The Trans-Visible Navigator: A See-Through Neuronavigation System Using Augmented Reality

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■ INTRODUCTION: **The neuronavigator has become indispensable for brain surgery and works in the manner of point-to-point navigation. Because the positional information is indicated on a personal computer (PC) monitor, surgeons are required to rotate the dimension of the magnetic resonance imaging/computed tomography scans to match the surgical field. In addition, they must frequently alternate their gaze between the surgical field and the PC monitor.**

■ OBJECTIVE: **To overcome these difficulties, we developed an augmented reality-based navigation system with whole-operation-room tracking.**

■ METHODS: **A tablet PC is used for visualization. The patient's head is captured by the back-face camera of the tablet. Three-dimensional images of intracranial structures are extracted from magnetic resonance imaging/computed tomography and are superimposed on the video image of the head. When viewed from various directions around the head, intracranial structures are displayed with corresponding angles as viewed from the camera direction, thus giving the surgeon the sensation of seeing through the head. Whole-operation-room tracking is realized using a VICON tracking system with 6 cameras.**

■ RESULTS: **A phantom study showed a spatial resolution of about 1 mm. The present system was evaluated in 6 patients who underwent tumor resection surgery, and we showed that the system is useful for planning skin incisions as well as craniotomy and the localization of superficial tumors.**

■ CONCLUSIONS: **The main advantage of the present system is that it achieves volumetric navigation in contrast to conventional point-to-point navigation. It extends augmented reality images directly onto real surgical images, thus helping the surgeon to integrate these 2 dimensions intuitively.**

INTRODUCTION

In 1986, the concept of the neuronavigator was first invented and described.[1] Since then, the neuronavigator has come into wide use as a surgical guiding tool that is indispensable for neurosurgeons during intracranial surgery. It indicates precisely where the surgeon is looking during surgery using magnetic resonance imaging (MRI)/computed tomography (CT) coordinates. With a neuronavigator, an operator can reach the target accurately and safely in an intracranial space with a limited operative field. Neuronavigators have greatly improved the quality and efficiency of surgery. Although various navigator systems have since been developed[2-4] and have become commercially available, their specifications are based on indicating the position of the probe using point-to-point navigation. This means that when the operator points to the surgical field with an indicating probe, the corresponding location is indicated by a cursor on the MRI/CT image. Surgeons, therefore, are required to

Key words
- Augmented reality
- Motion capture
- Navigator
- Tablet PC

Abbreviations and Acronyms
3D: Three-dimensional
AR: Augmented reality
CT: Computed tomography
HMD: Head-mounted display
MRI: Magnetic resonance imaging
PC: Personal computer
SD: Standard deviation
TVN: Trans-Visible Navigation

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create a three-dimensional (3D) mental image of the MRI/CT views to match the surgical field. In addition, they must frequently alternate their gaze between the surgical field and the personal computer (PC) monitor. To overcome this difficulty, several navigation systems have been developed using augmented reality (AR) techniques.[5-7] We have also invented a new guiding system that enables surgeons to see intracranial structures virtually overlaid on the patient's head as if they were looking directly into the head. We have named it the Trans-Visible Navigation System (TVN); this system fully adopts the AR technique.

In the TVN system, a tablet PC is used for the purpose of visualization (Figure 1). The patient's head, fixed to the operating table, is captured by the back-facing camera of the tablet. 3D images of intracranial structures such as brain tumors and blood vessels are generated from MRI/CT data and are superimposed on the video image of the head. When viewed from various directions around the head, intracranial structures are projected with corresponding angles as viewed from the camera direction, thus giving the surgeon the sensation of seeing through the head.

The TVN system incorporates a whole-operation-room navigation system. Conventional neuronavigator systems tracked the 3D position of a probe with 2 cameras (Polaris [Northman Digital, Canada]). Because tracking is performed from a single direction, blind spots are unavoidable, meaning that tracking is frequently interrupted during navigation by doctors, nurses, surgical microscopes, and other surgical equipment. In the TVN system, a motion capture system is used to make whole-operation-room navigation possible. Tracking can be accomplished if the probe reflective balls are captured by at least 2 of the 6 cameras, thereby making it possible to continue navigation with minimal blind spots.

The advantage of this new system over conventional systems is that it enables volumetric see-through navigation with minimal blind spots (Supplementary Video).

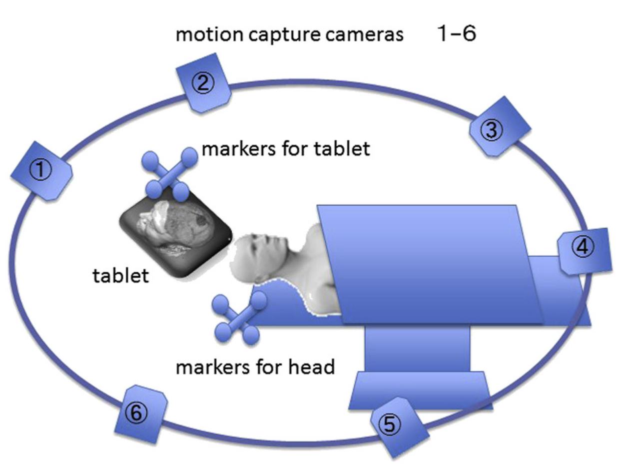

Figure 1. System diagram. Six motion capture cameras are placed on the ceiling of the operation room. Reflective balls are attached to the tablet personal computer and skull clamp.

METHODS

We used a 3D motion capture system equipped with 6 cameras (VICON, Oxford, UK) with 200-Hz sampling frequency. Six cameras for motion capture are installed on the ceiling of the operating room in a circle around the patient's head (Figure 1). The diameter of the circle is about 6 m. The location of the target object is calculated by the VICON system and data are transferred to a tablet PC Surface (Microsoft, Redmond, Washington, USA) via Wi-Fi. Overall mechanical accuracy is reported to be 0.57 mm.[4] All computation of image registration is performed on a tablet PC. Programming used Unity Pro (Unity Technologies, San Francisco, California USA).

MRI and CT data were obtained with a matrix of $512 \times 512 \times 270$ voxels and were coregistered after automatic image fusion corresponding to the skin surface. The voxel size was 0.5 mm isometric. We used imaging software (Amira [FEI, Hillsboro, Oregon, USA]) to generate segmental surface data in connection with the brain, tumors, the skull, arteries, and veins, etc. in OBJ format. These data were then transferred to the original software running on the tablet PC.

Motion Capture Cameras

VICON tracks the location of several reflective marker balls (diameter, 15 mm), which are placed on the tablet PC (6 markers), a pointing device (4 markers), and the patient's head (5 markers). The positions of the cameras are defined to minimize the blind spots produced by doctors, microscopes, and other large equipment. The VICON system defines a world coordinate system adapted to the operation room. During surgery, the system tracks the head of the patient and also the tablet PC in terms of world coordinates. Every further calculation is performed based on world coordinates.

Tracking Using a Tablet PC

A tablet PC is used for visualization purposes. Six reflective balls for motion capture are attached to the tablet. The vector and the line of sight position of the back-facing camera of the tablet are tracked by the VICON system and the data are transmitted from this system to the tablet via Wi-Fi.

Pointing Device

A stick-like device carrying 4 reflective balls for motion capture is used to point to any place in the world coordinate system to obtain coordinates for the fiducial points during registration of the patient's head.

Registration of the Head

The principle of the TVN system is to place the preoperative MRI/CT data in world coordinates in the same location, size, and angle as the patient's head. Three natural landmarks such as the nasion and the bilateral preauricular points were used as fiducial points for head registration. We developed 3 steps to accomplish this. First, the MRI/CT coordinates of these 3 fiducial points were registered by means of a mouse pointer on the PC screen. Second, the world coordinates of 3 fiducial points on the patient's head were obtained using a pointing device. The coordinates of 3 points on the MRI/CT corresponding to the 3 fiducial points were transferred to the tablet PC in such a way that the digital head model was overlaid in the same location as that of the real head in the operating room.

Coregistration of Virtual Image and Camera Image

This is the final stage in achieving AR. We used 2 steps.

Alignment of the tablet camera is tracked by the VICON system. The 3D rendered image of the virtual head is then generated as it appears on the tablet camera. The resulting image of the head is overlaid onto the camera image. Because the MRI/CT is already located in the same position as the actual head, the camera image and the virtual head fit together (Figure 2).

Dry-Laboratory Study. Before clinical trials, dry-laboratory experiments were performed using a plaster model of the head of a patient with a brain tumor made using a 3D printer. A pair of distinctive and practical landmarks that could be easily identified on both camera and virtual images were selected, and the discrepancy between the 2 images was measured on the tablet screen for the purpose of error analysis.

Accuracy Assessment. We used a specially designed accuracy assessment jig to assess the accuracy of the present TVN system. The assessment jig[8] consisted of cross markers and 3 fiducial points painted on a rigid sheet, as shown in Figure 3A,B. Fiducial points are arranged to constitute a trigon (160 mm × 100 mm) mimicking the bilateral ears and nasion. Because the TVN system shows an image overlaying the video image, the depth information is difficult to evaluate. We then measure the accuracy of X and Y with various distances (30, 40, 50 mm) between the tablet camera and the object (Figure 3C). The accuracy test was repeated 10 times for each camera—object distance and displacement error was measured.

Clinical Usage. We evaluated the feasibility of the system in 6 clinical cases (2 convexity meningiomas, 1 cerebellar metastatic tumor, 1 cerebellar hemangioblastoma, and 2 frontal metastatic tumors).

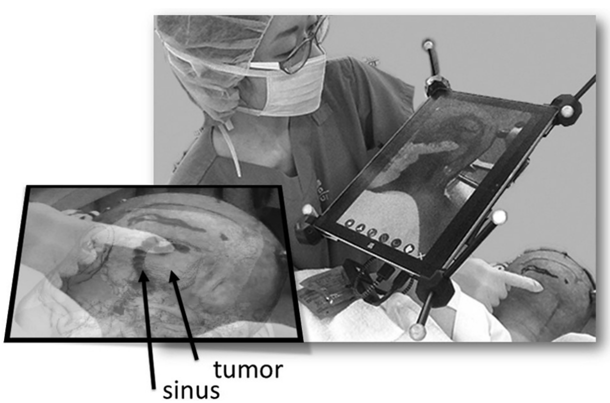

Figure 2. The surgeon holds the tablet personal computer and views the patient's head through the back-facing camera. (*Inset*) Virtual three-dimensional images are overlaid on the video image.

To ensure safety during surgery, we used a conventional navigation system simultaneously with the TVN. Because the tracking cameras of the conventional navigation system and the TVN did not conflict with each other, the conventional navigation system worked well, simultaneously sharing the same reference and pointing devices. We performed the registration of the patient's head for each system individually.

RESULTS

Dry-Laboratory Study

We performed the TVN see-through navigation using a plaster head model. Pairs of landmarks were selected and the distance between the corresponding markers were averaged to determine the overall alignment error of the projection image and the camera image.

An error evaluation test was conducted 10 times for 3 different camera—phantom distances (30 mm, 40 mm, and 50 mm). The alignment errors in the X—Y plane with a camera—jig distance of 30 cm, 40 cm, and 50 cm were found to be 1.03 mm ± 0.64 mm (standard deviation [SD]), 1.03 mm ± 0.54 mm (SD) and 0.90 mm ± 0.67 mm (SD), respectively.

Operating Room Experiment. We evaluated the position of 6 capture cameras located in the operating room to reduce the number of blind spots. The operating room was arranged similarly to an ordinary operating theater to include doctors, nurses, a surgical table, and several other items such as a microscope, surgical lights, and anesthetic equipment. The plaster model of the patient's head was fixed to the skull clamp as in an authentic surgery. Every possible place around the head model was then tracked by VICON using the tablet equipped with reflective balls. In our setup of the operation room, the camera arrangement was thought to be appropriate, with no blind spots.

CLINICAL TRIAL

Case 1

This was a 65-year-old woman with a convexity meningioma on the right central area.

The patient's head was registered using the nasion and bilateral preauricular points. The tablet was held in the surgeon's hand and moved around the patient's head to evaluate the overlaid scalp image on the tablet and to ensure that the edge of the virtual scalp was overlaid accurately on that seen in the camera image. Other visible landmarks such as the nasion, top of the nose, and eyelids were also used in the evaluation. The virtual tumor and veins were then displayed on the tablet. These images were displayed in such a way as to be overlaid on the camera image (Figure 4). Because the image of the surgeon's hand was also displayed on the tablet screen, the surgeon could easily plan the surgical approach and skin incision correctly. During surgery, the tablet was covered with a sterilized plastic bag and was held over the surgical field by an assistant to aid the surgeon in making an appropriate approach to the tumor both intuitively and accurately.

In planning this surgical approach, the surgeon had no need to alternate his gaze between the PC screen and the surgical field as when using the usual navigation system because the intracranial

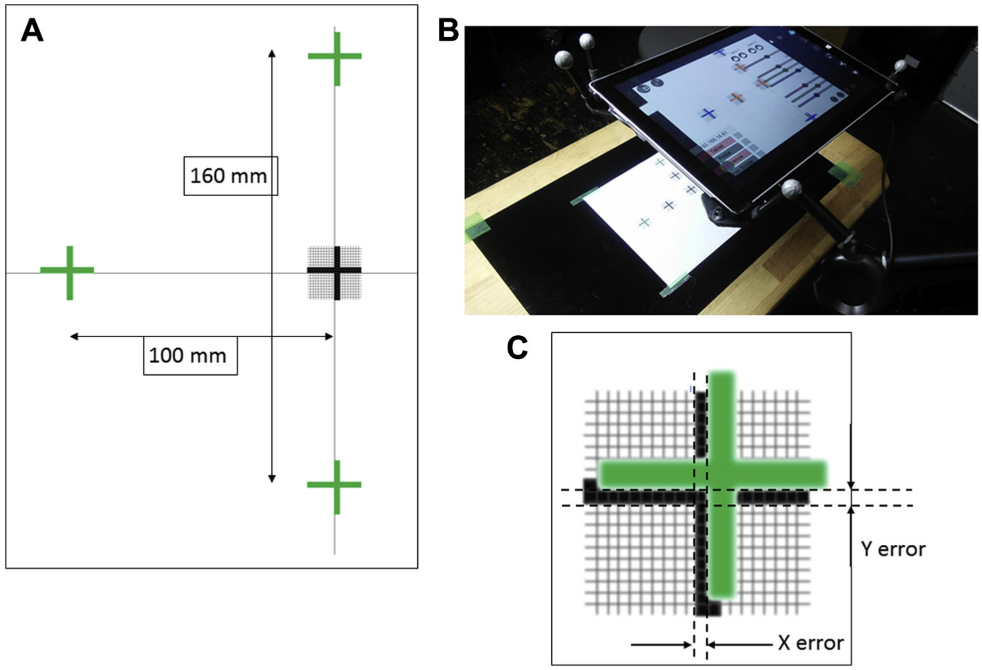

Figure 3. (**A**) Accuracy assessment jig. Green crosses are fiducial markers and a black cross was used as the measuring point. (**B**) The tablet was fixed over the phantom. (**C**) Video image of the cross mark (*black*) on the phantom and the three-dimensional image of the cross mark (*green*) indicate the registration error in the X and the Y axes.

target was directly overlaid on the video image of the patient's head. Because the extent of the tumor and intervening veins could be directly viewed, an appropriate approach avoiding the veins was determined correctly.

Case 2

A 68-year-old woman with a metastatic brain tumor received an operation with TVN guidance. The tumor was located in the right middle temporal gyrus. A virtual craniotomy was performed using the imaging software Amira in the appropriate place and at the correct size (Figure 5). The skull with craniotomy was visualized and overlaid by TVN on the surface of the head and the edge of the virtual craniotomy was correctly transferred with a finger by the surgeon.

Case 3

A 57-year-old woman with a diagnosis of a cerebellar hemangioblastoma underwent tumor resection. A ventricular tap was performed from the right occipital lobe before infratentorial tumor resection. TVN was used to guide the needle trajectory. The lateral ventricle was visualized on the tablet screen simultaneously with the video image of the tapping needle (Figure 6A). The trigon of the lateral ventricle was aimed at by extrapolating the direction of the needle seen from various angles (Figure 6B). The tapping was successfully performed on the initial tap with the TVN system.

Additional Time Expenditure Needed for Setting Up

Segmentation. We used Amira software for the extraction of the brain structures. For segmentation of the skin, bone, artery, vein, and tumor, it took only about 3 minutes for each structure if the segmentation was possible with only threshold standing on the image intensities. If the tumor, for example, was difficult to discriminate only with the intensities, manual extraction was required. For such cases, it took up to 30 minutes for segmentation.

Head Registration. Because we used only 3 fiducial points for registration, it took about 3 minutes for registration and 3 minutes for validation.

DISCUSSION

The present TVN system enables intraoperative see-through visualization of intracranial structures through the superimposition of 3D digital images onto a video image captured by the back-face camera of a tablet PC. The system is supported by a motion capture system (VICON) using 6 cameras installed on the ceiling of the operating room. The whole space of the operating room is scanned by the cameras to ensure that there are minimal blind spots.

The surgeon or the assistant holds the tablet during surgery and observes the patient's head through the tablet camera. Even when the head is viewed from other directions, intracranial structures

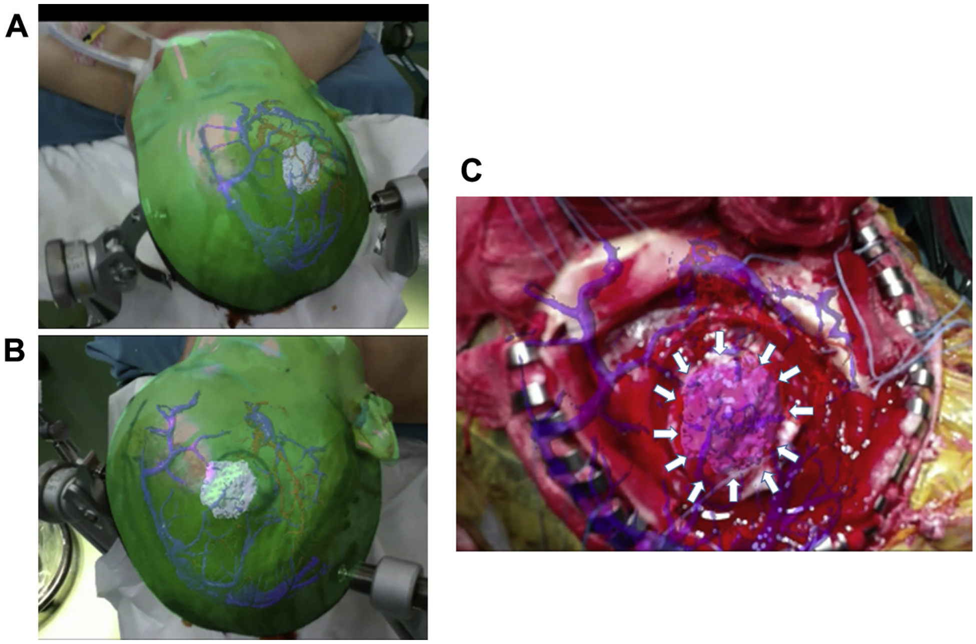

Figure 4. Trans-Visible Navigation screen shots of case 1. Superior sagittal sinus, bridging veins, and convexity meningioma are displayed. (**A**, **B**) The skin image is overlaid correctly on the video image of the head. (**C**) After craniotomy, three-dimensional image of the meningioma (*arrowheads*) is correctly overlaid on the real tumor.

are superimposed to follow the movements of the patient's head on the tablet. Visualization is therefore carried out on the tablet as if the head were translucent, and the internal structure is seen through the head. Ideal access to the intracranial target can be determined intuitively if these conditions are achieved before craniotomy. Moreover, if the bridging vein or structures to be protected are specified in advance, an appropriate approach to the target avoiding these areas can be intuitively determined. This is useful especially in the case of suboccipital craniotomy because the location of the sinus can be directly visualized.

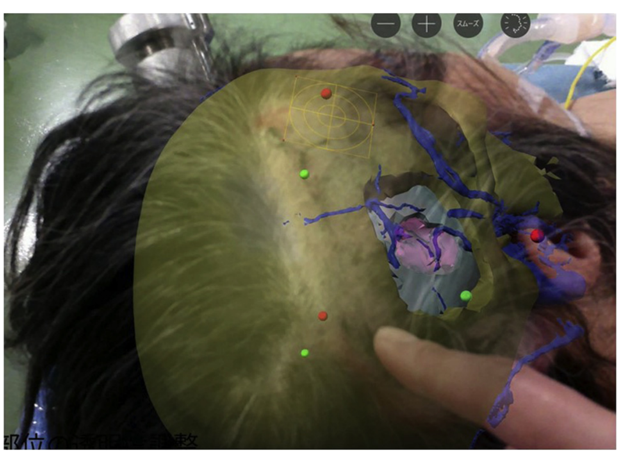

Figure 5. A Trans-Visible Navigation screen shot of case 2. Virtual craniotomy was easily transferred onto the head with the surgeon's finger.

The main advantage of the TVN system is that it achieves volumetric navigation, in contrast to conventional point-to-point navigation. It extends the usefulness of AR images by overlaying them directly onto real surgical images, thus helping the surgeon to integrate these 2 dimensions intuitively. Several other AR systems have been invented to integrate CT/MRI images and surgical fields. Image integration is performed by video projector,[6,9-12] head mounted display, or tablet PC.[5,10] A video projector is used in several reports that entail the projection of registered digital images onto the patient's head during surgery.[6,10-12] Images are well displayed even in hair-covered areas, but image distortion occurs in peripheral areas.[3] It is essential that the angle of projection is the same as the surgeon's angle of view. If it is not, deep-seated lesions are not properly projected. Use of a wearable goggle-type display is 1 option, but without information on the eye position of the surgeon, this leads to severe parallax. In this context, a head-mounted display (HMD) with camera vision is another option, and several studies[13,14] using such a display have been reported. The advantage of this system is that there is no parallax because of the surgeon's eye position, nor is there any obstruction between the surgeon and the surgical field. However, the HMD is too bulky and too heavy to wear throughout surgery. We can expect lighter and simpler HMDs to be developed in the future. Tablet PCs are another option because of their back-facing

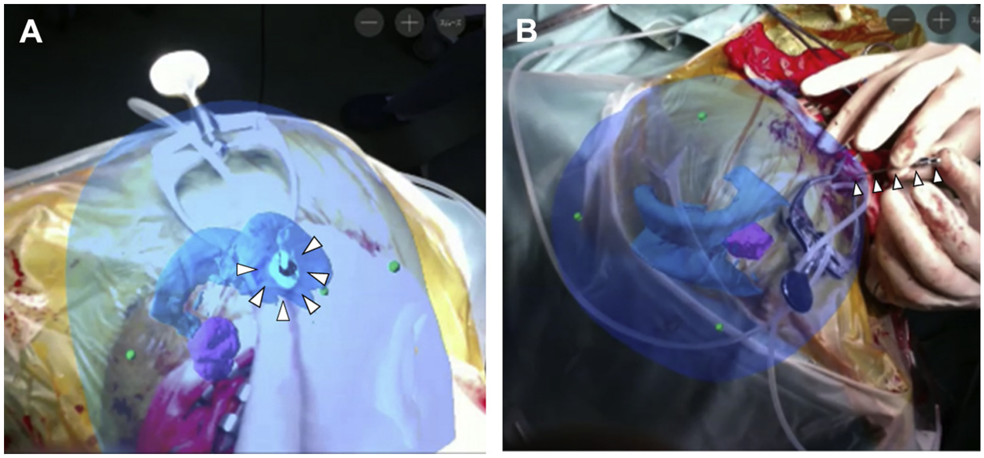

Figure 6. Trans-Visible Navigation screen shots of case 3. Ventricular tap was accurately performed using the three-dimensional image of the lateral ventricle. *Arrows* indicate the tapping needle.

cameras, and they are particularly convenient because they free the surgeon from the bulky HMD.[5,10] Although a tablet PC obstructs a clear working space, because it comes between the surgeon's eye and the surgical field, this does not present a particularly serious problem because it comes into the surgeon's view only when image guidance is needed.

The advantage of our system over the systems described by other research groups[5,10] is that there are no or few blind spots within the surgical area. We used a motion capture system with 6 cameras surrounding the surgical table. Blind spots were extinguished, and as a consequence, smooth and continuous navigation was achieved. The motion capture system was initially designed to record the motions of an actor's joints with the aim of providing motion data to be used to create the movement of animated characters. Recording occurs throughout the operation room with no blind spots.

In the 6 cases in which this system was used in our institute, it was found to be superior to conventional navigation systems, particularly in the following situations.

It is helpful in the planning of skin incisions, and is thus ideal in connection with preoperatively designed craniotomy. It has proved especially useful in tailored craniotomy. Before surgery, a craniotomy is planned to fit the tumor for the particular case on the 3D visualizing application Amira. The virtual craniotomy is then performed using Amira. The image with the craniotomy is superimposed onto the actual patient's head using the present see-through system, thus helping the surgeon to realize the tailored craniotomy. In subcortical tumors that are covered by cerebral cortex, it helps the surgeon to correctly delineate the tumor margin. In the case of deep-seated tumors, it helps the surgeon to identify the angle of approach, avoiding the cortical bridging veins and other eloquent areas.

However, there are disadvantages. As is depicted in the present cases, the indication for TVN resides mainly in marking the skin incision, craniotomy, and macroscopic procedure for a superficial lesion. After the microscope is introduced, the tablet is not applicable.

There could be 2 ways to overcome this problem. One is to locate the microscope with the whole-room tracking cameras with reflective markers. The 3D image simulating the microscope view is displayed on the tablet. A pointing device that carries the reflective balls as is used in conventional navigation is introduced under the microscope. The focal point of the microscope is indicated by the navigation cursor on the tablet. This method has been tried in 1 clinical case, and overlaying the 3D image on the microscope video image is planned but not yet implemented.

The other way is to use the current system in conjunction with a conventional navigation system as we have done in all clinical cases for backup. The orthogonal display mode of the conventional navigation system helps us to obtain depth information. A combination of the present navigation system with a conventional system is likely to be the most appropriate way to enable effective navigation.

In the present state of our system, further development is needed to enable effective application to deep brain areas under a microscope.

Limitations

Our system has not solved the problem of using historical image data. Intraoperative image updates using intrasurgical MRI/CT or brain shift simulation may be needed, which is not implemented in our system.

There is a time lag between tablet motion and 3D overlay. The lag is currently 0.4 seconds, which is tolerable for practical navigation but needs to be solved in future.

CONCLUSIONS

Our TVN system has the following advantages over conventional systems:

1. It is highly intuitive and does not require the surgeons to mentally visualize the 3D orientation of an MRI/CT image.
2. Surgeons do not need to alternate their gaze between the surgical field and the navigation screen.
3. There are almost no blind spots in navigation.
4. It is especially useful at the initial stages of brain surgery, for example in connection with skin incision, craniotomy, or corticotomy.

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