lights (11%) [3]. However, many surgeons pay little attention to their health, and their work-related illness have been reported to be above average in comparison with those of other industries [1]. Therefore, new technologies should be adopted in the workplace to reduce posture-related discomfort, provide better visualization during surgical procedures, and help with the management of pain.

Heads-up microscopy using a high definition 3D monitor has been proposed as an ergonomic alternative. This system transmits the surgical microscopic images to a 3D monitor for the surgeon and assistants to view in more comfortable positions. It also allows the surgeon to recognize the surgical environment easily [5]. However, in head-up microscopy, a surgeon’s head and eyes are directed toward a monitor, which causes an eye-hand coordination mismatch and requires an uncomfortable posture for surgeons. Head-mounted displays (HMDs) have been adopted to solve the above mentioned drawbacks in the case of endoscopy and laparoscopy, which use the same kinds of 3D monitors [6-13]. The use of HMD helps eliminate these problems by delivering optical information directly to the surgeon’s eyes, independent of the head and body position and the position of the sources of the images. Therefore, HMDs can relieve back and neck strain and improve technical proficiency. In addition, 3D functions of the HMD-based laparoscopic system and endoscopic surgery system provide benefits such as improved operation times, minimized complications, shortened learning curves, and greater surgeon comfort [14-15].

Despite the several advantages of the HMD, the associated disadvantages still limit its use in surgery. Many of proposed HMDs have inadequate resolution, and they are bulky, cave-like, and heavy [6-10]. Although, a higher resolution HMD have recently been proposed for endoscopy, it has a fully opaque and closed, non-see-through configuration [11-13]. Since this type of HMD can only deliver virtual information to the eye, it is difficult to obtain a direct physical view and to observe the surgical environment in the operating room. Therefore, in this study, we proposed a surgical
microscope system based on a high-resolution 3D HMD with a see-through configuration that enables optical superposition of digital information onto the physical view. With the use of the proposed system, 3D surgical images can be observed with more comfortable postures and a peripheral view of the surgical field can also be easily access during microsurgery via the see-through configuration. We designed and fabricated a stereoscopic surgical microscope and see-through 3D HMD, and we developed image processing software. The feasibility of the proposed HMD-based surgical microscope system is evaluated by preclinical examination, and the results were compared with the results obtained with the conventional eyepieces of the system.

Methods

Surgical microscope system using HMD

We implemented a surgical microscope system incorporating a see-through type 3D HMD and image processing computer, as shown in Figure 1-(a). A surgical microscope is developed that is composed of a binocular headpiece with adjustable eyepieces and two CCD cameras, optical see-through type 3D HMD mounted on a headband, and image processing software. The measured surgical images are directly observed through eyepieces, and the measured surgical images from two CCD cameras on the surgical microscope are sent to an image processing computer for better image quality and for 3D image reconstruction in real time, as described in Figure 1-(b). The processed images are displayed on a monitor and the proposed 3D HMD. 2D side-by-side images are displayed on the monitor, and 3D surgical images are displayed by the HMD.
Fig 1. (a) Surgical microscope system based on see-through type 3D HMD. (b) Measured surgical images by two CCD cameras are displayed on monitor in 2D and displayed on HMD in 3D after image processing procedure.

Stereoscopic microscope

We designed and fabricated a stereoscopic microscope with two CCD cameras for use as a surgical microscope. The device employed a binocular design with a single common main objective (CMO), as described in Figure 2. The microscope was composed of a light source, two CCD cameras, and optical components: one CMO, a pair of turrets, a prism, an eyepiece, and a CCTV lens. A white LED light source (NET-260SL, Mega Medical Co. Ltd.) was attached to the illumination port of the microscope. The continuous zooming turret, having a focusing component, a zooming component, and a compensating component was adopted, and it was connected to a DC motor and foot switch. A varifocal lens with a motor drive was used for auto focusing (AF). The step control was 0.18 degrees, and the AF precision was 1.2 μm. The magnification ratio was 1x to 4x, and the object distance was 200 mm ~ 400 mm. The CCTV lens was connected to the turret lens and delivered images to the CCD cameras. HD CCD cameras (HDC-SD041BS, WatchCam Co. Ltd.) were attached next to the CCTV.
The camera had a 1/3 inch CMOS sensor, and the total pixels were 2,010 (H) x 1,108 (V). The video output was set to 1,280 x 720, which was the same as the pixel size of the microdisplay for the HMD. The measured resolution of the microscope was 79 lp at 200 mm distance and 105 lp at 400 mm distance. The microscope was implemented with water resistance of IPX4.

Fig 2. (a) Optical design of stereoscopic microscope and (b) picture of fabricated stereoscopic microscope

Table 1. Specification of the optical system of the proposed stereoscopic microscope

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>79 lp at 200 mm</td>
</tr>
<tr>
<td>CCD resolution</td>
<td>1280 x 720</td>
</tr>
<tr>
<td>Magnification</td>
<td>Continuous zoom (1:4)</td>
</tr>
<tr>
<td>Object distance</td>
<td>200 ~ 400 mm</td>
</tr>
<tr>
<td>Autofocusing resolution</td>
<td>1.2 m</td>
</tr>
<tr>
<td>Display/IPX4 Waterproof</td>
<td>Eyepieces, monitor, HMD</td>
</tr>
</tbody>
</table>

See-through type 3D head mounted display
A see-through type 3D HMD was designed and fabricated for the purpose of obtaining not only the 3D surgical image but also direct physical sight. The binocular design has two separate displays with two input channels, one for each eye, and this makes it possible to observe stereoscopic images. Optics designing software (ZEMAX LLC, Optic Studio) was used to create an optical design employing two prisms and a curved mirror. As shown in Figure 3-(a), the image from the microdisplay was enlarged and reflected by the curved mirror and then transferred to the eye after being reflected on the surface of the prism. Using a compensation prism, the physical view can be seen without distortion. A polarizing film was attached on the prism surface and a \( \frac{1}{4} \lambda \) wave plate was placed between the prism and the curved mirror to minimize optical power loss. To reduce the weight of optical module, poly methyl methacrylate (PMMA) was used in the fabrication of the optical prisms and curved mirror, and the outside of the effective optical path was cut as shown in Figure 3-(b). Optical components were attached with optical adhesive, and two optical modules were placed at the designed positions in relation to the microdisplay.

A 0.61 inch organic light emitting diode (OLED) display (MDP02BCWF, MICROOLED) with pixel sizes of 1,280 x 1024 were employed as a high-resolution microdisplay. The output pixels are set to 1280 x 720 pixels. The microdisplay driving board with an HDMI interface and USB power port was custom fabricated. The electric control board was assembled with the optical module as shown in Figure 3-(b). The integrated HMD module was mounted on a headband, and the HDMI cable and USB power cable were housed at the rear of headband for comfortable weight balance. The design of the HMD and fabricated item itself are shown in Figures 3-(c) and 3-(d), respectively. The headband is designed to adjust in size to fit any user’s head. The height and angle of the HMD module was made to be adjustable, to match a user’s eye. The measured field of view was 41 degrees in the diagonal direction, and the distortion was 2.4%. The eye relief was 15 mm and the horizontal and vertical dimensions of the eye box were 10 mm and 4 mm, respectively. The measured weight of the HMD, without the headband, was about 92 g. To deliver the surgical image dominantly, a polarization window with a transparency of less than 10% was applied in front of the HMD. Therefore, we can observe the 3D surgical image as the primary image in the field of view and can also acquire a...
Peripheral view outside of the effective area.

Fig. 3. (a) Optical design of see-through type 3D HMD and (b) integration of control board and optical module. Headband design (c) and fabricated see-through type 3D HMD (d).

Table 2. Specification of the HMD

<table>
<thead>
<tr>
<th>Specification</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>HD (1280 x 720)</td>
</tr>
<tr>
<td>Display</td>
<td>OLED</td>
</tr>
<tr>
<td>Type</td>
<td>See-through (2D/3D)</td>
</tr>
<tr>
<td>FOV (Field of view)</td>
<td>41.4 degrees (diagonal)</td>
</tr>
<tr>
<td>Eye Relief</td>
<td>15 mm</td>
</tr>
<tr>
<td>Eye box</td>
<td>10 x 4 mm (H x V)</td>
</tr>
<tr>
<td>Distortion</td>
<td>2.4%</td>
</tr>
<tr>
<td>Interface</td>
<td>HDMI</td>
</tr>
<tr>
<td>Weight</td>
<td>92.15 g (without headband)</td>
</tr>
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</table>

Image processing software

The key roles of the image processing software are improvement of the image quality and format transformation for 3D HMD. In general, the side-by-side 3D image is made from half-size left and right images reduced in the horizontal dimension, but we used full-size left and right images to
achieve better image quality for medical applications. As shown in Figure 4-(a), the captured 1280 x 720 left and right microscope images are transformed into a 2560 x 720 side-by-side image for HMD by two main image processing procedures: stereo image alignment correction and color correction. The stereo image alignment correction function is intended to restore left and right image alignment error caused by optical misalignment of the microscope. In the stereo image alignment correction process, the left and right images are converted by homography matrix. The matched feature point pairs extracted by SURF algorithm in the left and right images are used to calculate the homography matrix. After correcting the stereo image alignment, the vertical error of the matched feature points was 0%, the rotational error was 1.1°, and the zoom size error was 2%. The color correction function is intended to repair the color distortion caused by the characteristics of the camera image sensor, and therefore to make the color of the image equal to the color of the real object. We used the colorimetric matching method to correct color distortion. In this method, the characteristics of the camera sensor are modeled from the XYZ values of the original object measured by the color meter device and the RGB values of camera image. After finding the matrix of the camera model, the invert matrix of the camera matrix is used to convert the camera image to the original color. We used the 140 color ColorChecker to find the matrix of the camera model, and after correcting the color, the average CIELAB color difference between the measured color and corrected color for the 140 patches was 4.35.

In addition, we developed the GUI for user convenience functions, such as still shot, recording, play, and pause as shown in Figure 4-(b). Also, camera settings such as brightness, contrast, and sharpness can be directly controlled, which reduces software load for image processing.
Result

HMD-based surgical microscope system performance

The performances of the proposed system were evaluated by measuring test samples of capsicum annuum. Figures 5-(a) and 5-(b) represent left and right images directly captured from the eyepieces and HMD at eye position, respectively. By those slightly different angled images we can observe 3D images through the eyepieces and the HMD. Different brightness and fields of view were observed due to the different optics between the eyepieces and the CCD camera. Brighter images were observed through the eyepieces, as shown in left top images of figure 6, and better fields of view were observed via the HMD. The camera setting and image processing procedure were optimized to acquire more comfortable and microscope-like 3D reconstruction images from the HMD. Through the HMD, we can mainly observe measured object and also we can recognize environmental situation from peripheral view due to its optical see-through design, as shown in Figures 5-(c) and 5-(d).
Figure 5. (a) Measured left and right images from eyepieces, and (b) measured left and right images from HMD, (c) and (d) A demonstration of the see-through type 3D HMD.

Preclinical study

We tested the feasibility of the see-through type 3D HMD-based surgical microscope system by preclinical trial surgery. The preclinical experiment was conducted according to the protocol of the Korea University Medical Center. Male mice were used at 8 week of age. Experimental methods involving animals were approved by IACUC of Korea University. Mice were anesthesia with 2.5% isoflurane. The surgical sites were aseptically prepared and draped to provide a sterile field. Axillary lymph nodes were exposed after dissection of the skin and fascia. 3 lymph nodes were collected in each site. Collected lymph nodes should be checked and confirmed by another surgeon. Non-absorbable suture was used for skin closure. Suture removal was performed 7 days later under isoflurane anesthesia as necessary. Mice were checked-up once a day until suture removal, then once every week for a month.

We used proposed surgical microscope with and without the see-through type 3D HMD for comparison, as shown in Figures 6-(b) and (c). The experiment was a preclinical test of axillary lymph node dissection in white mice. Seven ENT surgical specialists and eight residents participated in the test, all of whom were experts in microscopic procedures. The evaluation items were the success of
the operation, the eye fatigue test, and the postural discomfort test.

Figure 6. (a) Preclinical test of axillary lymph node dissection in white mice. Preclinical test with eyepieces (b) and with see-through type 3D HMD (c).

Firstly, the success of operation was evaluated with regard to four different categories, as shown in Table 3. The failure criteria for the preclinical trial surgery were as follows.

- If the operation time exceeds 1 hour
- If the tester cannot take more than 6 lymph nodes
- If the white mice have bleeding or are unable to survive

As shown in the Table 3, the experimental results demonstrate that six trials of the surgeries using proposed 3D HMD-based surgical microscope were successfully performed without bleeding. The average operation time was similar with eyepieces and with the 3D HMD.

Table 3. Result of preclinical experiment
<table>
<thead>
<tr>
<th>Category</th>
<th>Environment</th>
<th>result</th>
<th>Success/Fail</th>
<th>Experiment success criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average operation time</td>
<td>HMD</td>
<td>21min 41sec</td>
<td>Success</td>
<td>In 1 hour</td>
</tr>
<tr>
<td></td>
<td>Eyepieces</td>
<td>22min 42sec</td>
<td>Success</td>
<td></td>
</tr>
<tr>
<td>Number of lymph node sampling</td>
<td>HMD</td>
<td>6</td>
<td>Success</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Eyepieces</td>
<td>6</td>
<td>Success</td>
<td></td>
</tr>
<tr>
<td>Bleeding</td>
<td>HMD</td>
<td>No</td>
<td>Success</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Eyepieces</td>
<td>No</td>
<td>Success</td>
<td></td>
</tr>
<tr>
<td>Survival</td>
<td>HMD</td>
<td>Survival</td>
<td>Success</td>
<td>Survival</td>
</tr>
<tr>
<td></td>
<td>Eyepieces</td>
<td>Survival</td>
<td>Success</td>
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</table>

The eye fatigue test measured subjective fatigue from 0 to 7 points for tired eyes, sore/aching eyes, irritated eyes, dry eyes, eyestrain, hot/burning eyes, blurred vision, difficulty focusing, and visual discomfort. In addition, headaches, dizziness, nausea, and decreased concentration were also evaluated. The eye fatigue test was evaluated before and after the preclinical trial surgery tests.

In the preclinical test using the eyepieces of the surgical microscope, the eye fatigue scores were in the order of tired eyes (2.3), difficulty focusing (1.9), and vision discomfort (1.9). With the use of the proposed 3D HMD technology, the results were in the order of tired eyes (1.9), difficulty focusing (1.7), and eyestrain (1.2). The paired t-test of tired eyes showed that there was no significant difference between the use of eyepieces and the use of HMD ($P = 0.79$). However, in the case of visual discomfort the $P$ value shows $P = 0.097$, which means that the HMD has the potential to help in reducing visual discomfort.

Figure 7. Results of eye fatigue test
The posture discomfort test measured discomfort with a rating of from 1 to 5 points for discomfort associated with the lower back, upper back, hand/wrist, elbow, arm, neck/shoulder, eye, and head after the preclinical test. After the preclinical test using the eyepieces of the surgical microscope, the posture discomfort scores were in the order of neck/shoulder (2.9), eyes (2.7), and upper back (2.5). With the use of the HMD-based surgical microscope, the scores were in the order of eyes (2.2), head (1.9) and neck/shoulder (1.8). The mean of the posture discomfort score without using the HMD was 18.5, and with using the HMD it was 12.5. The results of the paired t-test of posture discomfort scores showed that there was a significant difference between the use of the eyepieces and the use of the HMD ($P = 0.00083$). This results confirmed that the proposed see-through type 3D HMD can reduce posture discomfort during surgical procedures, especially regarding neck and shoulder pain.

We analyzed the total scores for eye fatigue and posture discomfort. With the use of the eyepieces, the eye fatigue scores and posture discomfort scores were distributed from 3–51 points (average 15.1) and from 12–27 points (average 18.5), respectively. When the 3D HMD was used, the eye fatigue scores and posture discomfort scores were distributed from 4–33 points (average 14.5) and from 10–17 points (average 12.8), respectively. Paired test results showed that no significant difference exists between the total eye fatigue scores for the two technologies, but there was a significant difference between the total posture discomfort scores. In conclusion, posture discomfort can be reduced by...
using the proposed see-through type 3D HMD instead of the traditional eyepieces of the surgical microscope.

Figure 9. Comparison of the scores of eye fatigue and posture discomfort of HMD and eyepieces

Discussion

Surgical microscopy is an indispensable system for microsurgery. Although with current systems surgeons can match their eye-hand coordination during surgical procedures, their eyes must be kept on the fixed eyepieces of the microscope for long periods of time, which requires them to maintain uncomfortable postures that can cause musculoskeletal disorder. To provide surgeons with the freedom to change their viewing positions, we proposed a high-resolution see-through type 3D HMD-based surgical microscope system. With this system, surgeons can obtain high definition 3D surgical images with more comfortable and flexible postures by acquiring the images from a 3D HMD mounted on a headband, instead of keeping their eyes on fixed eyepieces. Furthermore, surgeons can observe a broader surgical environment in addition to the local surgical field by using the optical see-through type configuration in the HMD design. Although we employed an optical window to block the intensity of the physical view over 90% to provide a brighter surgical image, the see-through type configuration helps in obtaining the peripheral view more easily than a non-see-through type configuration would.
The results of the feasibility study conducted by preclinical trial surgery showed that the see-through type 3D HMD can provide surgical images with performance similar to that of conventional eyepieces in terms of eye fatigue. On the other hand, the proposed system showed better performances in terms of posture discomfort. Especially, the see-through type 3D HMD system was helpful in reducing pain in the back, neck, and shoulders, which are the main areas of pain experienced by surgeons.

In this proposed system, we employed a headband design to remove the weight from the user’s nose. We also used lightweight material for the optical module and the nonessential area was cut away to minimize the weight of the HMD. However, additional efforts are required to reduce the weight while maintaining a large field of view. By employing a thin and light weight optical module, such as waveguide or light guide, an HMD with more compact glasses can be achieved [20]. With recent technologies, additional functions of the HMD are easily accessible, such as voice control and a display of additional medical information. And by using several HMDs, assistants or students can see the same surgical images as surgeons, which will be helpful in making surgeries and medical education more effective. We are planning to improve the proposed system in our future work.

Conclusions

We have introduced a high-resolution, see-through type 3D HMD-based surgical microscope system that is suitable for stable and comfortable microsurgery with advanced functions such as flexibility of viewing posture and a broad surgical view. The results of the preclinical examination showed that the proposed system has sufficient performance to relieve posture discomfort. The proposed system would be very useful as an ergonomic surgical tool in various surgical fields.

Acknowledgments

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### Abbreviations

- **HMD**: Head-mounted display
- **FOV**: Field-of-view
- **CCD**: Charge-Coupled Device
- **PMMA**: Poly Methyl Methacrylate