

Digital Application to Display Brain Shift Simulation in Tumor Resection Procedures

Kush J. Hari¹, Rohan C. Vijayan², Ma Luo^{1,3}, Jaime Tierney^{1,3}, Jon S. Heiselman^{1,3}, Lola B. Chambless^{3,4}, Reid C. Thompson^{3,4}, and Michael I. Miga^{1,3,4,5}

¹Vanderbilt University, Department of Biomedical Engineering, Nashville TN USA

²Johns Hopkins University, Department of Biomedical Engineering, Baltimore MD USA

³Vanderbilt Institute for Surgery and Engineering, Nashville TN USA

⁴Vanderbilt University Medical Center, Department of Neurological Surgery, Nashville TN USA

⁵Vanderbilt University Medical Center, Department of Radiology and Radiological Sciences,
Nashville TN USA

ABSTRACT

The quality of neurosurgical planning can become compromised by soft tissue deformations that occur during surgery (i.e., brain shift). Conventional image guidance systems do not consider these intraoperative changes. In recent efforts, model-based strategies have been developed to estimate surgical load displacements and modify the patient's data intraoperatively to account for brain shift. While the efficacy of the model has been previously established, there is also an opportunity to further assist surgical planning with this pipeline. To address this, a mobile application designed for an Android tablet was developed to display simulated brain shifts that would occur during brain tumor surgery. The application has two primary functions to facilitate planning: a patient positioning mode and a simulation mode. The patient positioning mode allows the neurosurgeon to load the patient's preoperative MR data and create a surgical plan (i.e., head orientation and craniotomy location) for the procedure. The simulation mode then displays both the preoperative data and the model-predicted brain shift as a function of the specified orientation from the patient positioning mode. Additionally, to account for positional variations between planning and procedural implementation, the simulation mode also displays solutions with additional perturbations to the planned positioning to estimate shift possibilities. To assess the simulation mode prototype, practicing neurosurgeons were provided a prototype demonstration and interviews were performed to evaluate efficacy and design. Due to computational rendering and 3D rotation shortcomings based on clinical feedback, the prototype was redesigned into a full mixed reality simulation app on the Microsoft HoloLens. Preliminary survey responses show that the prototype could be an impactful surgical planning tool, especially among neurosurgeons with less experience.

Keywords: brain shift, Android, mixed reality, planning, HoloLens, craniotomy, image-guided surgery, image guidance

1. INTRODUCTION

The current standard of care for tumor resection procedures uses image guidance systems to develop a surgical plan from preoperative imaging data and assist in surgical navigation [1]. Overall, these systems have improved the quality of surgery by reducing surgical time, verifying craniotomy placement, and identifying eloquent areas of the brain that need to be protected during tumor resection [1]. However, these conventional image guidance systems are limited in that they do not consider the physical changes of the brain that ensue during surgery. These physical changes can misalign the brain relative to the preoperative data, thus invalidating the previously designed surgical plan, and could lead to surgical error [1].

Changes that cause mechanical deformation during surgery are commonly referred to as 'brain shift'. There are many causes for brain shift (retraction, resection, hyperosmotic drugs, cerebrospinal fluid drainage, etc.) [1,2]. While in previous work, the model herein has reported simulations of all of these, in this initial work, we will focus on the impact of gravity-induced shifts from the drainage of cerebrospinal fluid, and the influence of head orientation in this context [2].

Separately, it is important to note that much work has been done toward integrating traditional diagnostic imaging modalities for the operating room (OR). These techniques include intraoperative magnetic resonance imaging (iMR) and intraoperative computed tomography (iCT), which can accurately display soft tissue changes that occur during surgery [3, 4, 5]. While powerful, these methods are expensive, increase surgery time, and are cumbersome [3, 6]. These limitations have led to the pursuit of computational model-based solutions [3,7-9] although these methods have workflow challenges as well. Building on the promise of these new frameworks, the purpose of this research is to leverage computational brain modeling further by better integrating these simulation capabilities into preoperative planning.

In previous work, a computational brain pipeline was developed [7-9]. Given the preoperative image data and the craniotomy surgical variables, the deformation pipeline updated the images such that they accounted for brain shift [7-9]. Briefly, the first step of the pipeline was to form a patient specific mesh from the initial image data. Then, a wide variety of boundary conditions were generated to represent varying presentations that could be selected by the neurosurgeon. More specifically, the boundary conditions were based on the surgical variables determined in the craniotomy plan (craniotomy centroid, craniotomy location, and head orientation). Finally, an atlas of deformation solutions was created by applying the brain shift deformation to each node of the mesh based on the boundary conditions [7-9].

In order to efficiently create the surgical plan for the deformation model, an Android application was developed to plan the procedure [2,3]. Android Studio was used for the application framework due to its ability to access and integrate Java-based Android libraries. Furthermore, the app was tested on a Nexus 9 tablet, and the three-dimensional model rendering was implemented with the OpenGL Embedded Systems (ES) library. The app rendered the preoperative images on the tablet, which allowed the neurosurgeon to create a plan that could then be used in the deformation atlas.

While this aforementioned app provided input regarding positioning, there was no functional method of accessing and displaying how this information could potentially influence the intraoperative procedure [2,3]. To address this, the work presented here expands the app to create a second functional mode (i.e., a simulation mode). The simulation mode integrates a visual display of predicted brain shift based on the preoperative craniotomy plan and head positioning. It should also be noted that the app incorporates a suite of solutions that encompass a range of presentation possibilities about an initial plan developed by the clinician. With respect to display, the app renders brain shift simulation data in 3D by overlapping preoperative and simulated intraoperative geometric models. In addition, data are also provided demonstrating how brain shift may transform the patient-specific neuroanatomy by applying deformations to the 3D image volume. These capabilities are visualized in a 3-panel display that compares the preoperative image, the model-deformed image, and the difference image.

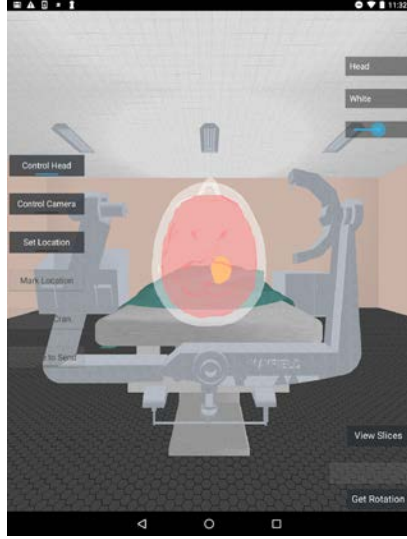
2. METHODS

2.1 Computational Model of Brain Deformation

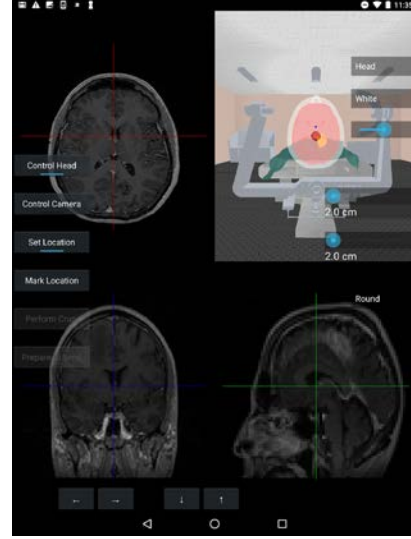
The brain shift model simulation platform [7-9] was previously developed in C++ with VTK libraries. While the core of the modeling pipeline remains relatively unchanged, some modifications were performed to better interface with the Android app. More specifically, the original distribution of boundary conditions was based on the inputted plan followed by a variety of configurations with perturbed positional parameters [9]. However, it was found that this approach did not provide a sufficient distribution to allow surgeons to get a sense of how positional changes influenced directional shift. As a result, the distribution of boundary condition parameters was revised to include 25 head orientation solutions in order to provide more understanding of positional changes relative to shift directionality.

2.2 Mobile App Development

As previously mentioned, an initial prototype of the Android application was developed to create a 3D rendered simulation of the case. The input to the simulation was ASCII VTK files in Polydata format along with PNG formatted image slices along the axial, coronal, and sagittal planes. With these data, a fully rendered virtual operating room with the patient's 3D models were displayed on the app as seen in Figure 1a [2,3]. The neurosurgeon could then rotate the head and the camera in order to better visualize the procedure. Moreover, once the head orientation was properly set, the neurosurgeon could set the location, size, and trajectory of the craniotomy, and then send those measurements to the brain shift simulation platform as seen in Figure 1b [2,3].



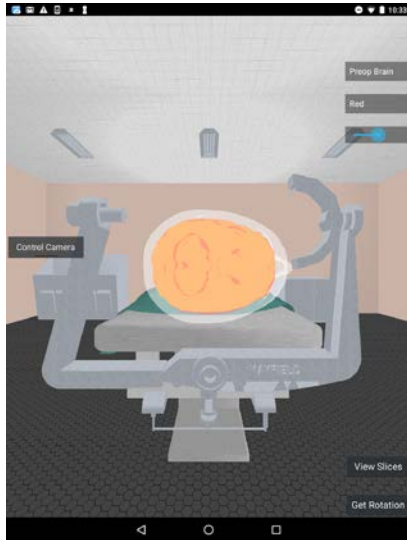
(a)



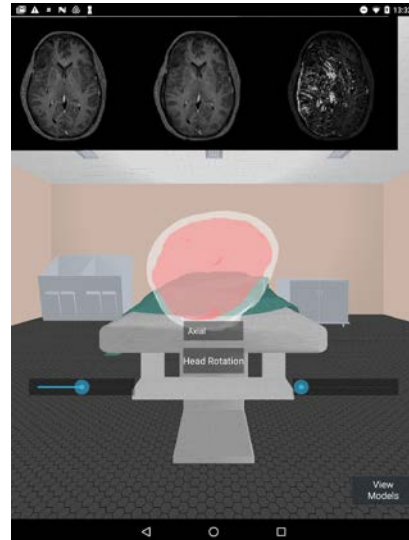
(b)

Figure 1: Patient Positioning Mode. (a) Model-based view of patient positioning mode allowing for configuration of head rotation. (b) Patient Positioning Mode on platform displaying slice images and 3D model for placement of predicted craniotomy location.

However, this initial app prototype was not capable of accessing and displaying the results of the deformation atlas [2,3]. To address this, the work presented here expands the app to create a second functional mode (i.e., a simulation mode). In the simulation mode, the app can display the corrected brain mesh (in yellow) on top of the original brain (in red) to create a 3D rendering of brain shift as shown in Figure 2a. The simulation mode can also display the preoperative tumor image slices, the deformed tumor images slices, and the image difference between the corresponding slices to model the 2-dimensional brain shift for the axial, coronal, and sagittal planes as shown in Figure 2b. In addition, this work also presents our findings from experienced neurosurgeons regarding the value of such a simple planning and simulation tool. These perspectives would be of great value to the community.



(a)



(b)

Figure 2. Simulation Mode. (a) Model-based view of simulation mode. (b) Simulation mode on platform with preoperative, model-deformed, and difference image shown above.

2.3 Mixed Reality App Development

As the simulation mode prototype was nearing completion, it was found that the Android tech stack could not create a fully realized app. This was primarily due to the unintuitive interface of the 3D meshes. As seen in Figure 2a, the goal was to display the initial brain mesh in red and the deformed brain mesh in yellow. However, instead of seeing both brains to demonstrate the 3D shift, the tablet only displayed a single brain colored in orange. Another problem with the Android tablet involved its computational rendering limitations. In order to display all 3 VTK models along with the image slices (approximately 128 x 256 x 256 image volume), the image quality had to be reduced by 80-90%, thus making it challenging to display the simulated shift through the tablet.

To address these problems, the app was redesigned into a mixed reality simulation. These simulations refer to an immersive medium where the user can interact with both physical and virtual elements integrated in the environment. This differs from virtual reality where the environment consists of only virtual elements. Mixed reality simulations were chosen due to their ability to display all relevant model information within the context of the real world.

The new prototype was developed for the Microsoft HoloLens 2 due to its ability to generate mixed reality simulations through stable hand tracking, voice tracking and eye tracking. The app itself was written in the Unity framework. Unity is a cross-platform game engine capable of developing various 3D rendered applications including mixed reality simulations. Compared to other mixed reality frameworks, Unity was chosen due to its interfacing capability with the Microsoft HoloLens 2 and its access to open software packages such as the Mixed Reality Toolkit. Similar to the simulation mode of the Android app, the HoloLens can display the corrected brain mesh on top of the original brain to create a 3D rendering of brain shift as shown in Figure 3a. The HoloLens can also display the same image slice panel from the simulation mode as shown in Figure 3b.

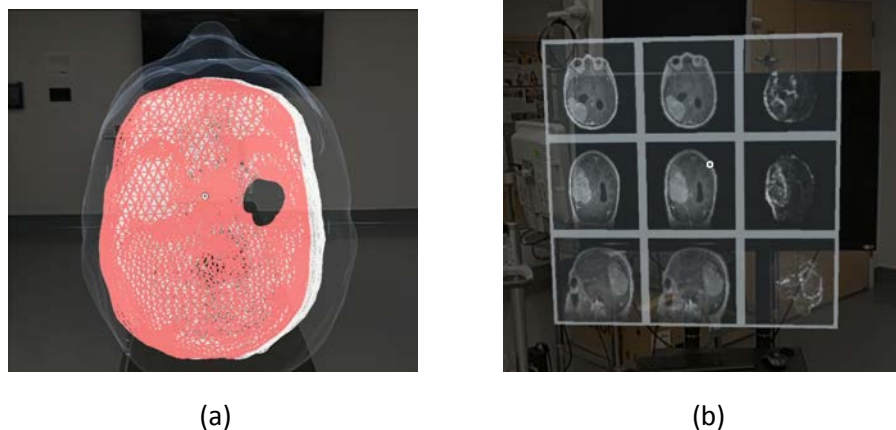


Figure 3. Mixed Reality App on Microsoft HoloLens. (a) Mixed Reality 3D display including the head, tumor (in black, the deformed brain (pink mesh) and the original brain (white mesh). (b) Mixed Reality 2D display showing shift along the axial, coronal and sagittal planes with the original image (first column), deformed image (second column), and image difference (third column).

2.4 Testing Procedures

To assess the Android simulation app and the HoloLens app, practicing neurosurgeons were provided a prototype demonstration and interviews were performed to evaluate efficacy and design. For the Android app, a mock craniotomy case was created to allow the neurosurgeons to gain familiarity with the app. The preoperative patient data was loaded into the app where the surgeon created a rough draft of the plan and sent the custom surgical variables to the deformation model. Once all 25 head orientation solutions were developed, they were loaded into the Android application, so the surgeon could evaluate brain shift simulation results. To save time, the solutions were precomputed into the tablet so the surgeon could immediately see the planner and simulation modes of the app. For the HoloLens app, the single deformation 3D models and image panels were loaded into the application for the surgeon to evaluate the simulation results (Figure 4).



(a)



(b)

Figure 4. HoloLens App Testing during Perception Study. (a) Prototype trial from outside perspective. (b) Prototype trial from surgeon's perspective.

3. RESULTS

The data from the user perception study was collected for both app iterations. Each neurosurgeon was presented both the Android application and the HoloLens application and were then interviewed with the same Likert scale questions. These questions asked about the general premise of a brain shift application regarding its use as a planning tool and teaching tool. The questions also focused on specific features of each prototype including the 3D model display and the 2D shift image panel.

The outcome of the Android app perception study was displayed in Table 1. Both neurosurgeons strongly agreed that a fully-realized application would be beneficial as a planning tool and a teaching tool. In regard to the current prototype, the surgeons either agreed or strongly agreed that the 2D shift image display was helpful and all surgeons were neutral on the 3D overlay of the deformed brain mesh on the original brain.

The outcome of the HoloLens app perception study was displayed in Table 2. Similar to the Android app, both surgeons strongly agreed that a fully-realized mixed reality simulation would be helpful in teaching and planning. Both surgeons also agreed that the 2D shift image display was helpful, but they each noted that they preferred the Android version since it updated based on head orientation. However, the surgeons strongly agreed that the 3D model shift display was significantly improved with the HoloLens application.

Table 1: Android app user perception study answers.

	App could improve surgical approach	App could be used as teaching tool	2D brain shift display was helpful	3D brain shift display was helpful
Surgeon 1	Strongly Agree	Strongly Agree	Agree	Neutral
Surgeon 2	Strongly Agree	Strongly Agree	Strongly Agree	Neutral

Table 2: HoloLens app user perception study answers.

	App could improve surgical approach	App could be used as teaching tool	2D brain shift display was helpful	3D brain shift display was helpful
Surgeon 1	Strongly Agree	Strongly Agree	Agree	Strongly Agree
Surgeon 2	Strongly Agree	Strongly Agree	Agree	Strongly Agree

4. DISCUSSION

In reference to the utility of a fully-realized simulation app to display patient-specific brain shift, all neurosurgeons interviewed strongly agreed that this app could improve their neurosurgical approach as the app could provide information about a patient's optimal head position and the impact of that orientation on brain shift. The neurosurgeons also stated that a fully-realized app would be useful as an instruction tool by supplying a visual method of teaching medical students, residents, and fellows. This tool can help teach good practice in tumor resection procedures by providing a general awareness of brain shift as a preoperative parameter rather than as an intraoperative obstacle.

Moreover, all neurosurgeons provided both positive and negative feedback about the specific Android app components and changes that need to be made. They stated that even though the 2D brain shift plane displays relevant information and it was helpful for those displays to update based on head rotation, the data were difficult to see, the head rotation scrollbars were unintuitive, and the displayed shift was too subtle. Also, it was indicated that the 3D displays need additional intuitive components that make it easier to distinguish deformation features.

However, for the HoloLens app, the neurosurgeons found the 3D display significantly better because it was easier to differentiate between the two brain meshes and understand the shift. This resulted in a more immersive experience, which further emphasizes the app's potential as a teaching tool. The HoloLens 2D display was also helpful to the neurosurgeons similar to the Android app; however, the display could be improved with more interaction. The HoloLens application can also be improved in the future by continuing to add functionality from the Android app. This includes the ability to display changes in brain shift deformation based on the rotation of the brain hologram, and the patient positioning mode such that neurosurgeons can create a surgical plan from the HoloLens. Furthermore, this mixed reality simulation could be used to compare virtual plans in the context of the physical patient provided a tracking device was rigidly fixed on the HoloLens and the display was calibrated. These improvements have the potential to further improve neurosurgical planning and teaching by providing new and alternative perspectives in brain shift display.

5. CONCLUSION

This work presented the first steps in developing an application to render brain shift to aid in neurosurgical planning. Overall, an efficient simulation app that can render brain shift would be a useful teaching and planning tool prior to surgery. The Android app prototype contains promising features by being able to juxtapose preoperative tumor slices with intraoperative slices from the deformation simulation platform at various head orientations. The HoloLens app prototype built on the successes of the Android app by displaying 3D brain shift in an effective and intuitive way. By improving the current brain shift displays and adding new functionality to the app such as shift display updates and 3D tracking, this simulation app could serve as an alternative to standard planning tools and could enhance surgical approaches to challenging cases.

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