Trackerless Surgical Image-guided System Design Using an Interactive Extension of 3D Slicer

Xiaochen Yang[1], Rohan Vijayan[2], Ma Luo[2], Logan W. Clements[2,5], Reid C. Thompson[3,5], Benoit M. Dawant[1,2,4,5], and Michael I. Miga[2,3,4,5]

[1]Department of Electrical Engineering and Computer Science, Vanderbilt University, Nashville, TN USA
[2]Department of Biomedical Engineering, Vanderbilt University, Nashville, TN USA
[3]Department of Neurological Surgery, Vanderbilt University Medical Center, Nashville, TN USA
[4]Department of Radiology, Vanderbilt University Medical Center, Nashville, TN USA
[5]Vanderbilt Institute for Surgery and Engineering, Nashville, TN USA

ABSTRACT

Conventional optical tracking systems use cameras near-infra-red (NIR) light detecting cameras and passively/actively NIR-illuminated markers to localize instrumentation and the patient in the operating room (OR), i.e. physical space. This technology is widely-used within the neurosurgical theatre and is a staple in the standard of care in craniotomy planning. To accomplish, planning is largely conducted at the time of the procedure with the patient in a fixed OR head presentation orientation. In the work presented herein, we propose a framework to achieve this in the OR that is free of conventional tracking technology, i.e. a trackerless approach. Briefly, we are investigating an interactive extension of 3D Slicer that combines surgical planning and craniotomy designation in a novel manner. While taking advantage of the well-developed 3D Slicer platform, we implement advanced features to aid the neurosurgeon in planning the location of the anticipated craniotomy relative to the preoperatively imaged tumor in a physical-to-virtual setup, and then subsequently aid the true physical craniotomy procedure by correlating that physical-to-virtual plan with a novel intraoperative MR-to-physical registered field-of-view display. These steps are done such that the craniotomy can be designated without use of a conventional optical tracking technology. To test this novel approach, an experienced neurosurgeon performed experiments on four different mock surgical cases using our module as well as the conventional procedure for comparison. The results suggest that our planning system provides a simple, cost-efficient, and reliable solution for surgical planning and delivery without the use of conventional tracking technologies. We hypothesize that the combination of this early-stage craniotomy planning and delivery approach, and our past developments in cortical surface registration and deformation tracking using stereo-pair data from the surgical microscope may provide a fundamental new realization of an integrated trackerless surgical guidance platform.

Keywords: Trackerless, surgical planning, neurosurgical procedure, craniotomy contour, reconstruction, tracking, 3D slicer

1. INTRODUCTION

In conventional image-guided surgery (IGS), the patient is located within the operating room physical space using optical tracking technologies. An image-to-physical registration is applied to present imaging information in relation to the patients physical anatomy. Once this registration is done, a tracked physical stylus can be used to navigate on and within the cranial surface and show the corresponding MR image slices on display. Typically, neurosurgeons will use this conventional image-guided setup to plan a craniotomy in reference to the tumor and other anatomical complexities. Procedurally, often this involves using the guidance display (as facilitated by the optically tracked stylus) to provide guidance for the marking of the patients skin to label the spatial extent of the

Further author information:
Xiaochen Yang: E-mail: xiaochen.yang@vanderbilt.edu

planned craniotomy. Once complete, the guidance system is withdrawn from the space and usually not utilized again until the cortical surface is presented. As surgery progresses, the guidance system can be used again to monitor progress.

Previous work by Miga et al. [1] demonstrated how preoperatively MR-imaged cortical surfaces could be aligned to intraoperative 3D textured point clouds. In subsequent work by Sinha et al. [2], they demonstrated how 3D textured point clouds could be used to track cortical surface deformations. Now recently, in work by Yang et al. [3][4][5], this investigative team demonstrated the ability to use a surgical operating microscope equipped with a pair of stereo-cameras to monitor deformations using computer vision techniques. More specifically, they compared the use of an optically tracked surgical microscope using conventional tracking to measure mock cortical surface deformations to that of an approach that uses sequential stereo-pair reconstructions with a visible cranial fixed target in the visual field to establish a reference frame (effectively a 'trackerless' approach, a similar approach was in used [6]) to measure mock cortical surface deformations. While interesting, this body of work only focused on characterization after the craniotomy was performed and assumed that conventional image-guided approaches were to be used at the initiation of surgery. In the methodology proposed here, we demonstrate a solution that allows for performing a craniotomy without the need for the conventional tracking approach, i.e. the last step needed to realize a complete trackerless methodology.

2. METHODS

2.1 Interactive Extension

3D Slicer [7] is a free, open-source, and integrated medical processing platform for surgical guidance. It is widely-used in clinical research applications since it provides many modules of common data processing for guidance environments. It also facilitates the development of new research functionalities and abstractions by clinical researchers rapidly. We built our trackerless surgical image-guided system as an interactive extension of 3D Slicer using the Python programming language. Within our work, we have the following components: (1) the 3D view is rendered using OpenGL, (2) the main user interface is developed by Qt [8], and (3) all data is processed with by VTK [9] and ITK [10] libraries. All of these can be easily accessed, modified, and integrated with common Python scripting which greatly shortens the development cycle.

The work proposed centers on an extension to this environment that: (1) provides a user-friendly interface for planning neurosurgical procedures, (2) imports and integrates relevant pre-operative data seamlessly, (3) creates a patient image data navigation environment using a computer-generated virtual stylus, (4) allows for the visual integration of a preoperative textured point cloud of the patients physical head and corresponding image data for planning, and (5) facilitates the determination of the craniotomy. Finally, the above navigational environment moves beyond the physical-to-virtual planning stage to being translated for use in the operating room for guiding the surgeon in designating/marking the craniotomy, all without the use of conventional tracking technology. The approach (represented in Figure 1) can be separated into distinct platform features. We should note that we have added functionality over conventional guidance displays as they are afforded to us and provided assistance with this virtual representation.

2.1.1 Simulation of conventional stylus in the OR

One important component is the ability to freely navigate and fully-visualize all patient data without tracking technology and in a manner that is similar to how a neurosurgeon plans a craniotomy. For this, a virtual form of conventional planning was created. A virtual stylus is used much like a real physical stylus on the physical patient to provide reference on the patients physical head as it relates to the underlying extent of lesion (provided by imaging data). More specifically, rather than registering the physical patient in the OR to the preoperative images set and planning the craniotomy as is done in conventional IGS, a realistic virtual environment is provided. Given the functionality of 3D Slicer for conventional IGS investigations, it was a natural choice to facilitate this planning phase. For example, the 3D view can be freely controlled, i.e. rotating (yaw, pitch, and roll) and zoom. In addition, the color and opacity of the model can be adjusted according to user preference. The opacity changes allow one to virtually interact with the head model in such a way that is very analogous to the OR setting (no visual reference of subsurface features), or one could change that in order to take advantage of the added visualization cues as in Figure 1 (top right panel) .

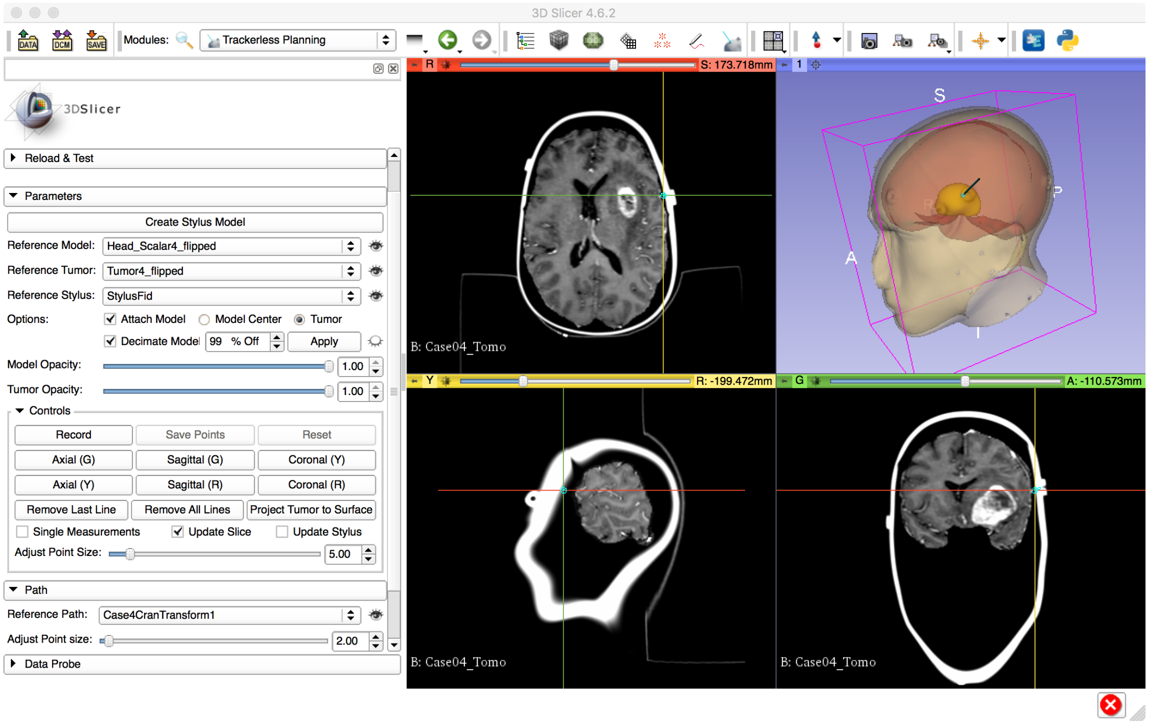

Figure 1. Overview of the trackerless surgical planning extension. Virtual stylus and traditional three-panel display allow simulation of conventional approach.

2.1.2 Simulation of conventional display in the OR

The next aspect that must be matched with respect to conventional craniotomy planning is that the MRI must be updated when moving the virtual stylus similar to that in conventional planning, i.e. with each virtual movement, the display can perpetuate the scrolling MRI anatomy visualization in its cardinal planes (axial, coronal, sagittal). This complete virtual guidance system function is a core functionality to our trackerless intraoperative craniotomy designation approach. Again to reiterate, traditionally, this is done by registering the image to physical space, then the physical stylus directed by tracking system can navigate the image space. Here, since our virtual stylus is driven by a mouse effectively, there is no need for image-to-physical registration. Once again, the ability to provide these three MR views is a standard function within 3D Slicer leading to its use as our platform of choice. 3D Slicer has added functionality, standard on most image processing platforms, which allows the user to more directly interact with the different views independently. This allows lesion extents to be determined in image-space with the subsequent update of the virtual stylus position such that image-space can provide a position to be marked for the craniotomy on the head surface. In conventional IGS systems, the standard procedure is that physical space stylus positioning, facilitates image space observations. The virtual platform allows for this, but also facilitates the reverse. The implications of this awaits further study. Nevertheless, Figure 1 shows the more traditional planning display approach whereby digitization by the virtual stylus on the head surface is propagating to the appropriate image cardinal planes within the MR images.

2.1.3 Adding capabilities for assisting in craniotomy designation

While cross-hair interrogation is utilized extensively in conventional guidance displays, i.e. if a point on the head is designated with tracked stylus, the cross-sectional images in the cardinal planes are displayed with cross-hair on the image surface border. We have also projected the cross-hairs in their proper 3D orientation on the virtual physical model. We have found that projecting these lines on the head model surface can assist in providing extent on the tumor boundary. This extension is designed to facilitate a means to designate the tumor boundary accurately on surface of patents head. Clearly, the tumor can be viewed by adjusting the opacity

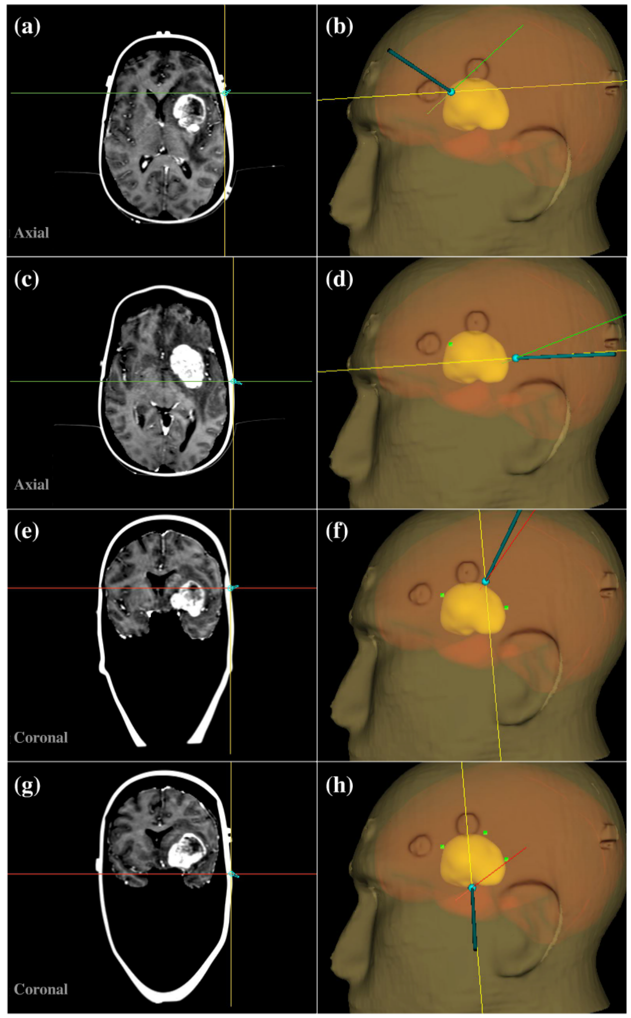

Figure 2. Determine boundary landmarks for tumors. (a) and (b) show the front boundary, (c) and (d) show the back boundary of the tumor, (e) and (f) show the upper boundary, and (g) and (h) show the lower boundary.

of head model. However, neurosurgeons usually will not directly mark the tumor boundary in this fashion in traditional guidance systems. Instead, surgeons will scroll the MR images to the specific slicer where the cross-section surface of the tumor is maximized. We have found in consultation with our neurosurgeons that there are additional MR-identified tissue features that surgeons will use to assist in craniotomy planning, not just the segmented enhancing features provided by typical image processing techniques. As an example, in Figure 2 the boundary of the tumor was determined by checking the axial and coronal view of the MR images. Figure 2 (a) and (b) show the front boundary while (c) and (d) show the back boundary of the tumor. The intersection of the axial view (cross-hair of yellow and green line) can be added on the 3D view. Once the boundary is determined, a green dot landmark can be marked on the boundary place, as shown in Figure 2 (d). Similarly, the top and bottom boundary can be decided by scrolling the coronal view of the MR image. After four boundary landmarks are marked using the techniques in Figure 2, the virtual stylus is placed at the center of these four points and the tumor can be projected to the head surface. This projects a cluster of yellow lines from the tumor to the stylus direction (see Figure 3 a and b) which provides accurate boundary border of the tumor on the head surface.

2.1.4 Freehand craniotomy designation

With the above display information providing fiducials and projected segmented structures on the patients virtual scalp, essential guides are provided for designating the craniotomy. Our planning approach also supports freehand drawing on the surface (like is done in the real OR) by effectively linking the virtual stylus as shown in Figure 3 (c). The planning phase is completed by saving the craniotomy contour which can subsequently be reloaded in 3D Slicer for future use for the physical craniotomy designation.

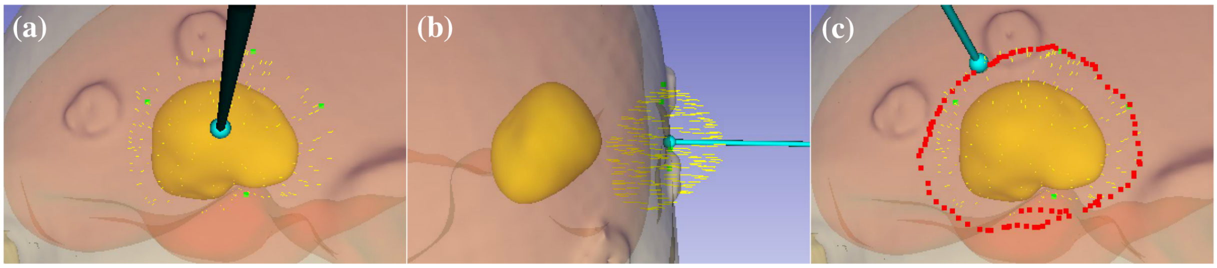

Figure 3. (a, b) Project tumor to surface and (c) draw craniotomy contour virtually.

2.1.5 Translating from planning to surgical guidance

To move from planning to delivery, the application will integrate the virtual head surface to the physical patients three dimensional textured point cloud (3DTPC). The 3DTPC can be provided by a variety of low-cost technologies. In the past, we have done extensive work with laser range scanning technology [11] that studied the use of face-based textured point clouds to perform a face-based registration for use within conventional IGS systems. Other technologies such as stereo-pair technologies [12], and structured light are also under investigation [13]. Once a 3DTPC of the patients head can be acquired, an iterative closest point registration can be performed to align. While conventional guidance provides a link between MR-image and physical space using optical tracking technology (essentially one 3D point at a time), this 3D texture-to-MR alignment is also a form of image-to-physical space representation. In our approach, we add grid-like distinct markings on the patient prior to acquiring the 3D textured point cloud of their head as physical reference (all without conventional tracking technology). One additional benefit is that with no tracking technology needed, this process could be done any time prior to the procedure. Recall that conventional guidance platforms require the establishment of a geometric reference to be attached to the patient so that tracking equipment can be moved around the operating room without losing patient reference. As a result, planning must be performed at the time of surgery. This is not the case for the methodology proposed herein. The added texture provides a real physical space of the actual patient to the projected craniotomy plan provided by the aforementioned steps. As an example, Figure 4 (a) shows a textured pattern on our mock patient. This presents the physical patient with an example physical pattern placed on the anticipated craniotomy surface. Figure 4 (b) and (c) shows examples of a 3DTPC-to-MR reference display that the surgeon could use as a reference to mark the physical patients craniotomy. In summary, rather than the conventional tracking providing the link, texture references become the link.

2.2 Experiments

The experimental system used in this work involves a head-shaped phantom in which real clinical MR brain data was appropriately scaled and positioned within the head to represent a mock surgical candidate. In order to evaluate the performance of this trackerless surgical image-guided system extension, we compared it with the conventional procedure that employs standard optical tracking instrumentation.

2.2.1 Conventional approach description

In this approach, the neurosurgeon begins by examining a given case on 3D Slicer in order to establish a geometric understanding of tumor size and location. Using this knowledge, the neurosurgeon chooses a suitable orientation for the physical phantom head. Image-to-physical space registration is then performed using the Fiducial Registration Wizard (SlicerIGT extension [14]), OpenIGTLinkIF [15], and the PLUS toolkit [16], an

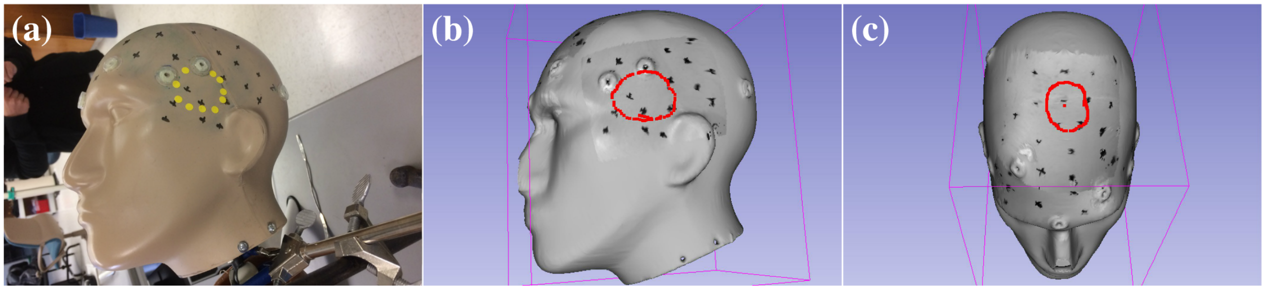

Figure 4. (a) Mock physical head with markings for added texture, and (b, c) after stereo-pair acquisition of physical patient, 3D point cloud texture-to-MR overlay which can be used within the operating room to designate physical craniotomy - two separate cases shown.

application that streams live tracking data to 3D Slicer. This point-based registration begins by selecting the center points of the attached MR-visible markers within the mock heads image volume. Within the mock OR, the corresponding fiducials are digitized using a Northern Digital Polaris Spectra (NDI, Waterloo, Ontario, Canada). These physical space fiducial centers are digitized in 3-D Slicer using OpenIGTLinkIF and the PLUS toolkit. Following rigid registration, the neurosurgeon uses the conventional image guided display and stylus to designate surface landmarks and visualize the extent of the tumor on the surface of the head. The neurosurgeon then draws the craniotomy contour on the surface of the head with a marker using the guidance display to assist. In this case, rather than a marker, the neurosurgeon uses the digitizing stylus to draw the craniotomy (this facilitates quantification of proposed craniotomy size and location for comparison). Our custom OpenIGT extension collects the digitized points in physical space and transforms them to provide a contour within image space that represents a conventional craniotomy approach.

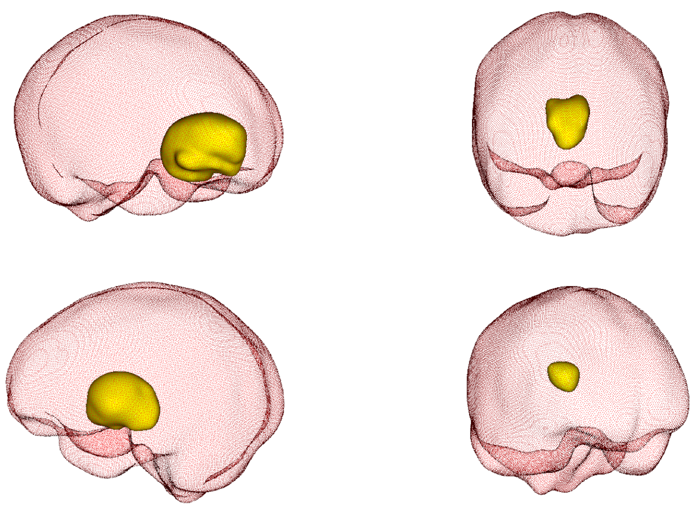

Figure 5. Four cases of clinical patient data for experiment showing different tumor presentations.

2.2.2 Trackerless approach description

For a given case, the neurosurgeon is asked to plan a tumor resection procedure using our 3D Slicer module. This begins by the case being uploaded into 3D Slicer and with the neurosurgeon viewing the fused image data in order to establish a geometric understanding of tumor size and location. Next, the virtual stylus and traditional cross sectional display (Figure 1) is available to the neurosurgeon to virtually perform the conventional approach.

The neurosurgeon uses the record function to trace a contour for the craniotomy using the cross-sectional display and landmarks as a guide. After planning is achieved, the physical head, e.g. Figure 4 (a), is imaged with the stereo pair and registered to image space using a surface based registration using the head geometries. Figure 4 (b) and (c) show the registered overlay of the 3D physical head textured point cloud, the image volume, and the virtual craniotomy as planned in our module. The 3DTPC-to-MR overlay is provided in a display for reference. The neurosurgeon can then, without the utilization of a tracker, use the visible pattern to reproduce the virtual craniotomy on the physical mock patient head, i.e. the texture provides the physical reference for drawing the proposed virtual craniotomy on the physical head.

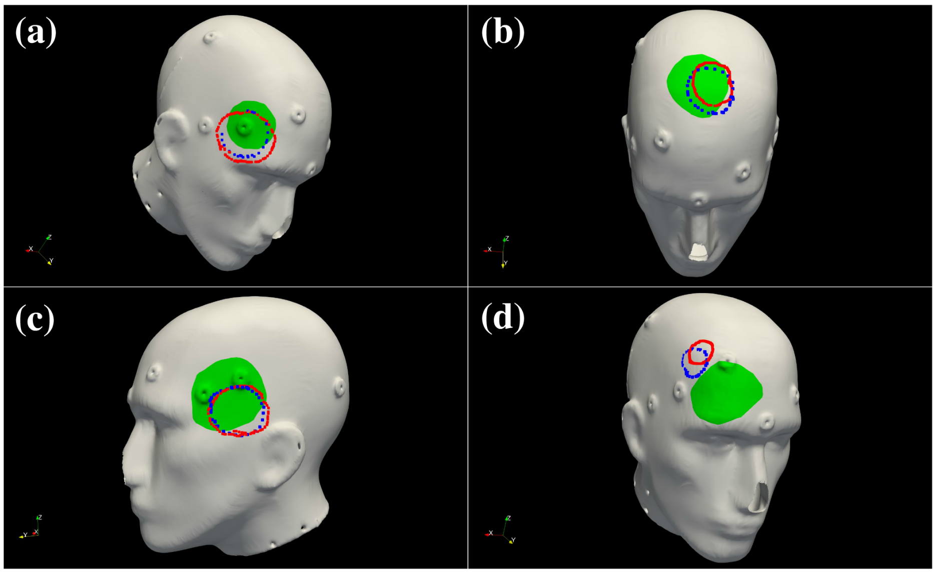

Figure 6. Comparison results of our novel approach, and conventional localization method in four (a-d) mock patients. The green patch represents craniotomy planned with conventional approach. The red contour is craniotomy plan with virtual stylus planner. The blue contour is the craniotomy plan on physical mock subject using novel 3D point cloud texture-to-MR display.

3. RESULTS

Using imaging data from four clinical cases at Vanderbilt University Medical Center (VUMC) retrieved under IRB approval (shown in Fig. 5), we explored the framework with cases involving different tumor sizes and located positions. A neurosurgeon with 20 years' experience performed all experiments. Figure 6 shows the results from each trial. The green area patch is the craniotomy using the conventional guidance approach. The red contour represents the planned craniotomy using the virtual stylus approach. Recall, this approach is essentially the equivalent of the conventional approach but performed completely in the virtual environment. The blue contour represents the designation of the craniotomy in its true physical space using our novel 3D point cloud texture-to-MR overlay (e.g. Figure 4 b, c) as the only guiding reference only, i.e. trackerless. Table 1 and Table 2 show the craniotomy planning centroid and area of each case in three planning (virtual craniotomy planning, physical craniotomy planning, and conventional craniotomy planning). The difference of centroid and area percent between virtual craniotomy planning and physical craniotomy planning is plotted in bar graph Figure 7 (a), which demonstrates the virtual-to-physical craniotomy contour fidelity. The clinical contour fidelity can be evaluated by comparing virtual craniotomy planning and conventional craniotomy planning (see Figure 7 b).

4. DISCUSSION

Recall, the primary task of the surgeon in this case is to look at the markings on the physical head, and the nearby display, and then draw a contour on the physical head without conventional guidance. In observing Figure 6,

Craniotomy Centroid			
	Virtual Crani. Planning	**Physical Crani. Planning**	**Conventional Crani. Planning**
Case A	[-80.85 -75.20 166.91]	[-79.95 -77.90 168.44]	[-80.69 -78.85 174.84]
Case B	[-141.29 -93.05 237.09]	[-139.28 -86.99 234.37]	[-127.57 -92.42 235.01]
Case C	[-206.03 -103.67 156.09]	[-206.64 -104.98 152.97]	[-203.53 -97.74 164.87]
Case D	[-89.15 -80.07 206.10]	[-85.06 -79.27 196.86]	[-107.53 -48.27 179.41]

Table 1. Craniotomy centroid of each case.

Craniotomy Area			
	Virtual Crani. Planning	**Physical Crani. Planning**	**Conventional Crani. Planning**
Case A	1634.70	1469.08	1673.50
Case B	1009.03	1223.41	2213.42
Case C	1468.94	1436.53	3042.29
Case D	363.29	472.38	2608.14

Table 2. Craniotomy area of each case.

we see remarkable agreement between red (free-hand craniotomy using our novel display) and blue contour (designation craniotomy plan on physical mock subject using novel 3DTPC-to-MR display). This demonstrates that the trackerless platform can be used quite well to translate a virtual plan to a physical outcome of craniotomy designation. The difference between that plan and the conventional approach (compare red/blue contour to the conventionally determined green region) is more vexing. However, we should note that the data associated with the conventional approach was from a previous study conducted approximately one year ago [17]. In reviewing that work, our neurosurgeon did inform us that his surgical approach had changed since then on these cases (in particular the result in Figure 6 d). While important, another important observation comes from the results in Table 2, and Figure 7. Here we see in each case that the conventional guidance method consistently provided a larger craniotomy plan. In these cases, we see an increase in area of the standard craniotomy over the novel-display stylus digitization version of 14%, 81%, 112%, and 453% for cases A, B, C, and D, respectively. This difference in craniotomy using this novel display is remarkable and certainly warrants further study.

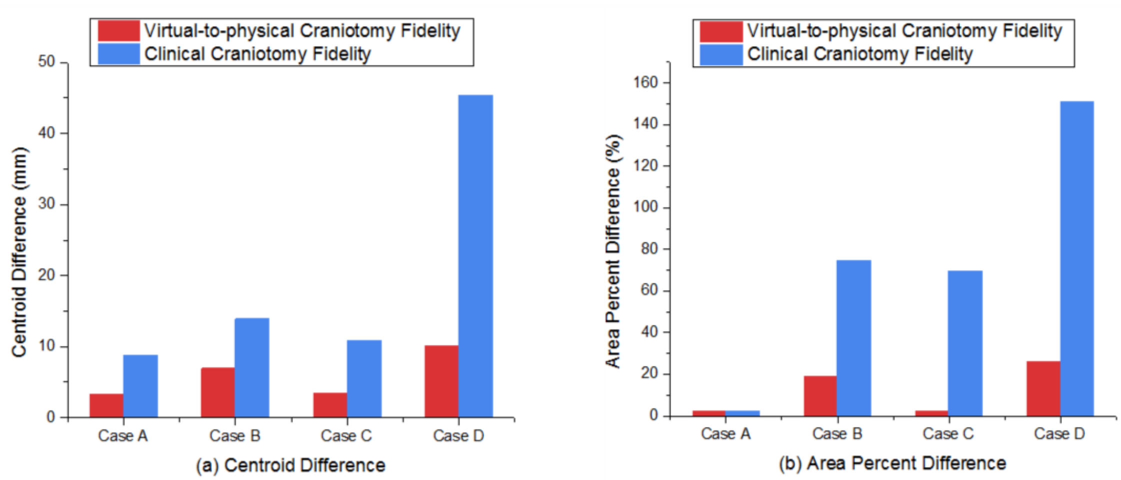

Figure 7. Bar plot of craniotomy planning data (a) centroid difference and (b) area percent difference of each case.

5. CONCLUSIONS

The paper demonstrates the feasibility of using a trackerless surgical image-guided system to plan and execute craniotomy. A well-developed interactive extension of 3D Slicer can simplify the procedure of pre-operative planning and provide a reliable craniotomy contour. The work herein when combined with our cortical surface registration, cortical deformation measurement methods, and finally computational brain shift prediction framework is a powerful paradigm that could potentially eliminate the need for conventional tracking technology and usher in integrated more nimble vision-based guidance systems for neurosurgery. In order to improve the fidelity of the analysis, the above experiments will be repeated with both our novel method and conventional methods being compared with less time between experiments.

ACKNOWLEDGMENTS

This work is funded by the National Institutes of Health, National Institute for Neurological Disorders and Stroke grant number R01-NS049251. We would like to acknowledge John Fellenstein from the Vanderbilt Machine Shop for his assistance in making our surgical setup.

REFERENCES

[1] Miga, M. I., Sinha, T. K., Cash, D. M., Galloway, R. L., and Weil, R. J., "Cortical surface registration for image-guided neurosurgery using laser-range scanning," *IEEE Transactions on medical Imaging* **22**(8), 973–985 (2003).

[2] Sinha, T. K., Dawant, B. M., Duay, V., Cash, D. M., Weil, R. J., Thompson, R. C., Weaver, K. D., and Miga, M. I., "A method to track cortical surface deformations using a laser range scanner," *IEEE transactions on medical imaging* **24**(6), 767–781 (2005).

[3] Yang, X., Clements, L. W., Conley, R. H., Thompson, R. C., Dawant, B. M., and Miga, M. I., "A novel craniotomy simulation system for evaluation of stereo-pair reconstruction fidelity and tracking," in [*Proc. of SPIE Vol*], **9786**, 978612–1 (2016).

[4] Yang, X., Clements, L. W., Luo, M., Narasimhan, S., Thompson, R. C., Dawant, B. M., and Miga, M. I., "Integrated system for point cloud reconstruction and simulated brain shift validation using tracked surgical microscope," in [*SPIE Medical Imaging*], 101352G–101352G, International Society for Optics and Photonics (2017).

[5] Yang, X., Clements, L. W., Luo, M., Narasimhan, S., Thompson, R. C., Dawant, B. M., and Miga, M. I., "Stereovision-based integrated system for point cloud reconstruction and simulated brain shift validation," *Journal of Medical Imaging* **4**(3), 035002 (2017).

[6] Skrinjar, O., Tagare, H., and Duncan, J., "Surface growing from stereo images," in [*Computer Vision and Pattern Recognition, 2000. Proceedings. IEEE Conference on*], **2**, 571–576, IEEE (2000).

[7] Slicer, D., "A multi-platform, free and open source software package for visualization and medical image computing." https://www.slicer.org/. (Accessed: August 2017).

[8] Qt, "Qt Powerful, Interactive and Corss-Platform Applications." https://www.qt.io/. (Accessed: August 2017).

[9] VTK, "The Visualization Toolkit." http://www.vtk.org. (Accessed: August 2017).

[10] ITK, "National Library of Medicine Insight Segmentation and Registration Toolkit." http://www.itk.org. (Accessed: August 2017).

[11] Cao, A., Thompson, R., Dumpuri, P. a., Dawant, B., Galloway, R., Ding, S., and Miga, M., "Laser range scanning for image-guided neurosurgery: Investigation of image-to-physical space registrations," *Medical physics* **35**(4), 1593–1605 (2008).

[12] Faria, C., Sadowsky, O., Bicho, E., Ferrigno, G., Joskowicz, L., Shoham, M., Vivanti, R., and De Momi, E., "Validation of a stereo camera system to quantify brain deformation due to breathing and pulsatility," *Medical physics* **41**(11) (2014).

[13] Chan, B., Auyeung, J., Rudan, J. F., Ellis, R. E., and Kunz, M., "Intraoperative application of hand-held structured light scanning: a feasibility study," *International journal of computer assisted radiology and surgery* **11**(6), 1101–1108 (2016).

[14] IGT, S., "Image-guided therapy in 3D Slicer." http://www.slicerigt.org/. (Accessed: August 2017).

[15] OpenIGTLink, S., "OpenIGTLink interface module for 3D Slicer." https://github.com/openigtlink/OpenIGTLinkIF. (Accessed: August 2017).

[16] Lasso, A., Heffter, T., Rankin, A., Pinter, C., Ungi, T., and Fichtinger, G., "Plus: open-source toolkit for ultrasound-guided intervention systems," *IEEE Transactions on Biomedical Engineering* **61**(10), 2527–2537 (2014).

[17] Vijayan, R. C., Thompson, R. C., Chambless, L. B., Morone, P. J., He, L., Clements, L. W., Griesenauer, R. H., Kang, H., and Miga, M. I., "Android application for determining surgical variables in brain-tumor resection procedures," *Journal of Medical Imaging* **4**(1), 015003–015003 (2017).