Towards Augmented Reality Guided Craniotomy Planning in Tumour Resections

Marta Kersten-Oertel[3(✉)], Ian J. Gerard[1,3], Simon Drouin[1,3],
Kevin Petrecca[2,3], Jeffery A. Hall[2,3], and D. Louis Collins[1,2,3]

[1] Biomedical Engineering, McGill University, Montréal, Canada
[2] Neurology and Neurosurgery, McGill University, Montréal, Canada
[3] Montreal Neurological Institute and Hospital, Montréal, Canada
marta@bic.mni.mcgill.ca

Abstract. Augmented reality has been proposed as a solution to overcome some of the current shortcomings of image-guided neurosurgery. In particular, it has been used to merge patient images, surgical plans, and the surgical field of view into a comprehensive visualization. In this paper we explore the use of augmented reality for planning craniotomies in image-guided neurosurgery procedures for tumour resections. Our augmented reality image-guided neurosurgery system was brought into the operating room for 8 cases where the surgeon used augmented reality prior to tumour resection. We describe our initial results that suggest that augmented reality can play an important role in tailoring the size and shape of the craniotomy and for evaluating intra-operative surgical strategies. With continued development and validation, augmented reality guidance has the potential to improve the minimally invasiveness of image-guided neurosurgery through improved intraoperative surgical planning.

Keywords: Augmented reality · Tumour resection · Craniotomy · Image-guided neurosurgery

1 Introduction

An increasing amount of research has focused on using augmented reality (AR) in image-guided surgery (IGS) applications. In AR, real and virtual objects are combined into a comprehensive visualization. In image-guided surgery (IGS) the *virtual* objects correspond to patient-specific models, plans and preoperative images. The *real* world corresponds to the surgical field of view, which may be captured using an external camera, surgical microscope or endoscope. This real world is then merged with the virtual objects to create the augmented visualization. The motivation behind using augmented reality in IGS is twofold: (i) AR provides a visualization that maps the preoperative images from the IGS (or navigation) display onto the patient, and (ii) AR allows the surgeon to see pertinent anatomy below the visible surface of the patient. AR visualizations therefore, have the potential to improve the surgical workflow, allow for easier intraoperative planning, and improve surgical guidance to the anatomy of interest thus contributing to the minimization of the invasiveness of these procedures.

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Providing evidence that AR has these benefits in IGS, however, is a challenging task. Indeed, validation of AR IGS systems is one of the main elements lacking from this field of research; few groups have gone beyond testing in the laboratory to using their AR IGS systems in the operating room [1]. Given the constraints of the OR, accessibility to surgeons and clinical cases, and the challenge of determining suitable validation metrics for visualization techniques, this is not surprising. Over the last several years, we have been using our image-guided neurosurgery system, IBIS (Interactive Brain Imaging System) [2], in the operating room to evaluate how AR can impact image-guided neurosurgery (IGNS). In our previous work in image-guided neurovascular surgery, we gave preliminary evidence that the benefit of AR is very task specific [3]. We showed that for different neurovascular pathologies, AR is useful for vessel differentiation, localization of small and deep vessels, and craniotomy planning (i.e. the removal of the skull bone to expose the brain). In this paper, we explore the use of augmented for craniotomy planning in tumour resections. We provide examples from three of the eight surgical cases in which our system was used, and summarize the experiences the surgeons that have had using our AR IGS system in tumour resections.

The paper is organized as follows; first in Sect. 2 we describe related work in the area of augmented reality image-guided neurosurgery. In Sect. 3 we briefly describe our research neuronavigation software IBIS that allows for augmented reality visualization, how we create the augmented reality view, and the processing and visualization of preoperative patient images. In Sect. 4 we describe the use of augmented reality in real surgical cases for craniotomy planning, and we conclude and discuss avenues of future work in Sect. 5.

2 Related Work

One of the first clinical applications of AR and currently the most popular is neurosurgery [1]. In the 1990s, Gleason *et al.* [4] first proposed using AR in neurosurgery. In their system, live video images of the patient were augmented with 3D segmented virtual objects (e.g. tumours) from preoperative patient data. The MAGI (microscope-assisted guided intervention) neuronavigation system, developed by Edwards et al. [5, 6], allowed for stereo projection of virtual images into a neurosurgical microscope for ear, nose and throat (ENT) surgery and neurosurgery. Birkfellner *et al.* [7, 8] developed the Varioscope AR, a custom-built head-mounted operating microscope where virtual objects were combined with the surgical scene. Sauer *et al.* [9] developed a video see-through augmented reality display that provided a surgeon with stereo video view of patient anatomy, such as lesions, at the actual location inside the patient. Cabrilo *et al.* used the Zeiss OPMI Pentero's Multivision function that injects virtual images into one ocular of the neurosurgical microscope to carry in the context of neurovascular surgery [10, 11]. Mahvash and Tabrizi developed a projector-based AR system where images of the pertinent patient anatomy are project onto the skin, skull or brain surface in real-time [12]. Each of these systems has been tested on phantoms and some on patients, providing some evidence that AR can be useful for particular tasks in the OR. In our paper we examine how AR can be used in the specific task of craniotomy planning for tumour resections.

For more information as to the use of augmented reality in IGNS the reader is referred to a recent survey of the field [13].

3 Materials and Methods

3.1 IBIS System Overview

To create augmented reality visualizations in the OR, we used a custom-built research image-guide neurosurgery system, IBIS. For augmented reality three components are necessary: the IBIS neuronavigation workstation, an image-capture device (here a Sony HDR XR150 video camera was used), and a Polaris tracking system (Northern Digital, Waterloo, Canada), which is used to track the patient, surgical tools and the camera. The neuronavigation workstation runs Ubuntu 12.04 (64-bit), with an Intel Core i7-3820@3.6 GHz on a quad-core processor with 32 GB RAM. The graphics card is a GeForce GTX 670 and the video capture card is a Conexant cx23800. The custom-built software is written in C++ and uses the Visualization Toolkit (version 5.10), the Qt 4 user interface platform, and Insight Registration and Segmentation Toolkit (version 4.4). Previous publications using the IBIS software have focused on using intraoperative ultrasound (iUS) [14] for brain shift compensation, using AR in neurovascular surgery [2, 3, 15], and improving AR visualization accuracy with iUS [16].

3.2 Augmented Reality Visualization

To create AR visualizations in the operating room, live images of the surgical scene are augmented with pre-operative patient models (e.g. segmented tumours and vessels). The live images are captured by a calibrated Sony video camera and the virtual and real elements are merged and displayed on the neuronavigation system to inform and guide the surgeon.

There are three prerequisites for creating an AR view: (i) a camera must be calibrated, (ii) the calibrated camera must be spatially tracked, and (iii) a patient-to-image registration must be computed. These three elements give us the information needed to create a mapping between the virtual world and objects, and the real world. The *calibration* procedure involves computing the intrinsic (i.e. focus and image center) and extrinsic parameters of the camera, i.e. the transformation between the attached tracker and the optical center of the camera. Calibration is done using an implementation of Zhang's method [17], in which the edges of a planar calibration grid or checkerboard pattern of known size are detected using different poses of a camera. By calibrating the camera, the transform between the image and real world coordinates can be computed. Camera calibration is performed pre-operatively in the lab, and *tracking* the video camera ensures the position of the camera in the OR is known at all times. In the OR, the surgeon performs a *patient-to-image registration* by choosing, with a tracked surgical pointer, anatomical landmarks on the patient that correspond to those chosen preoperatively on the patients MR images [18]. This determines the mapping between the physical space of the patient and the virtual space of their preoperative images. The location of the camera, the camera calibration matrix and patient-to-image

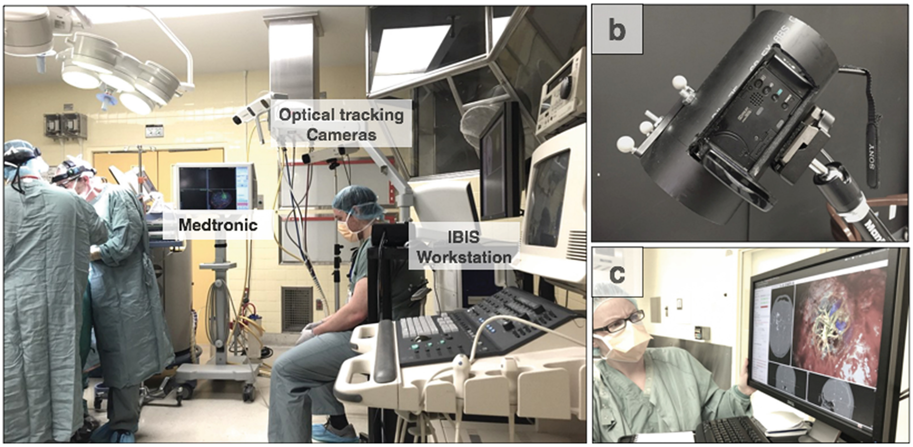

Fig. 1. The IBIS neuronavigation system in use in the OR: (a) The system is brought into the OR in parallel with the commercial Medtronic system. (b) A calibrated camera with an attached tracker is used to capture live images of the surgical scene. (c) The augmented reality visualization is displayed on the monitor of the IBIS workstation.

registration together provide us with the relationship between the pre-operative images and the live images of the surgical field of view, allowing for the creation of the AR visualization. In Fig. 1 we show the system being used in the operating room. For a more detailed description of the system, calibration and registration procedure, we refer the reader to [2].

3.3 MR Image Processing and Visualization

Data. In order to prepare for each case, the preoperative imaging data is processed to identify all structures and regions of interest. The data acquired for each of the patients was a gadolinium enhanced T1 weighted magnetic resonance image (MRI) obtained on a 1.5 T MRI scanner (Ingenia, Philips Medical Systems) at the Montreal Neurological Institute and Hospital (MNI/H). The MRI data was processed using a custom image-processing pipeline [4] that includes: de-noising [5], intensity non-uniformity correction [6] and normalization. As part of the pipeline, segmentation of cortical surface is done using the FACE method [7]. The automatic pre-processing is done using a local computing cluster at the McConnell Brain Imaging Centre (MNI) and takes 1–2 h.

The tumour is then manually segmented from the processed images using ITKSnap, and the visible vessels (typically the sinus and some large arteries and veins) are segmented using semi-automatic intensity thresholding also in ITKSnap. The processed images and patient-specific models are then imported into IBIS for visualization, planning and guidance (Fig. 2).

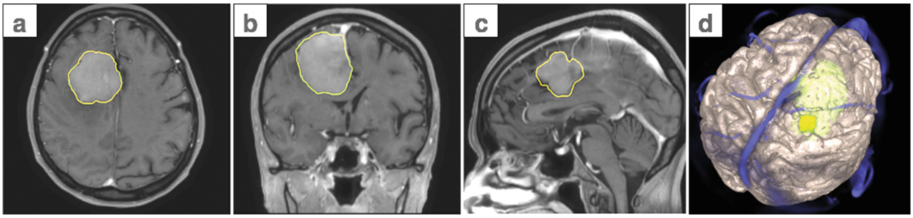

Fig. 2. Processed gadolinium T1 MRI from left to right: axial (a), coronal (b) and sagittal (c) slices showing the manually segmented tumour outline. (d) The 3D view shows the extracted cortical surface, vessels (purple) and segmented tumour (green). (Color figure online)

Visualization. Once the data has gone through the image-processing pipeline we create a 3D model with the cortical surface, extracted vessels and manually segmented brain tumour (i.e. Fig. 2(d)). During surgery, typically only the tumour and sometimes vessel virtual models are used in the AR view. Transparency is used to combine the virtual model with the real world such that the real world image is modulated to show the virtual objects below the surface in the region of interest (Fig. 3(c)). A typical problem with AR is that when transparency alone is used, i.e. the real and virtual objects are just alpha blended, then the virtual object appears to be floating above the real world. Therefore, to improve relative depth perception, we retain edges from the real world camera image (computed using a Sobel filter), so that the virtual object appears below the real world surface (Fig. 3(d)). For more information about our AR visualization the author is referred to [19].

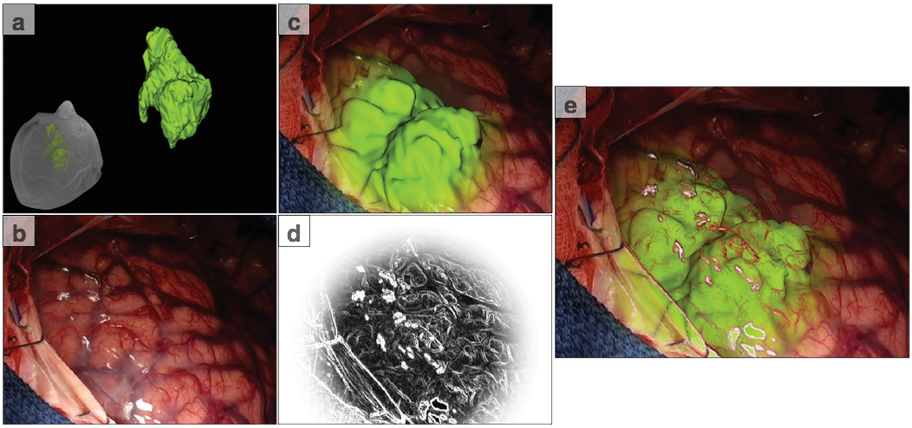

Fig. 3. (a) Segmented tumour and patient avatar. (b) Captured real world image of the cortical surface of a patient. (c) The transparency of the real world image is modulated to show the virtual segmented tumour object below the surface; however, the tumour appears to be coming out of the cortical surface, or possibly floating above it. (d) Edges of the image in (b) are computed using a Sobel filter and retained in the transparent part of the real world image, giving a correct perception of the relative depth between the real and virtual world (e).

3.4 OR Workflow

Camera calibration, image processing and the visualization of the patient-specific preoperative models are done prior to the surgical cases. As well, prior to surgery, patients consent to the use of our research neuronavgiation system, which has been approved by the Montreal Neurological Institute/Hospital Research and Ethics Board. The IBIS system is always brought into the OR in parallel with the commercial Medtronic StealthStation (Dublin, Republic of Ireland).

The system is set-up in the OR prior to the patient being brought in and therefore does not disrupt the OR workflow. The workflow is the same for each surgical case where augmented reality is used. Patient-to-image registration is performed after anaesthetization using the same anatomical landmarks at the same time on both systems (Medtronic and IBIS), in order to minimize disruption. Once the patient is registered the surgeon can use IBIS at any point in time during the surgery, AR visualization is always available and in our current protocol intraoperative ultrasound (iUS) is captured on the dura (to account for brainshift, i.e. the movement of the brain caused by the craniotomy and administrated drugs) both prior to and after resection.

Based on preliminary comments from the surgeons, we found that the task that may benefit most from AR visualization is craniotomy planning and therefore this is the focus of this paper. In this study, we asked the surgeon to use AR on the skin, bone, dura and cortex.

4 Results and Discussion

In the following section we describe the use AR in craniotomy planning, providing qualitative evidence on the usefulness of AR for the task of tailoring the shape and size of the craniotomy. Further, we present examples from three surgical cases where AR was used in the operating room for this task (Table 1).

4.1 Tailoring the Craniotomy

Determining the size and shape of a craniotomy is part of a planning process that takes into account both the location of the anatomy of interest and how the surgeon will access the anatomy through the opening of the skull. Ideally, the surgeon will design an opening that will allow access to all of the pertinent parts of the anatomy but minimize the amount of brain that is exposed. Augmented reality has the potential to facilitate this the task by allowing the surgeon to use “X-ray vision” to look through the surface of the skin and bone at the anatomy of interest. In doing so the surgeon can see the extent and margins of the tumour and use this to (1) plan the opening of the skin and (2) to determine the size and shape of the bone flap to be removed (e.g. Figs. 4, 5 and 6).

Planning the Skin Incision. By tailoring the skin incision to be smaller, there is less chance of infection and fewer stitches that are used, which can result in faster healing times. Of course, depending on the location and the size of the tumour the skin incision will vary in size however, smaller incisions are generally seen as optimal. Using

Table 1. Summary of the registration and calibration reprojection error and use of AR in each of three example cases. We focus on the technical details of the system, rather then the clinical details of the cases.

Case	Registration (RMS)[a]	Calibration error[b]	AR use
1 (Fig. 4)	3.7 mm	0.2 mm	The AR view was checked on the skin and bone after the surgeon traced the outline of the tumour. A good correspondence was found between the tracing and the AR view
2 (Fig. 5)	2.1 mm	0.18 mm	AR was used to trace the tumour on both the skin and cortex. A vessel was visible between the surface and tumour in the AR view that was taken into account during planning
3 (Fig. 6)	5.0 mm	0.2 mm	Due to a poor registration AR was used only after the surgeon traced the tumour using conventional neuronavigation and a discrepancy was seen between AR overlay and marked lines

[a] Patient-to-image fiducial registration error is calculated as root-mean square error on fiducial landmarks used to estimate the patient-to-image registration.

[b] Calibration error is computed as the average reprojection error between 3D points and their 2D projections in the AR display.

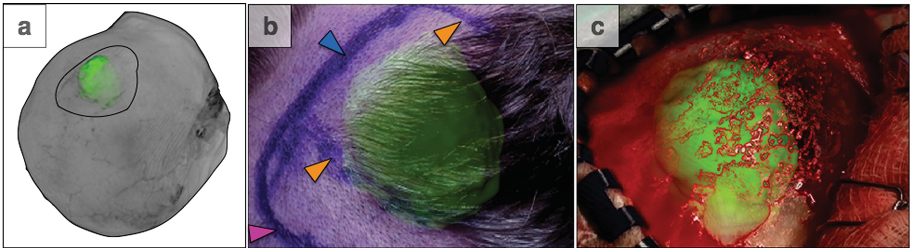

Fig. 4. (a) Case 1: 3D rendered MRI skin surface (from the back, with the patient's neck directed towards the top of the image) and segmented tumour virtual patient model, showing position of patient head and approximate location of the planned craniotomy. (b) In this case the tumour outline indicated by the orange arrow was done using the Medtronic system and checked using AR. There was a good correspondence between the AR view and the outlined tumour. The blue arrow indicates the boundary of the tumour and overlaps with the contour of the planned skin incision. The pink arrow indicates the superior boundary of the planned skin incision. (Color figure online)

augmented reality, the surgeon can trace the extent of the tumour on the skin using a sterile marker and plan as minimal a skin incision as possible.

When a good calibration and initial registration, are achieved, the AR view is deemed accurate and can be used by the surgeon for intraoperative planning. Currently, we access the accuracy of the AR view using the commercial system. In Fig. 4(b) we

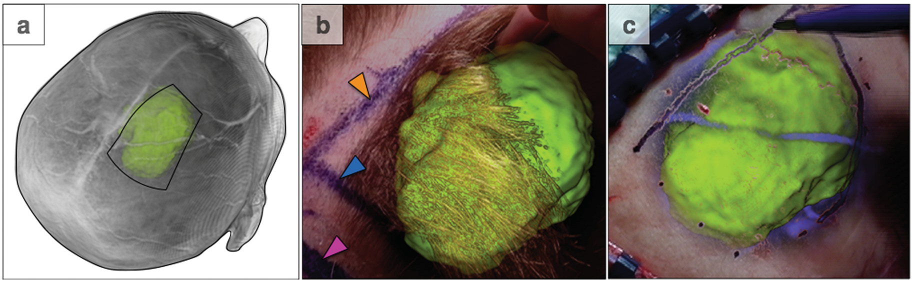

Fig. 5. Case 2: (a) 3D rendered MRI and segmented tumour virtual patient model, showing position of patient head and location of the planned craniotomy. (b) The surgeon uses AR to determine the location and extent of the tumour. The blue arrow indicates the posterior boundary of a bounding box around the tumour and the pink arrow indicates the planned posterior boundary of the craniotomy that will allow resection of the tumour. The orange arrow shows the medial extent of the bounding box around the tumour, which is also the planned craniotomy margin. (c) The surgeon uses the AR view to trace around the tumour (see the felt marker in the top right of the image) in order to determine the size of the bone flap. Note the vessel (in purple) that was visualized in the AR view and was taken into account for the craniotomy. (Color figure online)

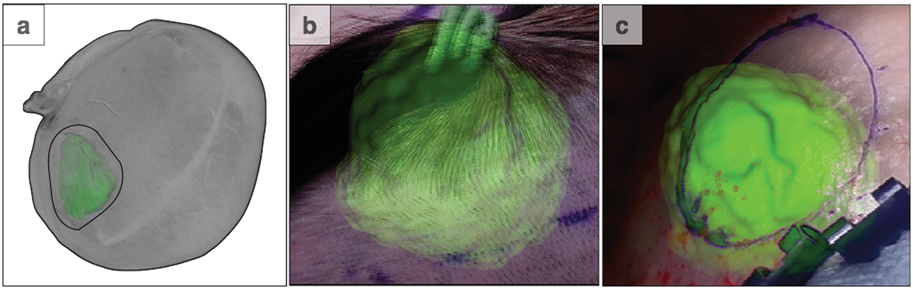

Fig. 6. Case 3: (a) 3D rendered MRI and segmented tumour virtual patient model, showing position of patient head and location of the craniotomy planned. (b) Tumour projected onto the scalp, due to a poor registration results in IBIS the surgeon used traditional the Medtronic system to trace the tumour. (c) A discrepancy can be seen (1–2 cm) between the outlined tumour, which was drawn using the Medtronic system, and the AR overlay given in IBIS.

show a good correspondence between real and virtual elements of the AR view. In Fig. 5(b) we show a case where the surgeon used IBIS AR to define the boundaries of the tumour and then based on this and his plan on how the tumour will be resected, determined the extent of the skin incision. Unfortunately, due to the compounding of errors from tracking, registration and camera calibration, the mapping between real and virtual models is not always accurate. In Fig. 6(b) we given an example of a case where, due to a poor registration result on our research system, the AR overlay is misaligned with the drawn tumour boundary, which was planned using the commercial navigation system.

Planning the Bone Flap to Be Removed. The size and shape of the bone flap to be removed is smaller than the skin incision and is planned to facilitate access to the pertinent anatomy. A surgeon can make use of AR visualization to trace around the points of the virtual tumour in order to determine the location, as well, as the shape and size of the bone flap to be removed. In Fig. 5(c) we see how the surgeon had used dots to outline the tumour and then connects these to create the contour of the tumour on the bone, in order to plan the surgical approach[1]. In this case, the accuracy of the AR overlay was deemed high based on a comparison with the commercial navigation system, which we use as a silver standard. In our third case in which there was a poor initial registration, the misalignment between the overlay and the planned craniotomy using the Medtronic system can be seen on the bone (Fig. 6(c)).

4.2 Other Uses of AR in Tumour Resections

Although in this paper we have focused on using AR for craniotomy planning, we've also explored the use of AR on the dura to plan the dural incision and on the cortex to plan the resection corridor and surgical approach (Fig. 7). By combining iUS that is taken on the dura, and updating the MRI images to account for brain shift and misregistration errors we can use AR to visualize the preoperative patient images and segmented tumour which have been correctly re-aligned to the reality of the patient [16].

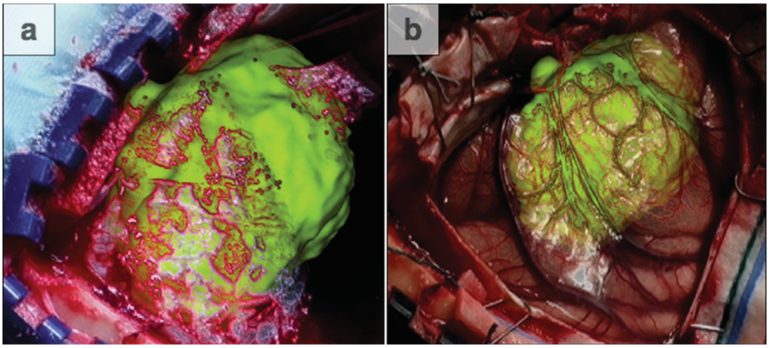

Fig. 7. Augmented reality visualization can be used on the dura (a) to plan the dural incision and on the cortex (b) to plan the resection corridor and surgical approach. This is the same case as in Fig. 5.

4.3 Qualitative Results

Comments from the surgeons suggest that an accurate AR overlay, can be beneficial and facilitate craniotomy planning particularly for smaller lesions. Furthermore, AR overlays can be useful in showing anatomy, such as vessels, in the surgical field of

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[1] A video of the surgeon using AR in this surgical case can be viewed at: https://www.youtube.com/watch?v=tru4uwQIvyI.

view that may impact the surgical plan (as in Fig. 5(c)) and help facilitate describing the surgical plans and patient anatomy to colleagues, residents and the OR staff. For example, in a case not presented here, a dural vessel inhibited the safe and complete removal of the dura. The AR view allowed for visualization of this vessel on the surface of the dura that in turn allowed for appropriate intraoperative planning and avoidance of a minor bleed during surgery.

We have found that although there is a learning curve to understanding augmented reality visualizations, as a surgeon becomes accustomed to these visualizations they find it can aid in intraoperative surgical planning. Whereas in the first cases we asked the surgeons to use augmented reality at particular points in surgery, in later cases, the surgeon (who had used AR the most) asked to see the AR visualizations at different points in surgery and suggested when and how it could be most useful.

5 Conclusions and Future Work

In this preliminary study we have looked at the possible benefit of using augmented reality in craniotomy planning for tumour resections. Our initial results suggest that with a good initial alignment between patient models and the real world, AR visualization of the tumour and vessels below the surface is useful in planning a craniotomy that may minimize the exposure of the brain.

According to the surgeons, AR visualization could be even more beneficial for smaller lesions where it may not be as evident how small the craniotomy may be while still allowing access for resection. The usefulness of this system is intimately tied to the accuracy of the AR visualization, which can vary widely by case. In order for widespread use of this technique more stable initial accuracy will be pivotal. Furthermore, the impact of the perception of the depth of the tumour in the AR view needs to be explored. In order to ensure an accurate overlay, in the future, we will explore the use of transcranial US to account for initial patient-to-image misregistration errors.

In future work, we propose to quantitatively determine the effect of using AR visualization on the size and shape of a planned craniotomy in a prospective study. In a recent study by Mahvash et al. [20], which compared craniotomy planning with no image-guidance to planning with guidance, the authors showed that all ten neurosurgeons in the study changed the craniotomy localization and skin incision initially planned with no guidance when image-guided tumour visualization was shown. Furthermore, the size of the craniotomy was significantly larger ($p < 0.035$) when no image-guidance was used. We would expect even more significant results with the use of reliable and accurate AR. One can imagine doing a similar study in which a surgeon first plans the craniotomy using traditional image-guidance and is then shown the AR view. We posit that the craniotomy plan would change to be smaller with this type of visualization.

In order to improve the surgical workflow, we plan to expand IBIS to allow for AR on a tablet device for in-situ visualization. This will obviate the need for the surgeon to look away from the operating field to the neuronavigation system and the visualization to be in front of the surgeon and above the patient, facilitating the marking of lesion boundaries and surgical plans on the surface of the patient.

Augmented reality visualization offers a promising avenue of research that has the potential to improve surgical workflows and further minimize the invasiveness of neurosurgery.

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