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Distorted depth perception under the microscope : compensation by surgical navigator and image projection

Amami Kato

Department of Neurosurgery, Kinki University School of Medicine, Osakasayama, Osaka 589-8511 Japan

Abstract

Object. Spatial perceptions by the naked eye and under the surgical microscope were compared between groups of experienced and inexperienced neurosurgeons to understand distortion in the three-dimensional recognition of the surgical field.

Methods. A phantom surgical field containing a start point, arbitrarily set virtual gate, and a target point was fixed under a video-see-through microscope which allows projection of navigational image into microscopic view. The surgical navigator was used to record the spatial position of the suction tip. Examinees were first shown the position of the invisible virtual gate. Then they were asked to point consecutively to three points with the suction tip under four different visual conditions; by the naked eye, under the microscope, under the microscope while watching a navigator monitor, and under the microscope with projection of navigational image. The pointing deviation from the suction tip to the virtual gate, the trajectory of suction tip and the operation time were evaluated.

By the naked eye, pointing accuracy did not differ between the two groups. However, accuracy under the microscope was significantly worse in inexperienced group. Further analysis demonstrated that these differences were attributable to inaccurate depth perception. With the navigational image projection, the accuracy and the operation time were significantly improved in both groups.

Conclusions. Under the microscope, the spatial perception was considerably distorted, especially in the depth component. Application of the navigator improved this perception considerably. The navigational image projection into the microscope further improved spatial perception and lead to better visuomotor coordination under the microscope.

Key words : neurosurgical microscope, depth perception, binocular vision, neuronavigation, virtual reality, image projection

Introduction

Under the surgical microscope, surgeons observe the surgical field under unique conditions. The effects of magnification and the unnatural binocular view on the surgeon's three-dimensional perception are complicated. We have found a considerable distortion in depth perception of the surgical field.[9] The recognition as well as correction of this visual distortion are undoubtedly important for improving the safety of neurosurgical procedures. In this study, we examined spatial perception under a video-see-through microscope to clarify the details of distorted perception of the phantom surgical field and tested compensation for this visual distortion using a surgical navigator[12,13] with and without the projection of the navigational image into the microscopic view.[23]

Methods

The experimental set-up consisted of a phantom representing the surgical field, a neurosurgical navigator[12,13] (CANS Navigator; Shimazu Corp., Kyoto, Japan) to record the positions of the suction tube (the pointing probe), and a video-see-through microscope (Fig. 1).

Examinee

The examinees were 12 medical doctors. Six of them were neurosurgeons who had experience with microsurgery for 3 years or more (experienced group), and the rest was residents who had experience with microsurgery for less than 1 year or not at all (inexperienced group).

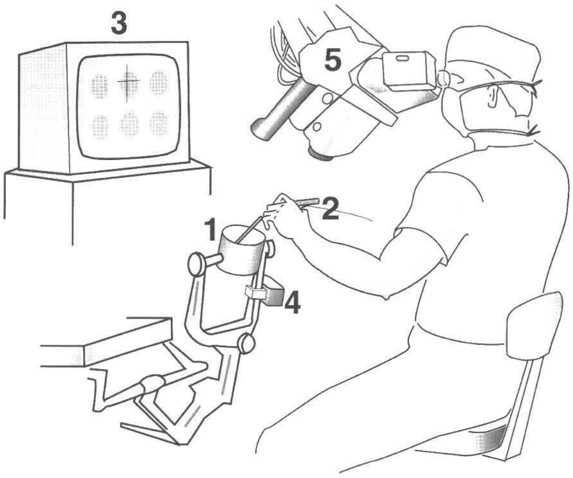

Fig. 1 The experimental set-up. The phantom is fixed with a resin head clamp and placed under the video-see-through microscope. 1: Phantom surgical field. 2: Suction tube. 3: Neurosurgical navigator. 4: Magnetic source of the navigator. 5: Video-see-through microscope.

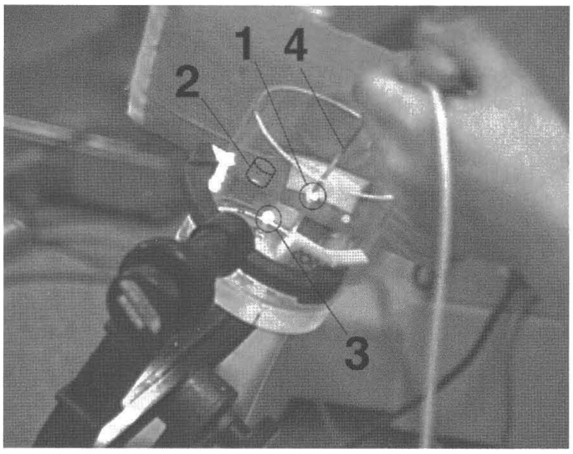

Fig. 2 The phantom surgical field containing 1: start point, 2: virtual gate and 3: target point. The virtual gate is an invisible zone arbitrarily set and only identifiable on the navigator display. The neurosurgeons were asked to point with the 4: suction tube from the start point to the target point via the virtual gate. The positions of the suction tip were recorded with the navigator for subsequent analysis.

Phantom

The phantom surgical field was an open cylinder (diameter, 10 cm; length, 10 cm) made of acrylic resin (Fig. 2). With a cylinder placed on its end, reference plane was set at the base according to an orthogonal coordinate system. A start point and a target point, made of small resin spheres (6 mm in diameter), were placed on thin rods at the coordinates $(-30, 0, 66)$ and $(27, 2, 10)$, respectively. T1-weighted MR images of the phantom were obtained for navigation at a slice thickness of 5 mm. The virtual gate, which was an imaginary cylindrical object 10 mm in diameter and length, was positioned on the MR images at the coordinates $(0, -30, 32)$. Thus, the virtual gate was an invisible zone, demonstrated only on the navigation display.

CANS Navigator

Utilizing electromagnetic coupling technology, the CANS Navigator detects and records the spatial position and orientation angle of a suction tip attached to a magnetic sensor. To use this navigator in the present study, the phantom and magnetic source of the navigator were fixed to a skull clamp made of carbon fiber resin and attached to an operating table, simulating the surgical setup. The coordinate system of the phantom was then registered using fiducial markers.[12,13]

Video-see-through microscope

The video-see-through microscope used in this study was based on a standard surgical microscope (OME-6000, Olympus, Tokyo, Japan) but with modified eyepieces, into which video pictures of the surgical field taken with two CCD units behind the objective lens were projected. Processing the video signals, another video image was projected into the microscopic field of view, at the right upper part of the operator's central visual field, for both eyepieces. Initially, this microscope was developed for open neuroendoscopy and the endoscopic image was projected onto the field of view.[23] In the present study, the navigational image was displayed. The operator can watch both the operative field and the navigational image in which the position of the

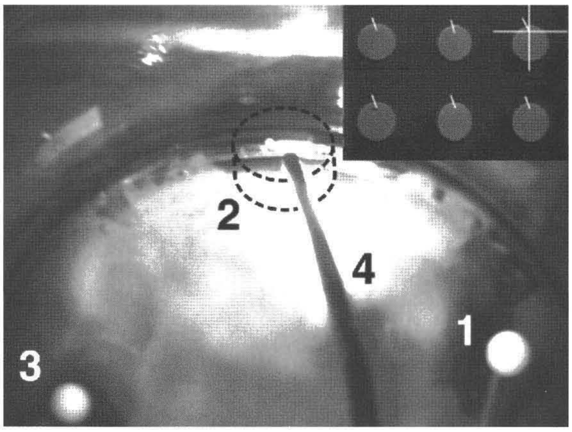

Fig. 3 Microscopic view of the phantom surgical field with the image projection. The navigational image indicating the suction tip at the center of the virtual gate is displayed at the right upper corner of the microscopic image. 1 : Start point. 2 : Virtual gate. 3 : Target point. 4 : Suction tube.

suction tip is indicated by a cursor simultaneously (Fig. 3). Coordinates of the suction tip were recorded on the CANS Navigator at 7 points per second on average and analyzed afterward.

Examination procedure

With the examinee seated, the examiner (M.H.) indicated to each examinee the position of the virtual gate by pointing to it for 1 minute with the suction tip. Five minutes later, each examinee was asked to manipulate the suction tip to locate it on the start point, the virtual gate, and the target point consecutively in this order as accurately and promptly as possible under each of the following four conditions ; by the naked eye, under the microscope, under the microscope while watching the navigation monitor, under the microscope with navigational image projection in its field of view. The exercise was performed eight times under each conditions. In the initial four exercises, the examinee was asked to point the suction tip at supposed center of the virtual gate for 5 seconds during manipulation so the pointing deviation could be evaluated.

Analysis

The distances from the center of the virtual gate to the suction tip were calculated from the three-dimensional data recorded by the CANS Navigator. The distances and time used were averaged for each trial for each individual, and the results were defined as the pointing deviation and operation time. The pointing deviations were further classified according to the depth component (component parallel to the optic axis of the microscope) and the horizontal component (component perpendicular to the optic axis). The trajectory of the suction tip was graphically displayed and morphologically examined. The statistical significance of the differences in these values was determined by the Student's paired t-test. Differences were considered to be significant at $p < 0.05$.

Results

Differences in mean pointing deviations and mean operation times between conditions

The mean pointing deviations for all the examinees and the respective standard deviations between individuals were 8.6±3.0 mm by the naked eye, 14.7±11.6 mm under the microscope, 4.2±1.6 mm under the microscope while watching the navigation monitor, and 4.0±1.6 mm with the image projection (Table 1). The mean operation times under the four conditions were 3.9±1.6 sec by the naked eye, 3.0±0.6 sec under the microscope, 9.5±3.3 sec under the microscope while watching the navigation monitor, and 5.8±2.0 sec with the image projection (Table 2). The operation time was longest under the microscope while watching the navigation monitor, in which the operator had to alternate his observations between the microscope and the navigational monitor.

Pointing deviations under the microscope

The mean pointing deviations for the experienced group were 7.7±3.3 mm by the naked eye and 7.0±3.0 mm under the microscope. Those for the inexperienced group were 9.5±2.3 mm by the naked eye and 22.0±12.1 mm under the microscope (Table 1). The pointing deviations did not differ significantly between both groups by the naked eye. However, in the inexperienced group, the pointing deviation under the microscope was twice of that by the naked eye ($p < 0.006$, Table 3), whereas in the experienced group the pointing deviation under the microscope was slightly less than that by the naked eye ($p < 0.5$, Table 4) both in depth and especially in horizontal components ($p < 0.03$). With respect to pointing fluctuation, the standard deviation under the microscope in the inexperienced group was significantly greater than in the experienced group, and it was also greater than by the naked eye. When the pointing deviations under the microscope were analyzed according to the depth and

Table 1 Pointing deviations of experienced and inexperienced neurosurgeons under the different visual conditions.*

	Pointing deviations (mm)			
	With naked eye	Under microscope	Under microscope with navigator	Under microscope with image projection
Experienced group	7.7±3.3 (4.7, −3.5)	7.0±3.0 (2.9, −3.2)	4.2±1.5 (2.9, −2.3)	3.9±1.2 (2.9, −0.8)
Inexperienced group	9.5±2.3 (8.1, 0.6)	22.0±12.1 (6.6, 19.2)	4.1±2.3 (3.3, −0.2)	4.2±2.0 (3.3, 1.0)
All examinees	8.6±3.0 (6.5, −1.4)	14.7±11.6 (4.8, 8.4)	4.2±1.6 (3.1, −1.2)	4.0±1.6 (3.1, 0.2)

*Values are expressed as the mean±SD (mean horizontal component, mean depth component). A negative mean depth component indicates pointing was deeper than the target.

Table 2 Operation time.*

	With naked eye	Under microscope	Under microscope with navigator	Under microscope with image projection
Inexperienced group	3.7±1.3	3.1±0.6	9.5±3.2†	6.5±2.3†
Experienced group	4.1±2.0	2.9±0.6	9.6±3.6‡	5.1±1.2‡
All examinees	3.9±1.6	3.0±0.6	9.5±3.3§	5.8±2.0§

*Values are expressed as mean±SD in seconds
†, ‡, §: Significant difference between marked values (†p<0.009, ‡p<0.01, §p<0.0003)

Table 3 Statistical comparison of pointing deviations of inexperienced neurosurgeons under the different visual conditions.*

	With naked eye	Under microscope	Under microscope with navigator	Under microscope with image projection
With naked eye	—	0.0006†	0.000002†	0.00002†
Under microscope	0.0006†	—	0.00005†	0.00005†
Under microscope with navigator	0.000002†	0.00005†	—	0.9
Under microscope with image projection	0.00002†	0.00005†	0.9	—

*Statistical comparison between conditions is made by Student's paired t-test and expressed by p-value.
†Statistical significance (p<0.05).

Table 4 Statistical comparison of pointing deviations of experienced neurosurgeons under the different visual conditions.*

	With naked eye	Under microscope	Under microscope with navigator	Under microscope with image projection
With naked eye	—	0.5	0.005†	0.0007†
Under microscope	0.5	—	0.009†	0.003†
Under microscope with navigator	0.005†	0.009†	—	0.4
Under microscope with image projection	0.0007†	0.003†	0.4	—

*Statistical comparison between conditions is made by Student's paired t-test and expressed by p-value.
†Statistical significance (p<0.05).

horizontal components, the deviation in the horizontal component was smaller than the deviation in the depth component. The directions of the deviations were so variable for each examinee that no particular tendency was observed.

Pointing deviations under the microscope using the navigator and image projection

The mean pointing deviations for the experienced group were 4.2±1.5 mm using the navigation monitor and 3.9±1.2 mm with image projection. Those for inexperienced group were 4.1 ±2.3 mm using the navigation monitor and 4.2 ±2.0 mm with image projection.

By introducing the navigator, the pointing deviation decreased significantly in both the inexperienced and the experienced groups ($p < 0.00005$ and $p < 0.009$, respectively, Tables 3 and 4). The absolute values of the deviation were around 4 mm (3.9-4.2 mm, Table 1) which is considered the limitation of manual holding of the suction tube with or without the navigator. The pointing deviation with navigational image projection was quite close to that while watching navigation monitor, but the operation time was significantly shorter ($p < 0.01$ for each group). Most of the operation time under the microscope while watching the navigator was used to put the cursor at the virtual gate on the navigator display (Table 2).

Trajectory of the suction tip

The trajectories of the suction tip under the above conditions are illustrated in Fig. 4. By the naked eye or under the microscope, the suction tip sometimes failed to pass the invisible virtual gate. The trajectory under the microscope while watching the navigator was the longest and showed the oscillation before reaching the virtual gate, whereas the trajectory with image projection was closest to the imaginary ideal trajectory connecting the start point, the virtual gate and the target point with a straight line. Under the microscope, the trajectory tended to bend upward compared with the trajectory by the naked eye.

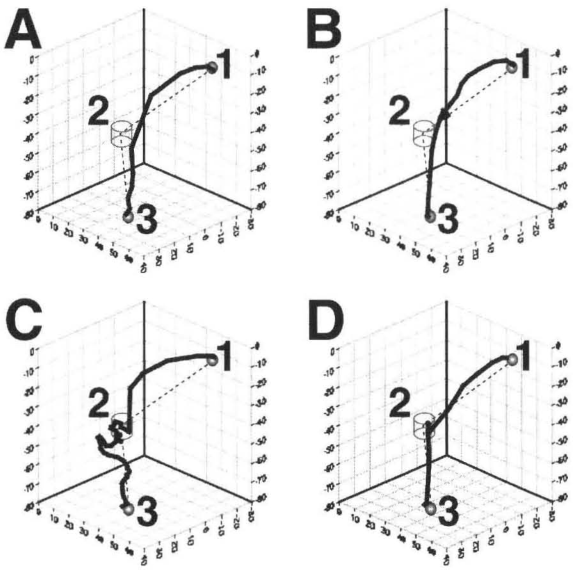

Fig. 4 Illustrative trajectories of the suction tip (black lines). A : by the naked eye. B : under the microscope. C : under the microscope while watching the navigation monitor. D : under the microscope with navigational image projection in its field of view. Note the trajectory does not pass the virtual gate in A and B, the trajectory is bent upward and oscillating around the virtual gate in C, and the trajectory is close to the shortest linear route (dotted lines) in D. 1 : Start point. 2 : Virtual gate. 3 : Target point.

Discussion

Depth perception under the microscope

In inexperienced surgeons, both the deviation and fluctuation in pointing were significantly greater under the microscope than by the naked eye, whereas in the experienced surgeons the deviation under the microscope was significantly smaller than that by the naked eye. These results suggest that the experienced surgeons fully utilized the fine spatial information from the microscope, whereas the inexperienced surgeons did not. Analyzing the pointing deviation by its depth and horizontal components disclosed that this discrepancy was attributable to the depth component, not the horizontal component. These tendencies were quite similar to the tendencies noted in our previous study[9] in which we used a popular neurosurgical microscope (OPMI CS ; Zeiss Corp., Oberkochen, Germany) and might represent universal phenomenon in use of the microscope. Moreover, the trajectories of the suction tip under the microscopic manipulation proved to be more or less curved upward regardless of operators' microsurgical experience. This indicates that the depth of the object proximal to the microscope focus might tend to be overestimated.

Under the microscope, manipulation is performed remotely using surgical instruments in a magnified surgical field. It may be considered as a primitive virtual reality (VR) in the microworld. Such a primitive VR world is reportedly different from the real world and unnatural, and specific visual characteristics are engaged.[8,14,17,24] Adaptation to the distorted visual field may occur fairly rapidly by experience and training,[11] but there is considerable variation among individuals.[16]

Visual cues

Depth perception is shaped by accommodation, convergence, and various visual cues such as familiar objects, motion, perspective, texture, shade, shadow, and size, in addition to binocular stereopsis.[7,18,20] The phantom used in this study was made simple to clarify the visual characteristics of the microscope. Therefore, depth information from the visual cues was very limited. In actual surgery, these visual cues would be abundant,[19] and other nonvisual factors such as the sense of position and tactile cues from the surgeon's hand may reinforce the depth information.

In the general microsurgical technique, use of the lowest level of magnification necessary for manipulation has been recommended.[3,19,25] In other words, the best technique is to use the visual cues as much as possible. Major visual cues might be lost, however, when the surgical field is unclear due to the bleeding or when the surgical field is too narrow for binocular stereopsis. Inexperienced surgeons or even panicked experienced surgeons might run the risk of inadequate manipulation from the loss of surgical orientation in such situations.

Application of the navigator and image projection

With the navigation system, the pointing became significantly accurate. This may mean that information from the navigator was used as another visual cue for locating the memorized target, since the VR gate was observed only on the navigator display. In actual surgical manipulations, surgeons refer to their knowledge of local anatomy around the lesion. This might not be enough, however, for correct surgical orientation, since memorized anatomical vision could be discrepant with the actual space. Inspection of the navigator screen displaying the position of the probe has been conventional during navigator-guided microsurgery. In our experiment, however, this inspection interrupted the manipulation under the microscope and prolonged the operation time by two to three times. Moreover, it is undesirable for the surgeon, because it forces moments of watching away from the operative field. Even a small movement of the tip of the navigational probe in a limited anatomical space may injure important structures, unless it is done under direct visual control through the microscope. Thus, the simultaneous observation of microscopic and navigational images is essential for safe and practical navigator-guided microsurgery. This can be conveniently achieved with our image projection system. In this study, manipulation under the microscope with navigational image projection was most accurate and prompt. This setting even improved the concavity of the trajectory, bringing it closer to the shortest linear route. With simultaneous observation of microscopic and navigational images, the operator would be confident of localizing the VR gate and could drive the suction tube without hesitation.

Recent neurophysiological studies have revealed a close correlation between depth perception and visually-guided hand movements in primates including humans.[2,5,15] At least five classes of neurons are so far identified that selectively respond to depth-selective visual-fixation, depth-movement, depth-rotation, visually responsive manipulation, and axis-orientation.[21] These neurons in the parietal association cortex form a neural network coding motion, spatial position, and spatial orientation of an object,[6,22] which is connected to the premotor area and plays an essential role in integrating all the visual cues needed for manipulation.[4,5,21] Since neural representation in the surgeon's brain of three-dimensional objects with real physical dimensions or their motion is essential for the visual guidance of goal-directed hand action, precise perception of the surgical space is mandatory for accurate microsurgical manipulation.

Interfacing between virtual and real worlds

More and more applications of VR technology are being introduced into the field of neurosurgery such as surgical navigation, endoscopy and robotics.[1] The interface between the real and virtual world is not less important than the creation of the virtual world itself, because the discrepancy between the two worlds may lead to incorrect or inappropriate surgical manipulations.

Methods of interfacing the two worlds can be classified as dense coupling and sparse coupling methods. Assume the real world to be an image of the surgical field and the virtual world to be the navigational image generated by the computer, direct overlay of the VR image on the surgical field, as in Volumegraph[10] for example, would be an illustrative dense coupling, where the overlapped VR image would hinder detailed inspection of the surgical field ; watching the navigator monitor at will would be an illustrative sparse coupling, where frequent changes in the line of sight would reduce the operative performance. The image projection method proposed in this study, allowing minimal switching between points of reference, enables simultaneous inspection of the virtual image and real image within the operator's central visual field. The operator can switch his gaze between images swiftly without moving his head, and focus readily on the surgery itself. Projection of navigational image into the microscope field is an effective and practical method of interfacing the real and virtual images in the microneurosurgery.

Conclusions

The relative visual distortion under the binocular surgical microscope became evident in this study. This distortion can be compensated for in part by use of the surgical navigator, especially coupled with image projection to the microscope. It may also be important to develop a binocular microscope which minimally distorts the spatial perceptions in order to improve the safety of microscopic surgery.

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