

Augmented reality-guided neurosurgery: accuracy and intraoperative application of an image projection technique

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OBJECT An augmented reality system has been developed for image-guided neurosurgery to project images with regions of interest onto the patient's head, skull, or brain surface in real time. The aim of this study was to evaluate system accuracy and to perform the first intraoperative application.

METHODS Images of segmented brain tumors in different localizations and sizes were created in 10 cases and were projected to a head phantom using a video projector. Registration was performed using 5 fiducial markers. After each registration, the distance of the 5 fiducial markers from the visualized tumor borders was measured on the virtual image and on the phantom. The difference was considered a projection error. Moreover, the image projection technique was intraoperatively applied in 5 patients and was compared with a standard navigation system.

RESULTS Augmented reality visualization of the tumors succeeded in all cases. The mean time for registration was 3.8 minutes (range 2–7 minutes). The mean projection error was 0.8 ± 0.25 mm. There were no significant differences in accuracy according to the localization and size of the tumor. Clinical feasibility and reliability of the augmented reality system could be proved intraoperatively in 5 patients (projection error 1.2 ± 0.54 mm).

CONCLUSIONS The augmented reality system is accurate and reliable for the intraoperative projection of images to the head, skull, and brain surface. The ergonomic advantage of this technique improves the planning of neurosurgical procedures and enables the surgeon to use direct visualization for image-guided neurosurgery.

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KEY WORDS augmented reality-guided neurosurgery; projection accuracy; intraoperative application; neuronavigation; diagnostic and operative techniques

In neurosurgical procedures, precise preoperative planning of a tailored craniotomy and the approach as well as intraoperative image guidance are essential. Visualization technologies improve the surgeon's orientation and the patient's safety during procedures.^{11,14,15} Navigation systems for intraoperative image guidance are widely used and are based on monitor visualization. Monitor-based solutions require surgeons to compare and analyze images on the monitor with the actual surgical field and to control an instrument in the target area at the same time. Safe navigated movement of the instrument using the displayed images on the monitor requires hand-eye coordination without involvement of the real surgical field. Providing simple and easy-to-use solutions supporting the transfer

and integration of image information into the surgical field is needed. One alternative technology is an augmented reality system that combines reality with virtual images in real time.^{1,17} Different types of augmented reality systems are available, that is, as optic or video head-mounted display (HMD). In addition, heads-up displays and monitor-based and projection-based configurations have been developed for different technical and medical areas.^{1,2,5,7,8,12,16} We designed and developed an augmented reality technique for image-guided neurosurgery to project a virtual image directly onto the patient's head, skull, and brain surface in real time. The aim of this study was to evaluate system accuracy using augmented reality with the direct projection of regions of interest (ROIs; segmented tumor,

ABBREVIATIONS HMD = head-mounted display; ROI = region of interest.

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vessels, functional areas) on a head phantom. In addition, the first intraoperative application was performed using the augmented reality system, which was compared with an existing navigation system to evaluate accuracy.

Methods

The augmented reality system was evaluated in using a head phantom and in neurosurgical procedures. The technique consists of 4 components: 1) virtual image creation, 2) real environment, 3) image projection, and 4) registration.¹³ A virtual 2D image was created in 2 ways: 1) to evaluate accuracy with the head phantom, we used a digital photograph-based method in which the tumor region was drawn using image editing software; and 2) for intraoperative applications, an MRI-based 3D model was used with visualization of the head or brain matched to the segmented tumor. A commercially available video projector (PicoPix 1020, Philips) based on LED technology was used to project the images. Registration was manually performed with 5 fiducial markers, which were placed around the tumor region.

Evaluation of Accuracy

To evaluate system accuracy, the intraoperative environment was simulated with a head phantom in 10 cases. Evaluation was performed in different cranial regions (frontal, temporal, parietal, and occipital), according to different defined tumor localizations: frontal in 2 cases, temporal in 2, midline (frontal and parietal) in 2, parietal in 2, and occipital in 2. For each case, 5 fiducial markers were placed on the surface of the head phantom (Fig. 1B) around the tumor region. A virtual image was created using a digital photograph of the head phantom with the fiducial markers. The photograph was taken from the same perspective used for image projection. Brain tumors were drawn in the different areas using image editing software (Fig. 1A). Different tumor sizes (range 0.3–14.04 cm²) were matched to the images. The created 2D images showing the tumor and fiducial markers were projected. The video projector and the phantom were placed at the same level in the vertical projection axis. Registration was performed in such a manner that the 5 fiducial markers on the virtual image were superimposed on the corresponding 5 physical fiducial markers on the head phantom (Fig. 1C). Given the anticipated incongruence between the projected 2D virtual image and the 3D convexity of the head, the error of projection after each registration was measured. The distance of the fiducial markers from one another was known and defined equally on the virtual image and the head phantom. The distance of the tumor borders from each fiducial marker was measured on the virtual image. The distance of each fiducial marker from the projected tumor borders on the head phantom was dependent on the accuracy of projection and the projection error. The projection error was defined as the difference between the distance of the 5 fiducial markers from the tumor borders on the virtual image and the distance of the 5 fiducial markers from the tumor borders on the head phantom. The registration was repeated 5 times for each localization, and the time needed for each registration was measured.

Intraoperative Application

The image projection technique was applied intraoperatively in 5 patients (2 women and 3 men, with a mean age of 58 years [range 52–69 years]) with brain tumors. Five fiducial markers were placed on the head of each patient around the tumor region. Afterward, preoperative contrast-enhanced T1-weighted MRI, which was used for standard navigation as well, was performed. Localization of the brain tumors was left temporal in 2 patients and left parietal, right parietal, and left precentral in 1 patient each. For each patient an individualized 3D model and a virtual image were created based on preoperative MRI. Imaging of the patient was performed to create a 3D model of the head and brain (MRIcro software, version 1.4, Chris Rorden). The brain lesion, visible by contrast enhancement (gadolinium), was segmented and automatically matched to the 3D model (Fig. 2). Fiducial markers were visible on the MRI-based 3D model as well (Fig. 3B). The created 3D model provided precise localization of the tumor and was used for image projection. The virtual image was projected onto the head of the patient and was registered in such a manner that the 5 fiducial markers on the virtual image were superimposed on the corresponding 5 physical fiducial markers on the patient's head (Fig. 3C). The projector position was fixed to ensure the same projection axis during surgery. The projection technique was used to plan the skin incision and the craniotomy and to visualize the tumor borders on the brain surface after dural opening. In addition, a neuronavigation system (StealthStation, Medtronic Inc.) was used for tumor localization and was compared with the augmented reality visualization technique. At first the augmented reality system was installed, and the 2D image was projected and registered with the visualization of brain tumor localization on the head surface. The standard navigation system was registered, and the navigated pointer was used to delineate the tumor borders (anterior, posterior, superior, and inferior) identified with navigation MR images on the navigation monitor. The difference between the tumor borders visualized with image projection and the navigated localization of the tumor borders (navigation pointer) was measured.

Results

System Accuracy

Augmented reality visualization of tumors on the head phantom succeeded in all 10 cases with different tumor sizes and localizations. In some cases additional anatomical structures were added to the virtual image for projection (Fig. 1). The quality of projection was good in all cases and allowed reliable visualization of the tumor borders and brain structures, such as gyri and sulci, on the head phantom. The fiducial marker-based registration of the virtual image to the head phantom was possible for all tumor localizations and after 5 repetitions. The mean time for registration was 3.8 minutes (range 2–7 minutes). The mean projection error was 0.8 ± 0.25 mm (range 0.1–1.4 mm). The mean projection errors in the various localizations were as follows: frontal 0.9 mm, temporal 0.6 mm, midline 0.7 mm, parietal 0.9 mm, and occipital 0.8 mm. There were no significant differences in accuracy in relation to tumor localization and size ($p = 0.3$).

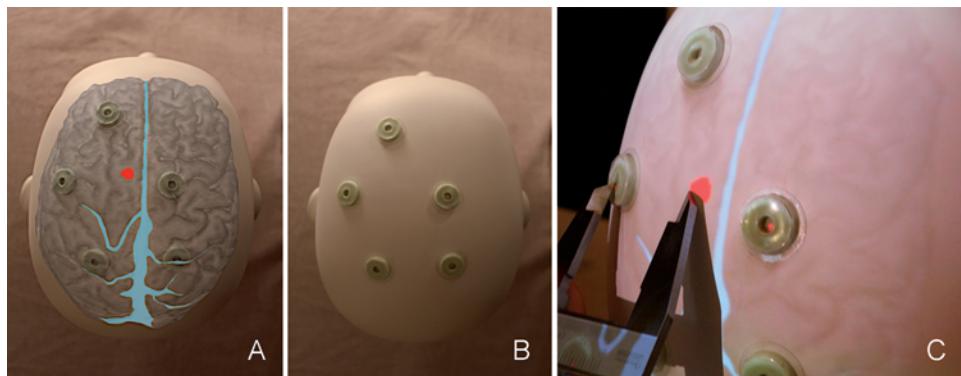


FIG. 1. Image (A) created for projection. The brain tumor (red) and MRI-based 3D model of the brain with the superior sagittal sinus and cortical veins (blue) are matched to an image. The image in panel A was created using a photograph of the head phantom (B). Projecting the virtual image in panel A onto the head phantom (C) after fiducial marker-based registration. After registration, the distance of the 5 fiducial markers from the visualized tumor border was measured. Figure is available in color online only.

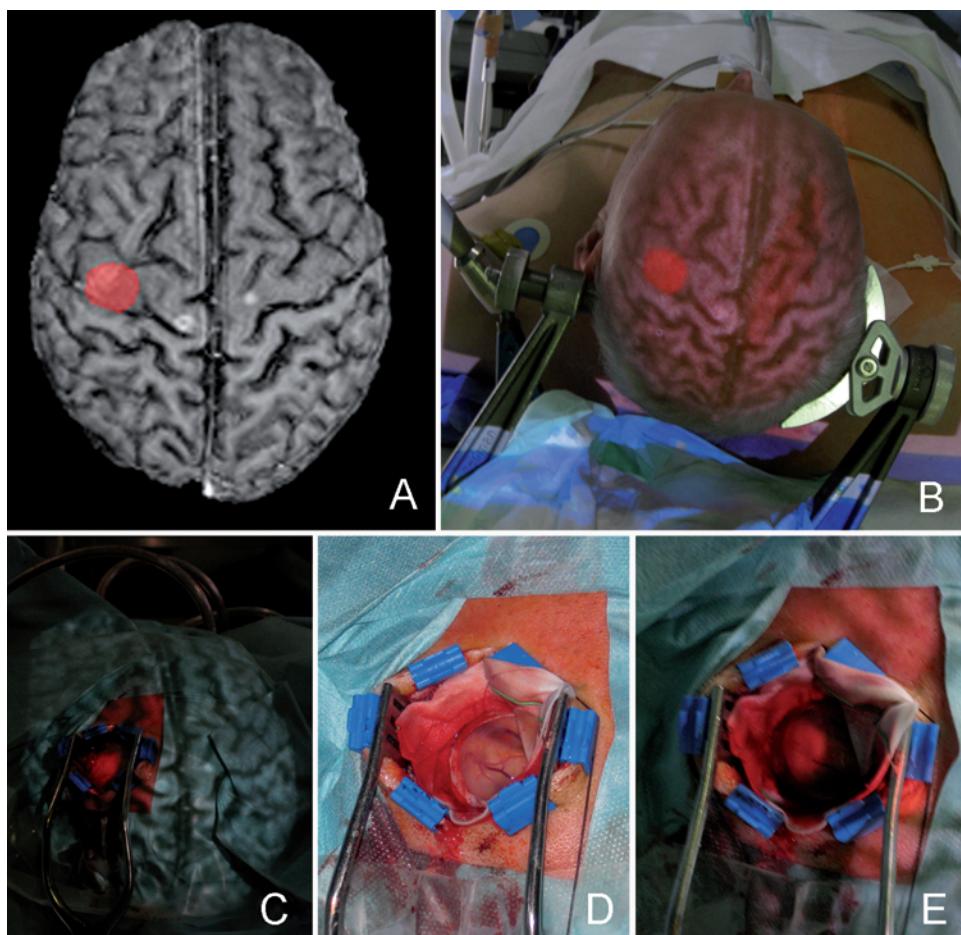


FIG. 2. **A:** Magnetic resonance imaging-based 3D model of the brain with segmented left precentral brain metastasis (red). **B:** After registration, the created image in panel A is projected onto the patient's head to plan for the skin incision and craniotomy. **C:** Intraoperative image projection after a small skin incision and before craniotomy with localization of the tumor (red) on the skull for direct planning of a tailored craniotomy. **D:** Brain surface after opening the dura mater. The tumor is not visible on the brain surface. **E:** Projection of the tumor on the brain surface. Figure is available in color online only.

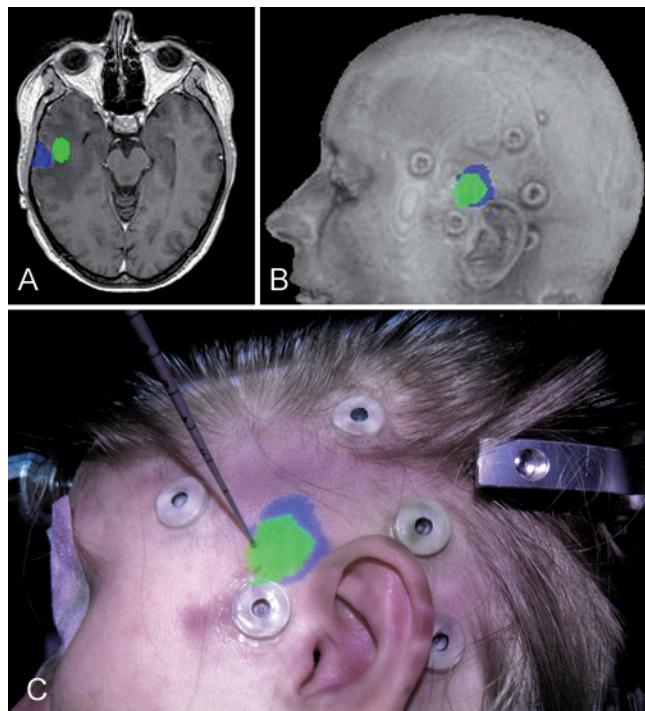


FIG. 3. **A:** Preoperative MR image obtained in a patient and segmentation of 2 brain lesions, an extraaxial (blue) and an intracerebral (green) lesion. **B:** Creation of an MRI-based 3D head model with visualization of the ROIs (2 lesions). Fiducial markers are well visualized. This image was used for projection onto the patient's head intraoperatively. **C:** Intraoperative picture with projection of the created image in panel B. Registration was performed manually: the 5 visualized fiducial markers on the image were superimposed onto the corresponding 5 fiducial markers on the patient's head. Accuracy was evaluated using a standard navigation system (navigation pointer) comparing the tumor borders and localization with the MRI on the navigation monitor. Figure is available in color online only.

Intraoperative Application

The clinical feasibility and reliability of the augmented reality system in planning the skin incision and the craniotomy and performing the tumor resection were proved intraoperatively in 5 patients. All patients had malignant brain tumors (metastasis in 3 patients, glioblastoma in 2 patients) and underwent image-guided tumor resection with the aim of complete tumor resection. The creation of MRI-based 3D models of the head and brain and segmentation of the brain tumors were performed quickly. Visualization and localization of brain tumors using the existing navigation system was possible in all patients. The quality of projection was good in all cases and allowed the precise identification of tumor borders in relation to real anatomical structures such as gyri, sulci, and cortical arteries and veins.

In addition, a neuronavigation system was used in all patients with good accuracy during image projection. The neuronavigation system confirmed the accuracy of image projection with high alignment of the tumor borders. The difference between the tumor borders visualized with image projection and those obtained with navigated localization (projection error) was 1.2 ± 0.54 mm. By projecting the 3D model of the brain surface with the segmented tu-

mor obtained from preoperative MRI, we could visualize localization of the brain tumor in relation to the whole brain in real time. Image projection was repeated after skin incision to project the tumor on the patient's skull and to plan the craniotomy. After performing the craniotomy and opening the dura, image projection was performed on the brain surface and localized the tumor on the brain surface exactly (Fig. 2). In contrast to the neuronavigation system, image projection allowed the neurosurgeon to look at the patient's head and begin planning the skin incision (Fig. 3), to perform the craniotomy with visualization of the tumor on the brain surface without the need to look at the navigation monitor, and to hold the pointer at the same time. The brain tumors were completely removed in all patients. Tumor resection was performed without complications or new postoperative neurological impairment in all patients. In 1 patient (left precentral metastasis) preoperative hand paresis improved after resection and disappeared completely after 5 days. Total resection was confirmed with postoperative MRI in all patients.

Discussion

In the present study we confirmed a reliable and accurate augmented reality technique,¹³ which is useful for preoperative planning and image-guided neurosurgery. The presented approach, with its promising visualization results, is novel for neurosurgical procedures and superior to already existing systems. Computer- and image-guided surgery has been widely performed using navigation systems, which display registered preoperative images (MRI and/or CT) on a navigation monitor during the operation. Using these systems requires the neurosurgeon to look at the navigation monitor to find the position of an instrument that must be controlled in the target area at the same time. Moreover, the visualized MRI and/or CT studies have a dimension and orientation different from the real surgical target. Therefore, the integration of image information into the real surgical environment itself, known as "augmented reality," can be very useful for surgeons. Providing simple and easy-to-use solutions for neurosurgical procedures and supporting the transfer of preoperative plans to the surgical field are needed. Several augmented reality systems have been developed for image-guided surgery, such as solutions with head-mounted display (HMD).^{1-3,5-10,12,16} Most systems work with the combination of a virtual image on one side and a video or picture of the environment on the other. In using navigation and registered microscopy together, borders of brain tumors can be made visible on the brain surface through a microscopic view. However, most neurosurgeons do not use microscopy from the beginning of the procedure to plan the skin incision and craniotomy. The idea of the presented augmented reality system is to integrate the information from MRI and/or CT into the surgical field (the patient's head) from the beginning of the planning to improve the orientation and safety of the surgery. For the neurosurgeon that means an enormous ergonomic improvement in looking directly at the head of the patient and for planning the approach. The ergonomic advantages improve planning of the skin incision and craniotomy in using this technique. In the

described method, the virtual image is directly projected without the need for surgeons to wear additional hardware like an HMD during surgery or the cumbersome use of a microscope from the beginning of surgery. This is an important advantage over the systems based on HMD. Furthermore, the costs of this alternative projection technique would be lower than the costs for special hardware and expensive navigation systems.

The image projection technique can be used for a “tailored” skin incision and craniotomy (Figs. 2 and 3). There is a benefit if one compares the presented augmented reality method with available simple navigation systems. The advantage of the former method lies in the ability to plan an approach more easily and faster by using these image projections with comparable accuracy. Furthermore subcortical lesions, which are not visible on the brain surface during surgery, can be visualized due to lesion projection on the brain surface while planning the approach and operative strategy. The brain surface and hairy scalp are irregular surfaces but they serve as good “screens.” Projecting an image onto the hairy scalp is very possible and can be done to see the location to perform any shaving. After shaving, an image can be projected onto the scalp. The intraoperative application of the augmented reality technique enables accurate brain tumor localization on the brain surface. A heads-up display system or microscope display requires additional hardware that is between the surgeon and the real surgical field. The idea of the augmented reality technique was to use the real environment itself as a screen, allowing improved spatial perception. In the first intraoperative application we were able to successfully implement this method and visualize the tumor on the head surface for planning the skin incision, on the skull for planning the craniotomy, and on the brain surface for resecting the tumor. A navigation system was used to evaluate and confirm accuracy.

The described augmented reality system contains the possibility of projecting any useful information exactly to the head, skull, or brain surface. Our first experiences show that this technique is optimal for small and large tumors or lesions located close to the brain surface. Depth visualization of ROIs is still a challenge in projecting 2D images.⁴ Otherwise existing navigation systems also have limitations in surgeries for deep and large lesions as a result of brain shift. For deep lesions the planned approach is more important than the image-guided visualization of the tumor borders. However, we believe that the described technique can be used very well to quickly and accurately guide surgery for deep brain tumors—not to project the deep tumor borders but to project the preoperatively planned approach and the craniotomy borders or any other useful information to the patient’s head, skull, or brain surface.

Every new technique goes hand in hand with problems and limitations, which should be discussed along with suggestions for possible solutions. The presented augmented reality technique, like existing navigation systems, is not accurate in identifying tumor borders after brain shift. The augmented reality system focuses on preoperative planning and intraoperative guidance; however, the system provides accurate brain tumor localization after open-

ing of the dura mater (Fig. 2). During and after the resection of brain tumors, brain shift increases and the utility of the presented technique is limited.

In the presented experimental setup, image projection onto a patient’s head, skull, and brain surface requires a direct line of sight, which may interfere with the surgeon, the microscope, and the instruments. However, our technique is in its beginnings and further development is necessary. Moreover, image projection does not need to be performed during the entire surgery but is instead used in steps before skin incision and craniotomy or on the brain surface if required. On the other hand, new projection technologies today make it possible to project an image from different angles and positions and with multiple projectors to produce an image. This technique and the possibility of compensating for image distortion have been widely used in the movie industry with good precision. The projection of 2D images onto a 3D head involves some problems—most relevantly, those associated with registration and image distortion. In this study registration was performed using fiducial markers that were placed on the patient’s head and were visualized on MRI-based virtual images. Although registration was possible with good accuracy, further development should enable automatic registration. Another problem is that any projection of an image causes image distortion, particularly at the outer border of the projection and on curved surfaces. The lowest grade of distortion exists in the center of the projection axis. Despite the image distortion in the augmented reality technique, our study shows that it is possible to project a visualized tumor on the head of a patient with a low projection error if the tumor is localized in the center of the projection axis. The low projection error showed that correct projection onto the curved surface of the head could be achieved with acceptable accuracy. However, for the projection of bigger structures, such as a 3D model of the brain, the distortion could be more relevant. Further development of the system will make it possible to compensate for this distortion and to implement special software to calculate an undistorted image.

Conclusions

We presented a reliable, accurate, and innovative augmented reality system for the direct projection of virtual images onto the head, skull, and brain surface in real time. We verified an accurate method and promising visualization results. The ergonomic advantage of this technique for neurosurgical procedures improves surgical planning and allows the surgeon to use direct visualization of ROIs on a patient’s head, skull, or brain for image-guided neurosurgery.

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Author Contributions

Conception and design: both authors. Acquisition of data: both authors. Analysis and interpretation of data: both authors. Drafting the article: both authors. Critically revising the article: both authors. Reviewed submitted version of manuscript: both authors. Approved the final version of the manuscript on behalf of both authors: Mahvash. Statistical analysis: both authors. Administrative/technical/material support: both authors. Study supervision: Mahvash.

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