

Graphical user interface for intraoperative neuroimage updating

Kyle R. Rick¹, Alex Hartov^{1,2,3}, David W. Roberts^{2,3}, Karen E. Lunn¹, Hai Sun¹,
Keith D. Paulsen^{1,2,3}

¹Thayer School of Engineering at Dartmouth College, Hanover, NH 03755

²Dartmouth Hitchcock Medical Center, Lebanon, NH 03766

³Norris Cotton Cancer Center, Lebanon, NH 03766

ABSTRACT

Image-guided neurosurgery typically relies on preoperative imaging information that is subject to errors resulting from brain shift and deformation in the OR. A graphical user interface (GUI) has been developed to facilitate the flow of data from OR to image volume in order to provide the neurosurgeon with updated views concurrent with surgery. Upon acquisition of registration data for patient position in the OR (using fiducial markers), the Matlab GUI displays ultrasound image overlays on patient specific, preoperative MR images. Registration matrices are also applied to patient-specific anatomical models used for image updating. After displaying the re-oriented brain model in OR coordinates and digitizing the edge of the craniotomy, gravitational sagging of the brain is simulated using the finite element method. Based on this model, interpolation to the resolution of the preoperative images is performed and re-displayed to the surgeon during the procedure. These steps were completed within reasonable time limits and the interface was relatively easy to use after a brief training period. The techniques described have been developed and used retrospectively prior to this study. Based on the work described here, these steps can now be accomplished in the operating room and provide near real-time feedback to the surgeon.

Keywords: image-guided, MRI updating, registration, brain modeling, brain shift

1. INTRODUCTION

Efficient frameless image-guided neurosurgery depends upon the seamless flow and coregistration of three essential forms of data: preoperative magnetic resonance (MR) or computer tomography (CT) imaging volume, location of the patient's head, and the positions of various surgical tools. Using the preoperative imaging scan as an atlas, the surgeon can accurately place tools and identify structures within the brain. However, over time the accuracy of the image-guidance system can deteriorate due to brain shift. Brain shift, including the loss of cerebral spinal fluid, gravitational sagging, hyperosmotic drugs and surgical interventions, such as retraction or resection, can significantly increase the registration error between preoperative structures and the actual locations of the corresponding features during surgery. Several studies have been performed that illustrate varying cortical shifts of 1.2 to 20 mm, of which the greatest component of displacement was found to be in the direction of gravity [1-3].

Intraoperative image updating is required to aid in correcting the above mentioned brain shift error. Our group is pursuing the use of an intraoperative finite element brain deformation model as an alternative to costly, intrusive and inconvenient intraoperative magnetic resonance scans (iMR). Intraoperative ultrasound and three-dimensional (3-D) digital pictures of the craniotomy site taken through the operating microscope may provide sparse data to be used with the patient specific finite-element model (FEM) to generate volumetric calculations of brain tissue displacement.

Further author information: (Send correspondence to K.R.)

K.R.: Email: kyle.rick@dartmouth.edu, Telephone: 1 603 646 1483

A.H.: Email: alex.hartov@dartmouth.edu, Telephone: 1 603 646 3936

D.R.: Email: david.w.roberts@dartmouth.edu, Telephone: 1 603 650 8736

K.L.: Email: karen.lunn@dartmouth.edu, Telephone: 1 603 646 1094

H.S.: Email: hai.sun@dartmouth.edu, Telephone: 1 603 646 1094

K.P.: Email: keith.paulsen@dartmouth.edu, Telephone: 1 603 646 2695

This paper will discuss the development of a Matlab graphical user interface (GUI) that allows the user to collect surgical data in order to accurately register the patient with the preoperative MR/CT images, overlay intraoperatively acquired ultrasound images and use a finite element brain shift model to update the preoperative scans during surgery. The main purpose of the GUI is to streamline the complex flow of data (Figure 1) so that the above computational techniques can be carried out during surgery and thus provide direct, near real-time feedback to the neurosurgeon. This valuable information aids the neurosurgeon in accounting for the brain shift related to gravitational sagging.

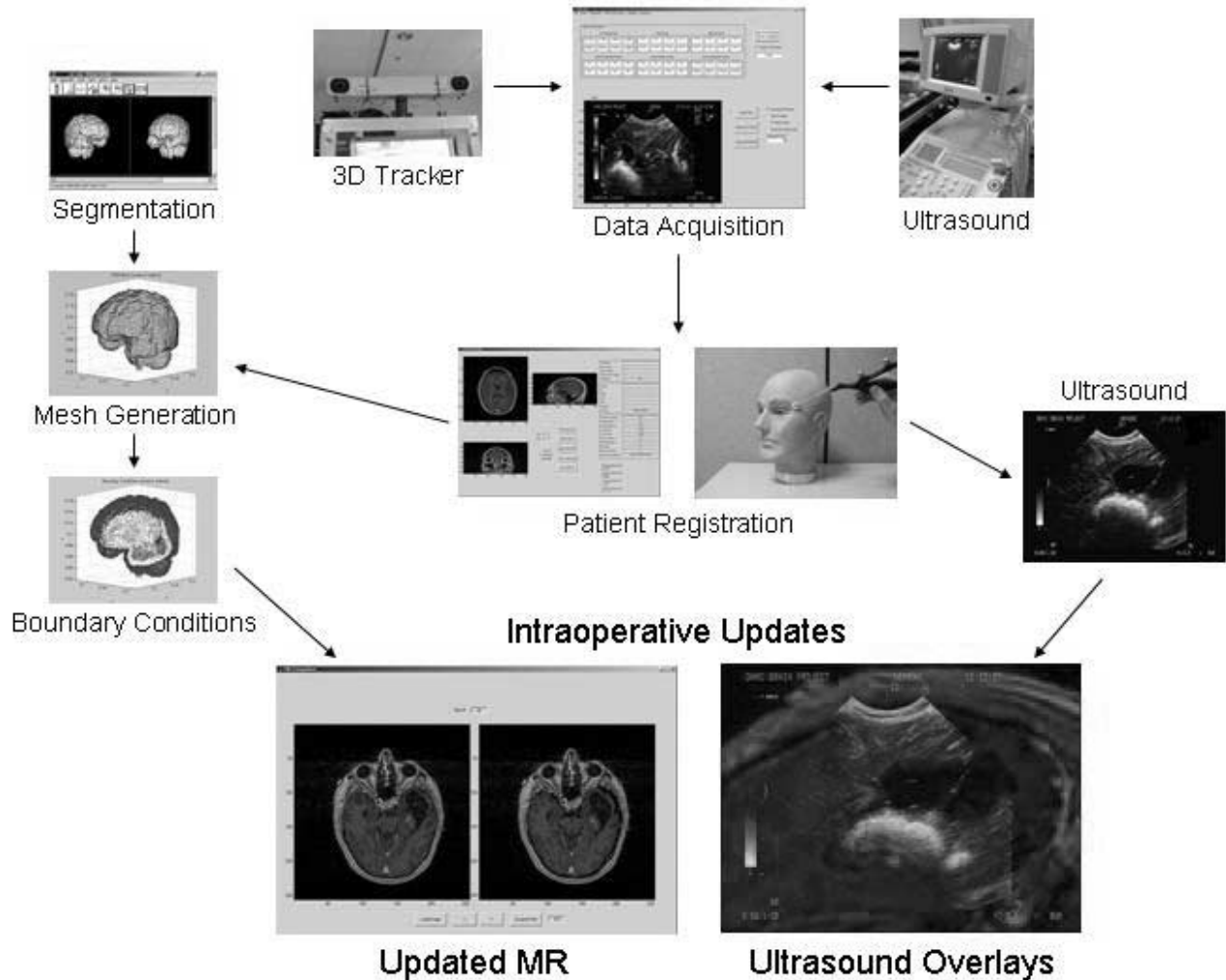


Figure 1: The flow of data streamlined by the GUI. Data is acquired and then used in the FEM generation, patient registration, ultrasound overlays and to intraoperatively update the pre-op MR based on volumetric FEM predictions of brain shift.

2. MATERIALS AND METHODS

2.1 Data Acquisition

The GUI for intraoperative neuroimage updating discussed in this paper was developed using the Graphical User Interface Development Environment (GUIDE) within Matlab 6.1 (The Mathworks, Inc., Natick, MA). The main interface panel is shown in Figure 2. From this panel the user can initialize communication with the 3D tracking system. If the tool is within the tracking volume, tool positions are reported by the 3D tracking system and actively displayed to the user. Currently six tools (three active and three passive) can be tracked simultaneously.



Figure 2: The main GUI window initiates communication with the 3D tracker, tracks tools and acquires ultrasound images. Other GUI windows can be called from the menu options at the top of the figure.

Once communication has been established, the user can obtain either single or sequenced tool positions. The user can also elect to “grab” color-Doppler or gray scale ultrasound images with the corresponding tool positions. The Matlab routines that control the frame grabbers were developed at Czech Technical University [4].

2.2 Patient Registration

Registering the patient to the pre-operative MR is a two-step process. First, the centers of donut-shaped fiducial markers are digitized using a passive stylus probe. Second, the same points must also be identified in the pre-operative MR by using the Patient Registration GUI (Figure 3), which can be called from the main panel. From there, the user can read in a Dicom MR/CT imaging volume. The volume is stored as a 3-D array and the Dicom header as a structured array (patient information, voxel size, etc.). The user can then scroll through the image volume to locate the fiducial markers within the imaging volume. These points are then paired with points digitized by a passive stylus probe in the patient frame of reference. The transformation matrix, ${}^{mr}T_{pat}$, which describes the relationship between the two reference frames is computed from these data and registration error results are reported to the user.

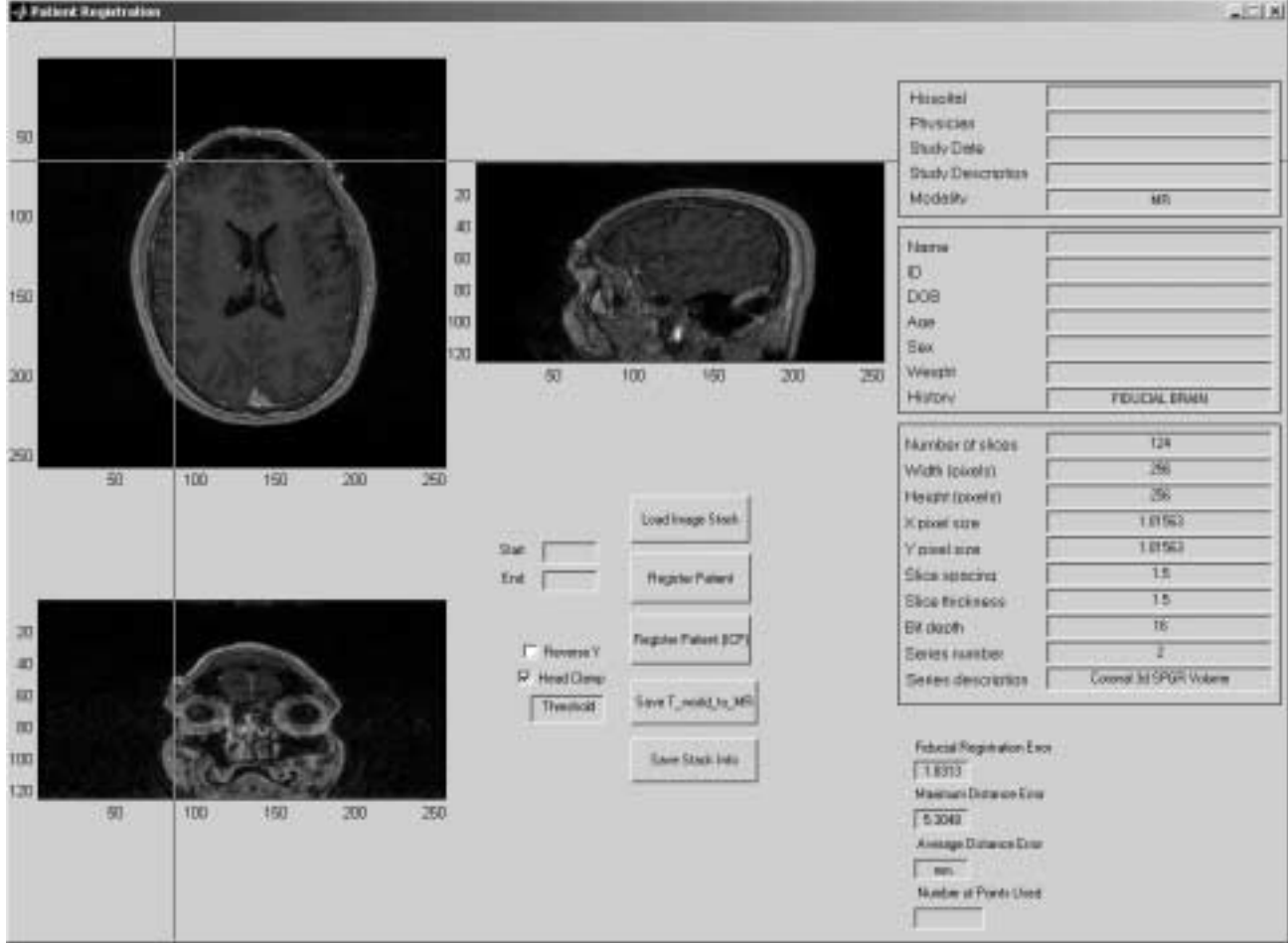


Figure 3: Patient Registration GUI involving the manual selection of fiducial markers in the MR frame of reference. Patient data is displayed and registration errors are reported to the user after the patient and MR/CT frames of reference are coregistered.

2.3 Ultrasound Overlays

After the successful calculation of the ${}^{mr}T_{pat}$ transformation matrix from the registration stage described above, the user can then call the “Single Reconstruction” GUI from the main GUI (Figure 5, computer monitor). This allows the surgeon to frame-grab an ultrasound image, compute the corresponding plane in the MR/CT volume and overlay the two images by simply pressing a button attached to the ultrasound scan head. These steps are carried out by first rigidly attaching an active infrared tracker (Model TT002-C; Traxtal Technologies, Toronto, Ontario, CAN) to the ultrasound scan head using a custom collar. As described by Lunn et al. [5], the active ultrasound scan head can be calibrated by registering the CT image volume of the calibration tank with the 3D tracking coordinate system. Further, imaging of N-shaped wires of known locations within the calibration tank allows the computation of the transformation matrices from the 3D tracking system to the ultrasound tracker and from the ultrasound tracker to the ultrasound imaging plane. The MR/CT plane that corresponds to the ultrasound imaging plane is then calculated using the following equation (See Figure 4):

$$P_{mr} = {}^{mr}T_{pat} {}^{pat}T_{3DTS} {}^{3DTS}T_{tr} {}^{tr}T_{us} P_{us}$$

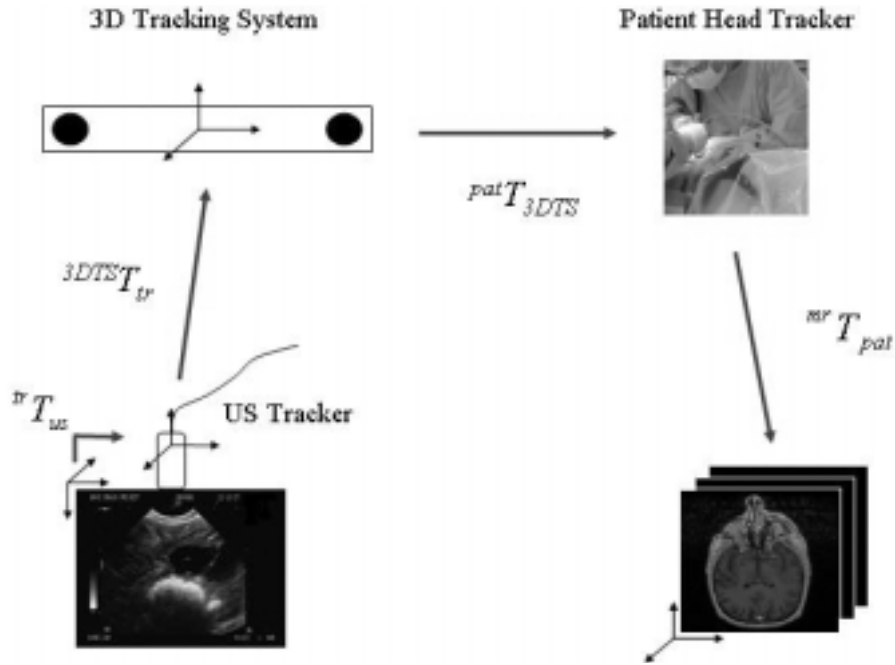


Figure 4: Different reference frames involved in computing the equivalent plane in the MR/CT volume. For example, ${}^{pat}T_{3DTS}$ corresponds to the transformation matrix from the 3D tracking system to the patient tracker frame of reference.

2.4 Model Generation

Before the surgery proceeds, an MRI series of the patient brain is obtained for surgical navigation purposes (T1-weighted, 1.5 mm slices). A 3-D representation of the brain is segmented from the original MRI volume using Analyze AVW Version 5.0 (Biomedical Imaging Resource, Mayo Foundation, Rochester, MN). A marching cubes algorithm [6] is used to create a surface description of the segmented brain. This surface description is then used in the creation of a 3-D tetrahedral mesh with custom-made software [7].

The finite element brain shift model needs three types of data in order to execute: files containing mesh information (nodes, elements and boundary elements), a material file containing the tissue properties of the different elements in the mesh (white and gray matter, as well as cerebral spinal fluid) and a boundary conditions file to characterize the forcing conditions. For simplicity, the brain was assumed to be homogenous and the material properties were set according to the findings of Miga et.al. [8]. The nodes on the boundary of the brain mesh are assumed to be fixed in the normal direction and allowed to slip tangentially. These nodes are also impermeable to fluid drainage along the cranial wall, except at the site of the craniotomy, where the nodes are stress-free and drainage is allowed. The surface nodes at the site of the craniotomy were selected based on their projected images in a co-registered real-time operating microscope image. Microscope-based image-guided neurosurgery proposed by several groups, including ours, establishes an accurate correspondence between a 2-D microscope image and the 3-D preoperative MR [9,10]. This allows us to project a 3-D point in the MR space into a co-registered microscope image. In the operating room, after the craniotomy, a microscope image of the surgical scene was recorded. The boundary of the craniotomy site in the image was outlined manually. The surface nodes in the finite element mesh generated from the preoperative MR were identified. To avoid the ambiguity resulting from the loss of dimension in a 3-D-to-2-D projection, only the surface nodes from the brain hemisphere close to surgical focus were projected. The nodes with their projected images located within the outlined boundary were identified as the surface nodes at the site of the craniotomy. Next, a fluid level is approximated and prescribed below the bottom edge of the craniotomy and perpendicular to the direction of gravity in order to simulate the loss of cerebral fluid by leakage and any suction performed during the surgery. The nodes above this fluid level are unsaturated and stress free. This allows the brain to sag away from the skull near the craniotomy. At the brain stem, the interstitial pressure has been designated as 0 mmHg in order to induce drainage by causing a pressure gradient to develop. The brain stem surface is allowed to translate as observed clinically [11].

The volumetric displacement data predicted by the finite element model was then used to update the original MR / CT scans. At each voxel location, the model is undeformed back to the original MR space in order to determine the voxel intensity value and then reformed into the final gray scale images [11]. The updated MR / CT volume that is most concurrent with surgery is displayed to the surgeon.

3. RESULTS AND DISCUSSION

3.1 Case Study

The following section shows the results from a specific case study. The procedure involved was a left temporal craniotomy for removal of a cystic lesion and tumor in the left temporal lobe. The patient was supine with the head turned to the patient's right.

3.2 Registration

The fiducial registration error (FRE) for this case was 1.4 mm. This error estimate is calculated by transforming the fiducial markers digitized in the patient frame of reference into the MR frame of reference. The FRE is the RMS difference between the fiducial points in the MR frame of reference and the fiducial points in the patient frame of reference transformed to the MR frame of reference.

3.3 Ultrasound Image Overlays

Figure 5 shows a photograph taken during ultrasound scanning in the OR. Back-to-back monitors display the preoperative MR (upper left), the current ultrasound field of view (upper right) and their coregistered overlays (lower central). Figure 6 illustrates the overlay technique previously discussed in more detail. The ultrasound images shown were acquired before the dura was removed, after some gravitational sag and near the end of the resection.



Figure 5: Ultrasound image, the equivalent MR slice and the overlay of the two being displayed to the surgeon on identical back-to-back displays. Pressing a button on the ultrasound scan head (background) allows the surgeon to acquire instant feedback on the extent of brain shift and the progression of the surgery. The “Single Reconstruction” GUI is shown on the monitor.

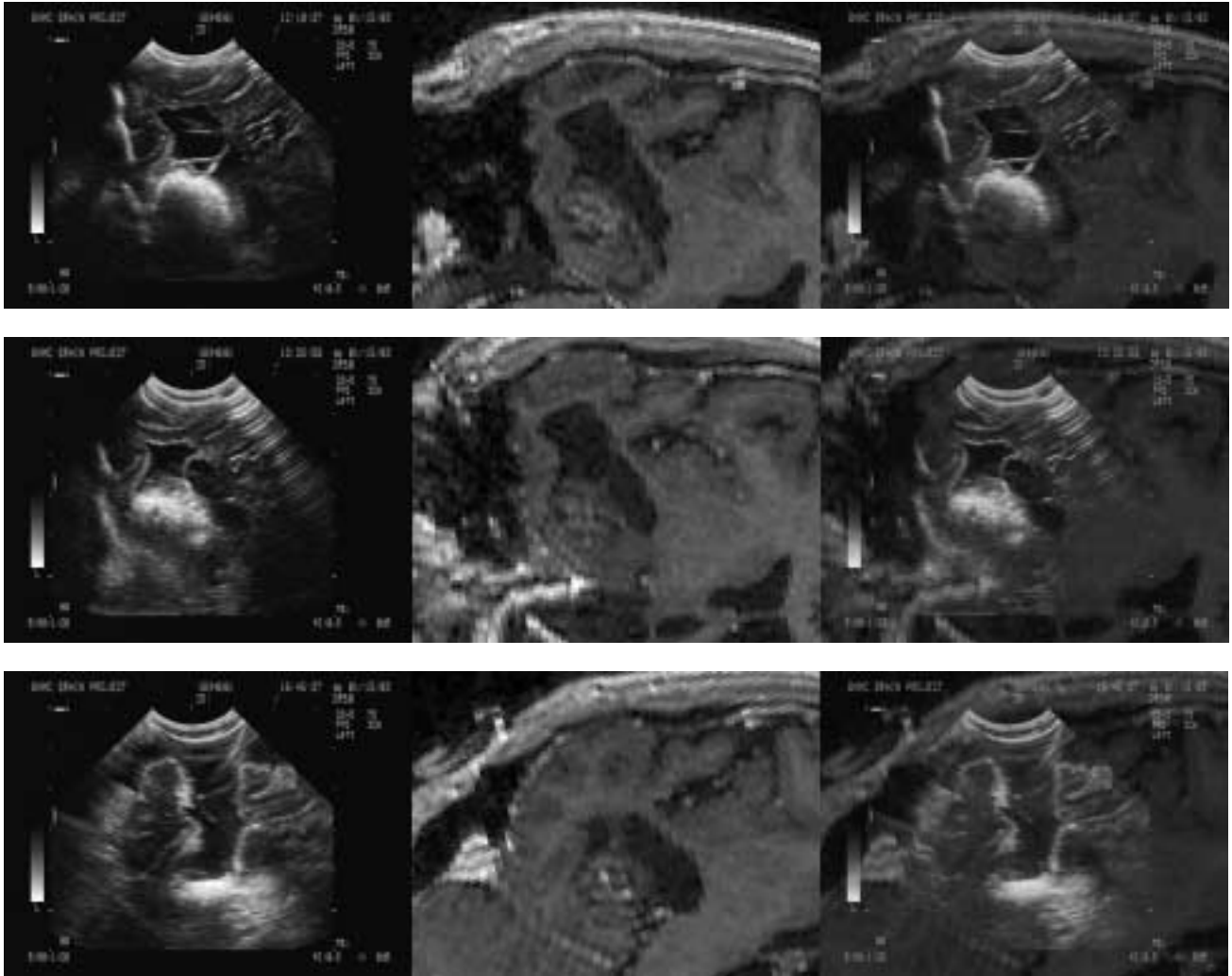


Figure 6: Ultrasound images (left) and the equivalent MR slices (center) depicting a cyst (black region) and a tumor located lateral and inferior to the cyst. The first row of images was taken before the dura was removed. The second row was taken after some gravitational sag. The third row was taken near the end of the case. The resection cavity is apparent in the third row of images.

The surgeon can obtain instantaneous image overlays of various orientations by simply pressing the button attached to the scan head. The use of this overlay technique aids the surgeon in identifying unknown brain features in the ultrasound image by using the better resolution of the MR/CT imaging volume. Structures can also be more apparent in the ultrasound image as well. This also can help the surgeon navigate within the brain and verify the progress on a tumor resection or check the placement of implanted probes used in monitoring epilepsy patients. With further analysis, the tissue movement observed in the ultrasound images can be used as sparse data to run the intraoperative finite element brain deformation model.

3.4 Modeling Results

The following series of images (Figures 7 and 8) show various steps in the generation of the intraoperative finite element model and the predictions of tissue displacement compared to the observed displacement. Figure 7 illustrates the finite element mesh created intraoperatively and the corresponding boundary conditions concurrent with surgery.

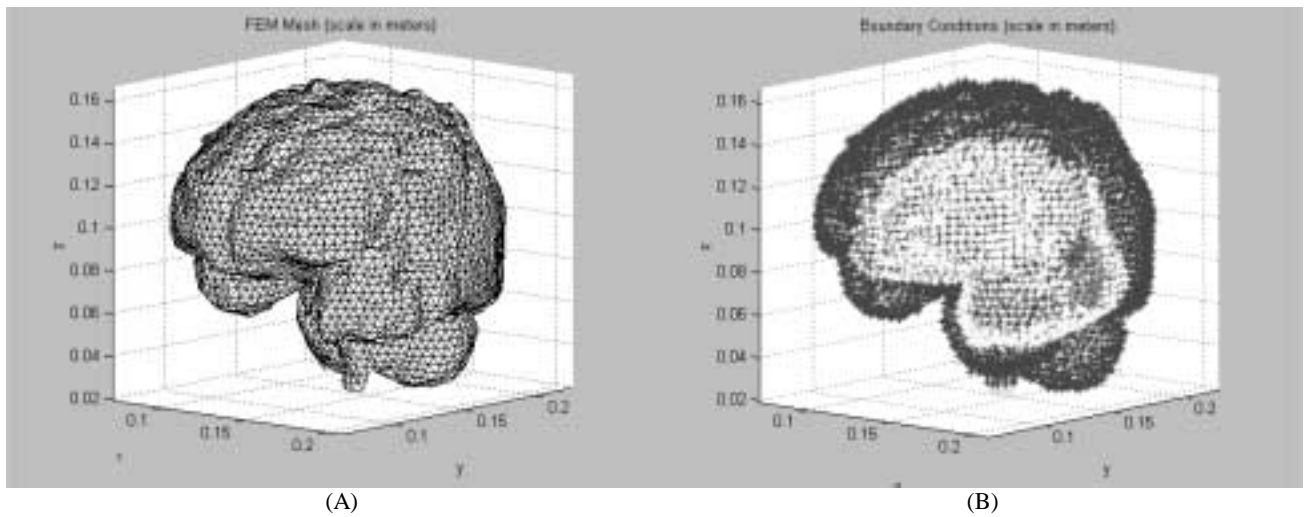


Figure 7: A surface rendering of the finite element mesh generated in the operating room (A) and the assigned boundary conditions (B). The gray region of nodes within the white nodal area represents the craniotomy; the white nodes are those above the prescribed cerebral fluid level; the black region of nodes represents those below the fluid level; the light gray nodes at the base of the brain represent the brainstem.

The calculations of tissue displacement due to gravitational forces predicted by the finite element model are shown in figure 8 below.

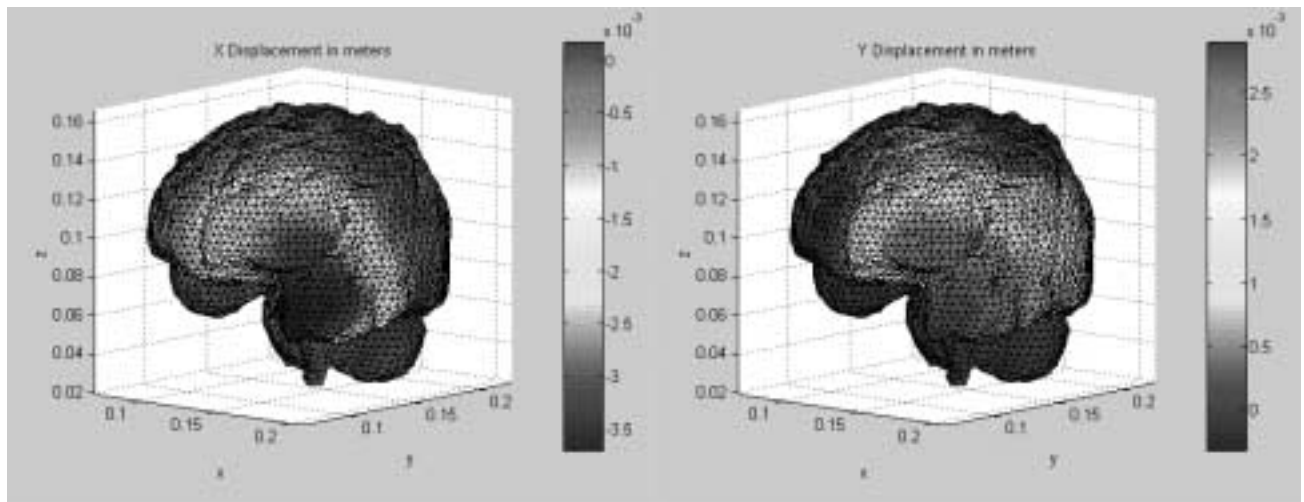


Figure 8: Surface rendering of gravitational sag in meters from the finite element model in the $-X$ and Y directions. The unit vector for gravity in this case is nearly into the page.

3.5 Display of Updated MR Volume

At any time throughout the surgery the surgeon can acquire points along the surface of the brain or surrounding tissues using a sterile stylus. The tip location is then projected into the MR frame of reference and displayed as a red dot in the corresponding MR slice as illustrated in figure 9.

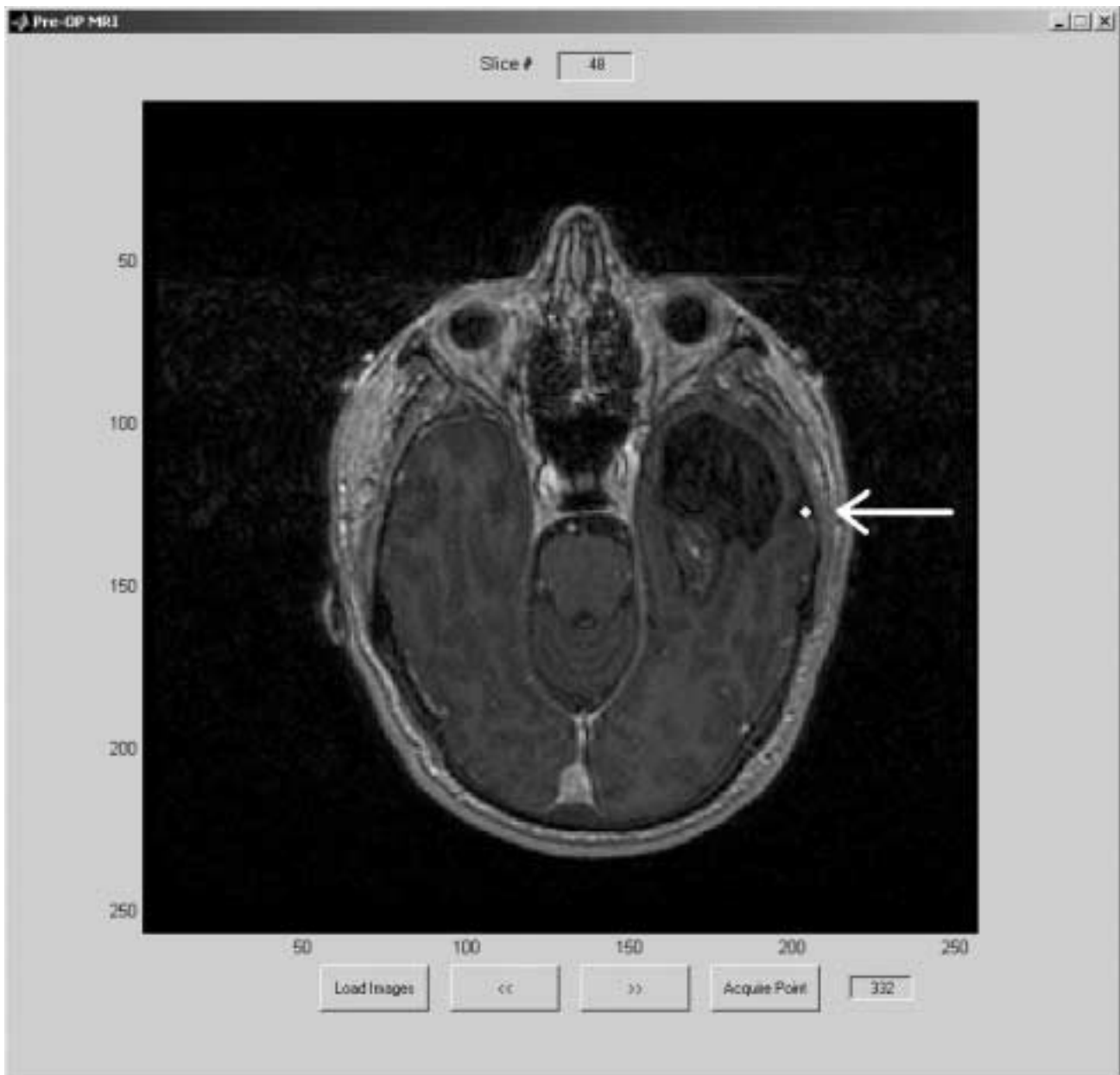


Figure 9: The GUI that allows the surgeon to acquire points on the surface of the brain using a sterile stylus and project the tip location on the original MR (white dot, located just right of the cyst).

Updated MR/CT views that illustrate tissue movement are now provided to the surgeon (Figure 10). This GUI allows the user to scroll through the MR/CT and observe tissue deformation. The original MR/CT volume is displayed next to the updated MR/CT volume. The surgeon can also acquire points with the sterile stylus and the projected point is displayed in both images. The points illustrated in figures 9 and 10 are the same surface landmark at different times in the surgery. Figure 10 shows the landmark after some gravitational sag. The landmark that was originally on the surface of the brain has clearly displaced approximately 5mm into the brain on the pre-op MR scan. This 5mm can be recovered using the finite element model to predict sag, and the point again appears to be on the surface.

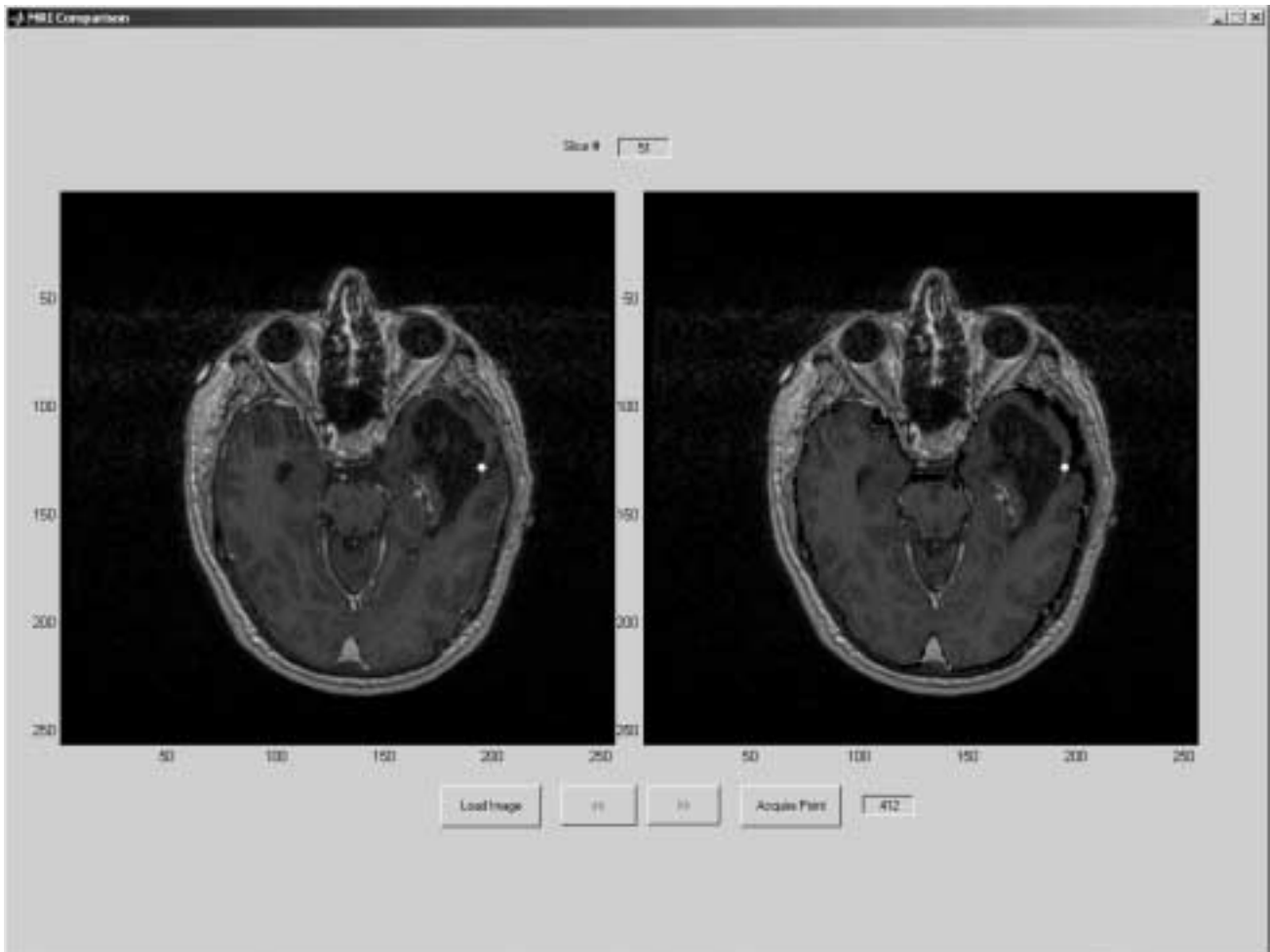


Figure 10: GUI window that allows the surgeon to acquire points on the surface of the brain with a sterile stylus and project the tip location onto the original (left) and updated MR (right). This point is the same location on the surface of the brain as shown in Figure 9, only after gravitational sag.

3.6 System Errors

Errors can originate from the discrepancy between the initial alignment of the ultrasound image with that of the MR image as well as due to differences between the actual and predicted brain shift. Tracking error associated with the 3D tracking system is 0.35 mm 3-D RMS [12]. There are also errors associated with registering the patient to the preoperative MR/CT scan. The centers of the fiducial markers are manually extracted from the MR/CT scan and the surgeon digitizes the approximate center of the fiducial marker on the patients head. Identifying these points incorporates some human error. These same errors are also associated with the calibration of the ultrasound scan head and with the digitizing of cranial surface landmarks used in observing tissue displacement. Lunn et.al. observed that when using co-registered ultrasound, “features can be localized with a mean vector error of 1.36 mm and brain tissue can be tracked with a mean error of 0.94 mm” [13].

Some inaccuracies also stem from the creation of the finite element model mesh. Small portions of brain tissue could have been excluded during the segmentation and the smoothing steps used. These studies also assume that the brain is homogenous, when in fact there are several different types of tissue and fluid within the cranium.

4. CONCLUSION

The results of this work provide the surgeon with a near real time, updated image volume that incorporates observed brain shift that is concurrent with surgery. The graphical user interface allows the operator to provide timely feedback to the surgeon and use imaging techniques that have been developed and used prior to this study. The ultrasound overlay images generate additional information that may not be apparent in the MR/CT volume as well as illustrate tissue movement and resection. Using boundary conditions obtained in the operating room enables calculation of displacement data using the finite element brain deformation model in order to update the original image volume.

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