

A Microscopic Optically Tracking Navigation System That Uses High-resolution 3D Computer Graphics

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Abstract

Three-dimensional (3D) computer graphics (CG) are useful for preoperative planning of neurosurgical operations. However, application of 3D CG to intraoperative navigation is not widespread because existing commercial operative navigation systems do not show 3D CG in sufficient detail. We have developed a microscopic optically tracking navigation system that uses high-resolution 3D CG. This article presents the technical details of our microscopic optically tracking navigation system. Our navigation system consists of three components: the operative microscope, registration, and the image display system. An optical tracker was attached to the microscope to monitor the position and attitude of the microscope in real time; point-pair registration was used to register the operation room coordinate system, and the image coordinate system; and the image display system showed the 3D CG image in the field-of-view of the microscope. Ten neurosurgeons (seven males, two females; mean age 32.9 years) participated in an experiment to assess the accuracy of this system using a phantom model. Accuracy of our system was compared with the commercial system. The 3D CG provided by the navigation system coincided well with the operative scene under the microscope. Target registration error for our system was 2.9 ± 1.9 mm. Our navigation system provides a clear image of the operation position and the surrounding structures. Systems like this may reduce intraoperative complications.

Key words: computer graphics, microscope, neuronavigation

Introduction

There are many important structures in brain and precise knowledge of three-dimensional (3D) anatomical structure is needed during brain surgery to avoid intra-operative complications. Though two-dimensional medical images such as magnetic resonance images (MRIs) and computed tomography (CT) images have been used to inform surgeons of anatomical structure, multi-modality fused 3D computer graphics (CG) images are becoming more common as image processing technology develops.^{1–5)} Recent studies have shown that multi-modality fused 3D CG images are useful for depicting complex brain anatomy, such as that involved in skull base disease,^{3,6,7)} and we recently reported that high-resolution multi-modality fused 3D CG images were useful for preoperative planning.^{8–10)} Our multi-modality fused 3D CG images are created by registering

all the necessary structures, including perforators and stretched cranial nerves, and constructing a 3D model using a surface-rendering method and a volume rendering method. In the surface-rendering method, the model employs multiple modalities and multiple thresholds for one tissue. As a result, we are able to create high-resolution 3D CG images that depict brain tissue with the same accuracy as the actual operative field.

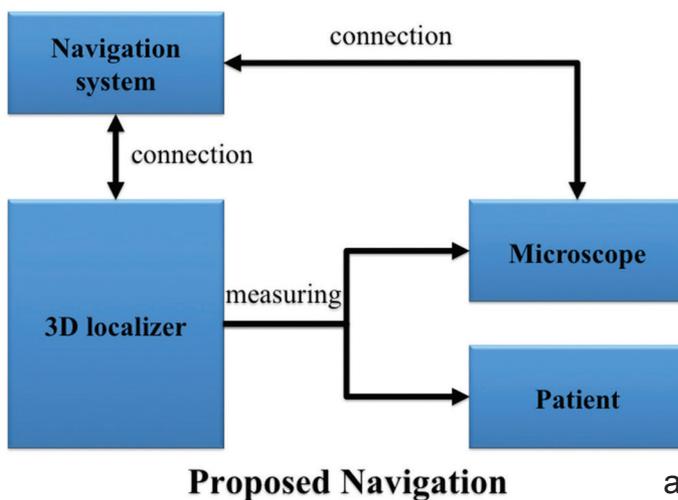
Despite these advances, 3D CG images are not commonly used to provide intraoperative assistance because existing commercial operative navigation systems can show only simple 3D CG images that originate from a medical image, and are not able to show 3D CG images that are sufficiently detailed for use as a source of information.^{11–14)} To address this issue, we aimed to create an operative navigation system that is capable of using high-resolution 3D CG images. This article presents the technical details of our microscopic optically tracking navigation system.

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Materials and Methods

I. Navigation system

We incorporated information on the position, focal length, and magnification of the operating microscope into our navigation system, creating a microscopic optically tracking navigation system^{15,16)} (Fig. 1a). The navigation system consists of three components: (1) the operating microscope, (2) the registration system, and (3) the image display system. The operating microscope (OME-9000; Olympus, Tokyo) is used together with optical trackers (Rigid Body, Northern Digital Inc., Ontario, Canada) and a communications unit. Optical trackers are attached both to the patient's body and the operating microscope (Fig. 1b, *arrow*), and real-time positions are monitored using an optical tracking device (Polaris, Northern Digital Inc., Ontario, Canada). The communications unit transmits the focal length and magnification of the microscope to the registration system. The registration system calculates matrices such as the registration matrix between the patient tracker coordinate system and the patient image coordinate system, relative matrices between trackers, the camera calibration matrix between the microscope camera and the microscope tracker, and the projection matrix corresponding to the microscope camera. The image display system creates a real-time navigation view based on the matrices from the registration system (Fig. 1b, *arrowhead*). In the image, 3D CG are displayed in the same field of view as the operative scene under the microscope (Figs. 3, 4).



Point-pair registration is used to create a calibration matrix between the patient tracker coordinate system and the patient image coordinate system. To reduce measurement errors, fiducial markers are attached to the skin of the patient (two on the bilateral roots of the zygoma and two on the forehead) and are used for registration¹⁷⁾ (Fig. 2a). Camera calibration data are acquired in advance for each magnification and focal length of the microscope.

All processing is performed on a personal computer (Precision M6800; Dell, Plano, TX, USA; CPU: Intel Core i7-4930MX, 3.0GHz; RAM: 16.0 GB; graphics card: NVIDIA Quadro K5100M).

II. Assessment

To assess the accuracy of this system, nine neurosurgeons (7 males, 2 females; mean age 32.9 years) participated in an experiment using a phantom model.

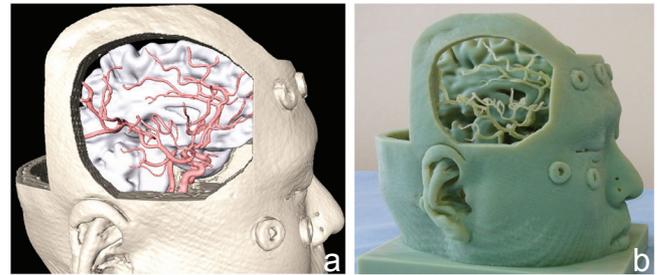


Fig. 2 a: A 3D model constructed from magnetic resonance images obtained from a healthy male volunteer. b: A phantom model constructed from the 3D model using a 3D printer. 3D: three-dimensional.



Fig. 1 a: A conceptual diagram of the navigation system. b: An image of the navigation system. The *arrow* indicates the optical tracker, and the *arrowhead* indicates the cable that exports the real-time position information and the focal length and the magnification information of the operative microscope to image display system. *: monitor of the navigation system, **: monitor of the operative microscope.

Five neurosurgeons were specialists in neurosurgery and four were non-board-certified residents. Accuracy was quantified using target registration error (TRE),¹⁸⁾ which is the distance between the true position of a target in the phantom model and its measured position in the imaging space after registration. TRE was calculated for the following targets: tragus, nasion, posterior limit of splenium of corpus callosum, and fastigium.

The phantom model was created from T_1 - and T_2 -weighted MRI and time-of-flight magnetic resonance angiography (TOF-MRA) images that were obtained from a healthy male volunteer using a 3.0-T system (Signa 3.0T; GE Healthcare, Milwaukee, WI, USA) equipped with an eight-channel phased-array head coil. The imaging parameters for T_1 -weighted images were: repetition time (TR), 5.9 ms; echo time (TE), 2.4 ms; slice thickness, 1.5 mm; field of view (FOV), 24 cm; matrix size, 256×256 ; flip angle, 15° . The imaging parameters for T_2 -weighted images were: TR, 4,200 ms; TE, 85.4 ms; slice thickness, 1.5 mm; FOV, 24 cm; matrix size, 256×256 ; flip angle, 90° . The imaging parameters for TOF-MRA were: TR, 22 ms; TE, 2.2 ms; slice thickness, 1.0 mm; FOV, 24 cm; matrix size, 256×256 ; flip angle, 20° . Data were provided as image stacks coded in digital imaging

and communication in medicine (DICOM) format and were processed with Avizo 6.3 software (Visualization Science Group, Bordeaux, France) on a personal computer (Precision T7500; Dell, Texas, USA; CPU: Intel Xeon X5550, 2.67 GHz, 2.66 GHz; PAM: 8.00 GB; graphics card: NVIDIA Quadro FX5800) for 3D image reconstruction using a previously reported method.⁸⁻¹⁰⁾ The 3D CG image was stored in Standard Triangulated Language¹⁹⁾ format and the phantom model was created from this data using a 3D printer (Connex 500, Stratasys Ltd., Eden Prairie, MN, USA).

Results

The setup of the navigation system and the final navigation system are shown in Fig. 1. We were able to create a high-resolution 3D polygon model from T_1 - and T_2 -weighted MRI and TOF-MRA data (Fig. 2a) and created a phantom model from this 3D CG model (Fig. 2b). The image on the monitor of the navigation system corresponded well with the operative scene under the microscope when the microscope was tilted (Fig. 3a, b) and when the magnification and focal length of the microscope were changed (Fig. 3c, d). The image on the monitor of the navigation system changed as quickly as

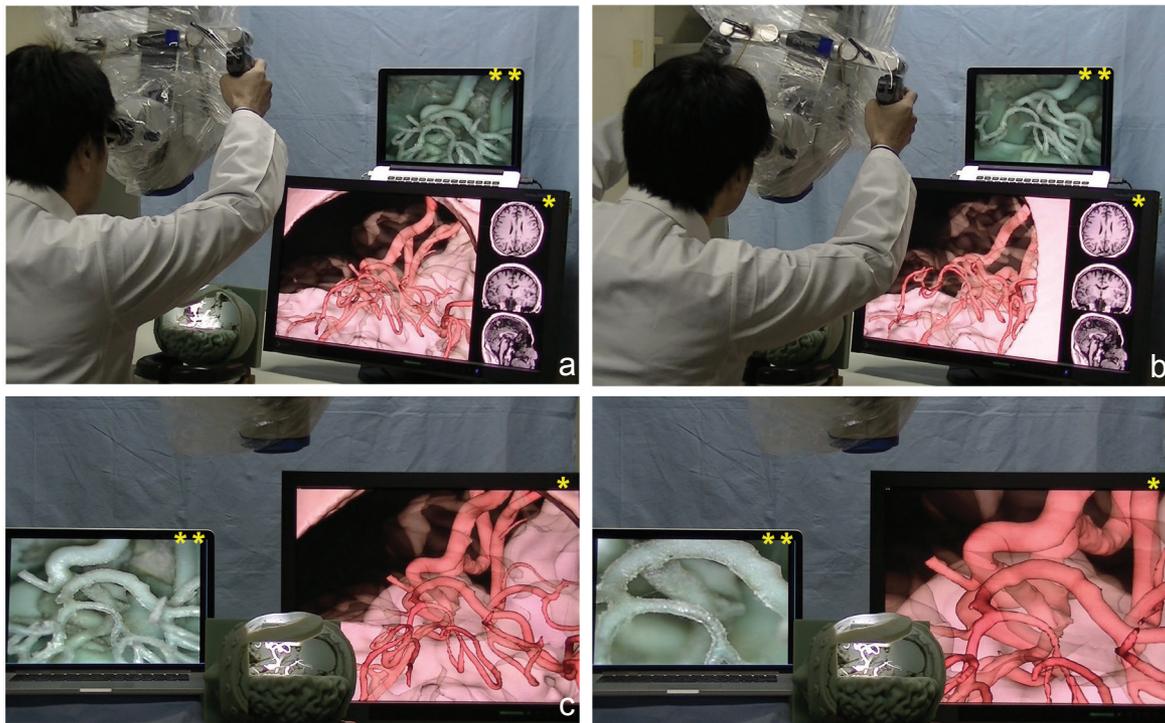


Fig. 3 The 3D CG image displayed on the monitor of the navigation system corresponded with the operative scene under the microscope before (a) and after (b) tilt of the microscope to right side, and before (c) and after (d) the magnification of the microscope was increased. *: monitor of the navigation system, **: monitor of the operative microscope, CG: computer graphics, 3D: three-dimensional.



Fig. 4 The opacity of each structure in the 3D CG image could be changed on the monitor of the navigation system, revealing anatomical structures that were obstructed from view in the phantom model. **a:** Image before opacity was manipulated. **b:** Image after the opacity was changed to make the brain translucent. **c:** Image after the opacity was changed to make the brain transparent. CG: computer graphics, 3D: three-dimensional.

the operative scene under the microscope when the axis of microscope was systematically tilted forward, backward, and side-to-side, and when the magnification of microscope was systematically changed. It was possible to change the opacity of each structure in the 3D CG image on the monitor of the navigation system, so that the image showed the anatomical structures that were obstructed from view in the phantom model (Fig. 4).

The mean \pm standard deviation TRE for our navigation system for all four locations and all nine neurosurgeons was 2.9 ± 1.9 mm.

Discussion

We have developed a microscopic optically tracking navigation system that uses high-resolution 3D CG images. In this study we showed that the 3D CG image displayed on the monitor of this navigation system corresponded well with the operative scene under the microscope.

One of the biggest merits of this system is that it enables neurosurgeons to intuitively comprehend the 3D anatomical structure peripheral to the operation position when using the microscope. Existing commercial operative navigation systems are able to show only simple 3D images that originate from a medical image, and are not able to show small anatomical structures such as perforators and cranial nerves that have been three-dimensionally stretched by a tumor.^{20–22} As a result, conventional navigation systems do not show high-resolution 3D CG images that are of sufficient detail to be used for intraoperative assistance, and operation position has to be confirmed on two-dimensional DICOM images when using existing commercial operative navigation systems.¹² Surgeons could estimate 3D anatomical structure peripheral to the operation position from two-dimensional images during surgery,

but this significantly increases the load placed on the surgeon. The navigation system we have developed allows surgeons to intuitively comprehend the 3D operative anatomy peripheral to the operation position because the 3D image displayed on the monitor of the navigation system is as accurate as the actual operative field^{8–10} and is in line with the field-of-view of the microscope.

Other merits of our microscopic optically tracking navigation system include the sharing of operation position information between the operator and the assistant and the measurement of operation position without the surgeon having to move the microscope away from the operative field, which increases safety. The sharing of operation position information may be useful for avoiding intraoperative complications, especially for novice surgeons, because it enables the assistant to guide the surgeon and correct the operative plan if the surgeon becomes disoriented during surgery.

Disadvantages of this system at present are that the surgeon has to look away from the operative field to see the navigation display, and the 3D models used in the navigation system cannot be updated as the brain structure is deformed. It is possible to solve the first issue by using augmented reality, i.e., by overlaying the 3D CG image on the microscope view. At present it is difficult to give a 3D appearance to the overlaid 3D CG images, because the overlaid 3D CG images are usually deep-seated structures such as tumors or cerebral arteries, so they look as if they are floating when displayed in the microscopic view.^{11,13,15,16,23} As such, we have not yet tried using augmented reality in this system, and development of a method to view the navigation display without looking away from the operative field is a challenge that remains. Though it is not possible to solve the second issue at the present time, development of a method to update the image on the navigation

system as the brain structure is altered would be useful, and is a challenge for future consideration.

The TRE for our system was as good as that for other reported systems.^{24–28)} Nevertheless, a TRE of 2.9 ± 1.9 mm is still too large to detect small anatomical structures using the navigation system, even if the 3D CG is as accurate as the actual operative field. Therefore, improvement of the accuracy of the system will be a future task.

Conclusion

We have developed a microscopic optically tracking navigation system that uses high-resolution 3D CG images. In this study we showed that this system provided a 3D CG image that coincided with the operative scene under the microscope. This system may reduce intraoperative complications because it will enable surgeons to intuitively comprehend the 3D operative anatomy.

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Conflicts of Interest Disclosure

The authors report no conflict of interest (COI) concerning the materials or methods used in this study or the findings specified in this article. All authors who are members of The Japan Neurosurgical Society (JNS) have registered online Self-reported COI Disclosure Statement Forms through the website for JNS members.

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