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Development and evaluation of a "trackerless" surgical planning and guidance system based on 3D Slicer

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Abstract. Conventional optical tracking systems use cameras sensitive to near-infrared (NIR) light and NIR illuminated/active-illuminating markers to localize instrumentation and the patient in the operating room (OR) physical space. This technology is widely used within the neurosurgical theater and is a staple in the standard of care for craniotomy planning. To accomplish, planning is largely conducted at the time of the procedure in the OR with the patient in a fixed head orientation. We propose a framework to achieve this in the OR without conventional tracking technology, i.e., a "trackerless" approach. Briefly, we investigate an extension of the 3D Slicer which combines surgical planning and craniotomy designation. 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 procedure by correlating that physical-to-virtual plan with an intraoperative magnetic resonance imaging-to-physical registered field-of-view display. These steps are done such that the craniotomy can be designated without the use of a conventional optical tracking technology. To test this approach, four experienced neurosurgeons performed experiments on five different surgical cases using our 3D Slicer 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 craniotomy planning approach and our past developments in cortical surface registration and deformation tracking using stereo-pair data from the surgical microscope may provide a fundamental realization of an integrated trackerless surgical guidance platform. [DOI: 10.1117/1.JMI.6.3.035002]

Keywords: trackerless; surgical planning; neurosurgical procedure; craniotomy contour; reconstruction; tracking; 3D Slicer.

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1 Introduction

In conventional image-guided surgery (IGS), the patient's tumor is estimated at the time of surgery in the operating room (OR) physical space using optical tracking technologies and image-to-physical registration methods. More specifically, an image-to-physical mathematical transform is determined by identifying corresponding features in both the patient's images and the physical patient in the OR. Once this registration is done, a tracked physical stylus can be used to navigate on and within the cranial surface by showing on a display the magnetic resonance image (MRI) slices that correspond with the stylus tip interacting with the patient in physical space. Typically, neurosurgeons will use this conventional image-guided setup to plan a craniotomy that is dependent on tumor location and other anatomical considerations. This typically involves using the guidance display (facilitated by the optically tracked stylus) to provide assistance with marking the spatial extent of the planned craniotomy on the physical patient. More specifically, optical tracking consisting of a camera and tracked stylus is used to localize physical points that correspond to image-based counterparts. These points are used to provide a relationship between image and physical patient space. With respect to the display, the conventional display consists of a four-panel arrangement of images with sagittal, axial, coronal slices and a fourth panel that is commonly an isometric view. Once the craniotomy designation is complete, the guidance system is removed from the immediate patient space and is 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 MRI cortical surfaces could be aligned to the three-dimensional textured point clouds (3DTPCs) collected intraoperatively. A subsequent work by Sinha et al.[2] demonstrated how three-dimensional (3-D) textured point clouds could be used to track cortical surface deformations. Recently, in work by Yang et al.,[3–5] the ability to use a surgical operating microscope equipped with a pair of stereo cameras to monitor deformations using computer vision techniques was demonstrated. More specifically, using a mock deformable cortical surface phantom, surface deformations were measured using an

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optically tracked surgical microscope (i.e., via NIR tracking, the scope focal point is akin to a physical stylus) and then compared to an approach that utilizes sequential stereo-pair reconstructions[6,7] with a fixed visible target reference in the microscope field of view (effectively a “trackerless” measurement approach). This work focused only on characterization after the craniotomy was performed and assumed that conventional image-guided approaches were to be used to plan the craniotomy. In this paper, we demonstrate a method that allows a craniotomy to be planned without the use of the conventional tracking approach. The purpose of providing the conventional approach within this work is to specifically compare neurosurgical craniotomy preparation with our proposed approach. This work is the last step needed to realize a complete trackerless methodology, for neurosurgical procedures without conventional tracking, i.e., a trackerless approach.

2 Methods

2.1 *Interactive Extension*

The 3D Slicer[8] is an open-source, 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 research functionalities and abstractions by clinical researchers. Our proposed trackerless surgical image-guided system is an interactive extension of the 3D Slicer using Python. The module has the following components: (1) the 3-D view of the patient brain and tumor is rendered using OpenGL, (2) the main user interface is developed by Qt,[9] and (3) all data are processed using VTK[10] and ITK[11] libraries. All of these can be easily accessed, modified, and integrated with common Python scripting, broadening the feasibility of using this module in a clinical setting.

The developed module has been customized for neurosurgery by: (1) providing a user-friendly interface for planning neurosurgical procedures; (2) importing and integrating relevant preoperative data seamlessly; (3) creating a patient image data navigation environment using a computer-generated virtual stylus; (4) allowing the visual integration of a preoperative textured point cloud of the patient’s physical head and corresponding image data for planning; and (5) most importantly, facilitating the determination of the craniotomy. The navigational environment proposed is to guide the craniotomy location and extent without the use of conventional tracking technology. The interactive extension (represented in Fig. 1) can be separated into distinct platform features and it has functionality over conventional guidance displays because of the provided assistance using the virtual representation.[12]

2.1.1 *Simulation of the stylus in the operating room*

An important feature of the trackerless surgical planning extension is the ability to freely navigate and visualize the patient’s preoperative MRI without tracking technology, in a manner similar to the current conventional craniotomy planning. To accomplish this, a virtual form of conventional planning was created. A virtual stylus, similar to the real physical stylus on the physical patient, is used to provide a reference on the patient’s virtual head as it relates to the underlying extent of lesion (preoperative

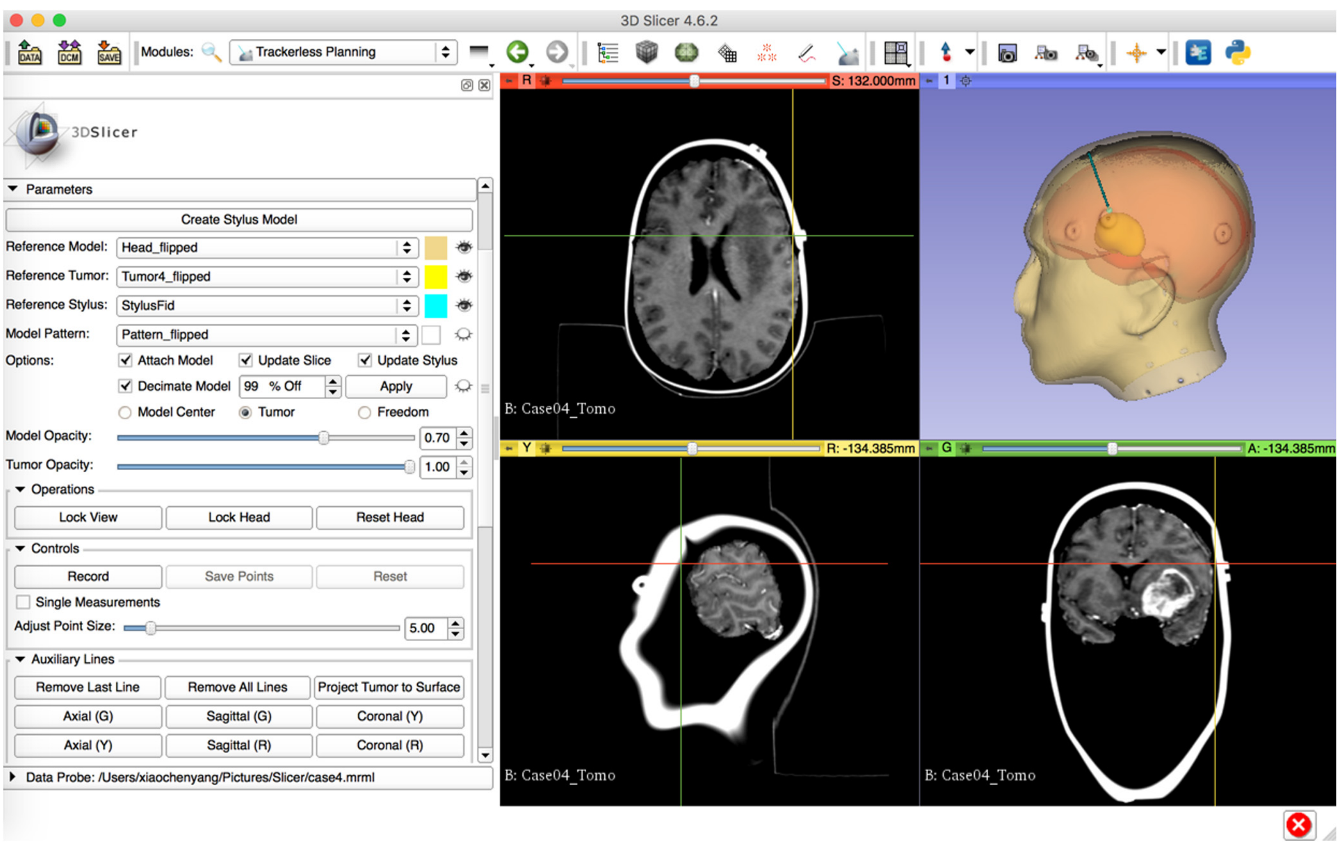

Fig. 1 Overview of the trackerless surgical planning extension. The virtual stylus and traditional three-panel display of the MRI mirrors the display in the conventional approach.

MRI). Rather than registering the physical patient in the OR to the preoperative images in order to plan the craniotomy (conventional IGS), a realistic virtual environment is provided to accomplish the goal without the patient. Given the functionality of the 3D Slicer for conventional IGS investigations, it was a natural choice to facilitate this planning phase. The 3-D 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 (neurosurgeon) preference. The opacity changes allow one to virtually interact with the head model in either a way analogous to the OR setting (no visually observable reference to tumor), or in a way enabling the neurosurgeon to take advantage of the added subsurface visualization cues, as shown in Fig. 1 (top right panel).

2.1.2 *Simulation of conventional display in the operating room*

The next aspect that must be matched, with respect to conventional craniotomy planning, is that the MRI must be actively updated when moving the virtual stylus in a manner similar to that in conventional planning, i.e., with each virtual movement, the display can perpetuate the MRI anatomy visualization in its cardinal planes (axial, coronal, and sagittal). This complete virtual guidance system function is a core functionality to our trackerless intraoperative craniotomy designation approach. Traditionally, this is done by registering the preoperative MRI image to physical space, allowing the physical stylus to navigate the image space while physically touching the patient’s head surface. In our configuration, the virtual stylus is driven by the computer mouse, so there is no need for image-to-physical registration. The 3D Slicer has added functionality, standard on most image-processing platforms, which allows the user to more directly interact with the different MRI views independently. This allows lesion extent to be determined in image space with the corresponding update of the virtual stylus position such that image space can provide a position to be marked for the craniotomy plan on the head surface. More specifically, as a surgeon would choose to designate locations using the MRIs, the virtual stylus is automatically controlled to be at the closest point on the head surface in the model to assist in virtual craniotomy demarcation. In conventional IGS systems, and as alluded above, the standard IGS procedure is that physical space stylus positioning by the surgeon facilitates image space extent observations. While the virtual platform also allows for this, it does also allow for the counterpart where positioning in the MRIs facilitates a virtual stylus position on the virtual head surface. Figure 1 shows the more traditional planning display approach where digitization by the virtual stylus on the head surface propagates the appropriate image cardinal planes within the MRIs.

2.1.3 *Adding capabilities for assisting in craniotomy designation*

While crosshair interrogation of the patient MRI 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 crosshair on the image surface border. As indicated above, we also project the crosshairs in their proper 3-D orientation on the virtual physical model. As shown in Fig. 2, we use these crosshair lines on the head model surface to assist the neurosurgeon in determining the extent of the tumor boundary.

This extension facilitates a means to designate the tumor boundary accurately on the virtual surface of a patient’s head. Clearly, the tumor can also be viewed in the planning extension by adjusting the opacity of the head model. Through consultation with the neurosurgeons participating in this study, we found that there are additional MR-identified brain features that surgeons use to assist in craniotomy planning versus just the segmented enhancing tumor provided by typical image-processing techniques. Typically, surgeons account for major landmarks and structures to avoid during their craniotomy planning as well. As an example of labeling tumor extent in the module, in Fig. 2, the boundary of the tumor was determined by checking the axial and coronal views of the MRIs. Figures 2(a) and 2(b) show the front boundary, whereas Figs. 2(c) and 2(d) show the back boundary of the tumor. The intersection of the axial view (crosshair of yellow and green lines) can be added on the 3-D view. Once the boundary is determined, a green dot landmark can be marked on the boundary place, as shown in Fig. 2(d). Similarly, the top and

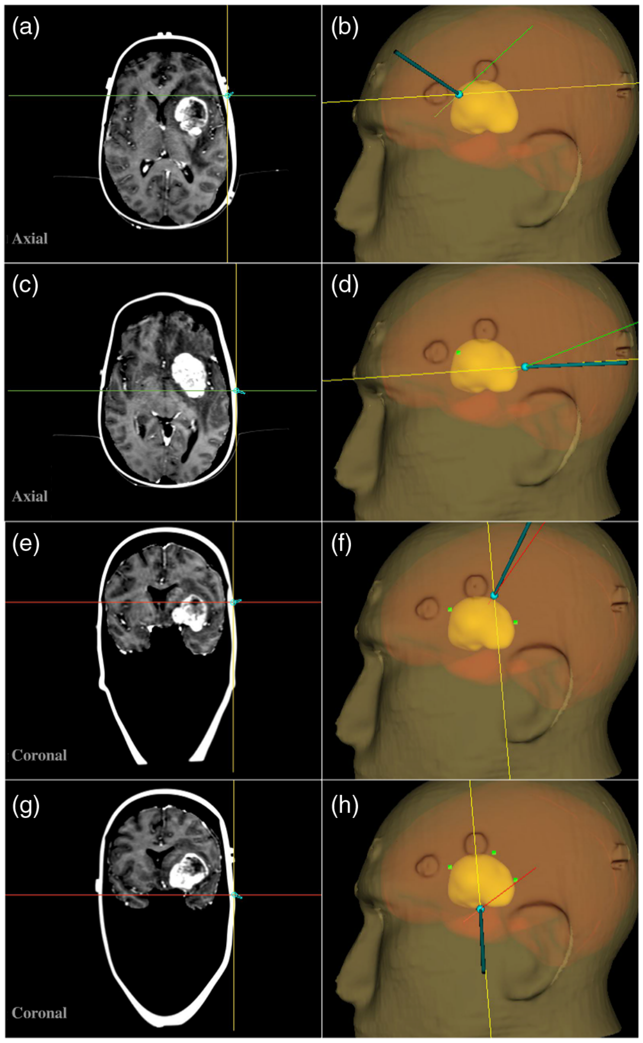

Fig. 2 Visualization of determine boundary landmarks for tumors: (a), (b) the anterior boundary; (c), (d) the posterior boundary of the tumor; (e), (f) the superior boundary; and (g), (h) the inferior boundary. In every pair of images, the crosshairs on the MRI correspond to the stylus position on the virtual head.

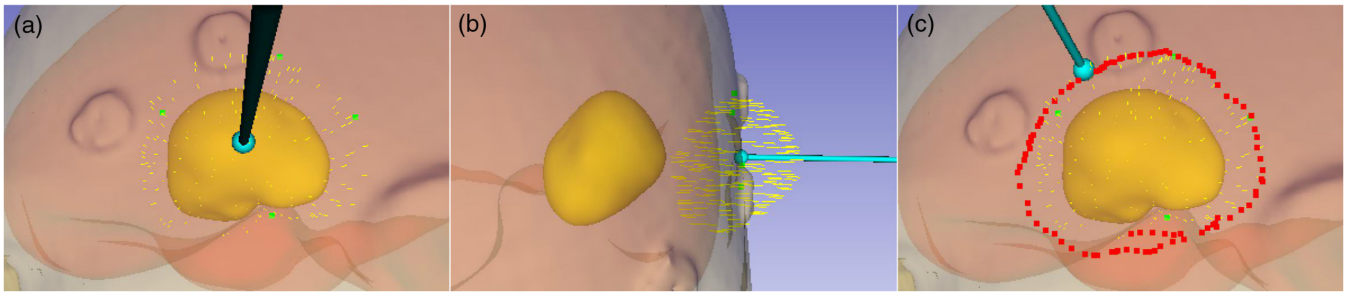

Fig. 3 (a), (b) Project tumor to surface and (c) virtually drawn craniotomy contour.

bottom boundaries can be decided by scrolling the coronal view of the MRI. After four boundary landmarks are marked using the techniques in Fig. 2, the virtual stylus is placed at the center of these four points and the tumor location can be projected to the head surface. This projects a cluster of yellow lines from the tumor to the stylus direction [see Figs. 3(a) and 3(b)], which provides an accurate boundary border of the tumor on the virtual head surface. This provides the neurosurgeon with a visual reference of the tumor, including size and location on the virtual patient's head. The final craniotomy contour plan is decided by the surgeon from the information provided, with the projection serving typically as a guide in the ultimate craniotomy designation.

2.1.4 *Freehand craniotomy designation*

In the trackerless planning tool protocol relayed above, the neurosurgeon now has display information that provides landmarks and a projected tumor location on the patient's virtual scalp. These are essential guides to aid in designating the craniotomy plan. The planning approach, quite simply, is a freehand drawing on the surface (like is done in the real OR), facilitated by effectively coupling the virtual stylus, as shown in Fig. 3(c), to the surface where planning information is present. The planning phase is completed by saving the craniotomy contour, which can subsequently be reloaded in the 3D Slicer for future use for the craniotomy designation on the physical patient just prior to the start of the procedure.

2.1.5 *Translating from virtual planning to physical surgical guidance*

To move from planning to execution, the application will integrate the virtual head surface to the physical patient's acquired 3DTPC. The 3DTPC can be provided by a variety of low-cost technologies, for example, laser range scanner. Other technologies such as stereo-pair technologies[13] and structured light[14] are also under investigation. Here, the DAVID SLS-3 3D scanner (DAVID Vision Systems, Koblenz, Germany) is used to scan the patient's head. Once a 3DTPC of the patient's head can be acquired, an iterative closest point registration can be performed to align with MRI. In the past, we have done extensive work with an optically tracked laser range scanning technology[15] that studied the use of face-based textured point clouds to perform a face-based registration for use within conventional IGS systems. Here, we use similar orbital/head-surface registration methods, as was used in Refs. 15 and 16. Conventional guidance provides a link between the MRI and physical OR space using optical tracking technology. The 3-D texture-to-MR alignment in our method is also a form of image-to-physical space representation. In our approach, we add distinct markings in a grid-like fashion on the patient prior to acquiring the 3DTPC of their head as a physical reference (all without conventional tracking technology). One additional benefit of this method is that, with no need for tracking technology, this process can be done at any time prior to the procedure after the patient imaging is acquired, e.g., in the patient's room while waiting to be transported to the OR (provided surfaces are prepared for surgery). Conventional guidance platforms require a geometric reference to be attached to the patient so that tracking equipment can be moved around the OR without losing patient reference. As a result, craniotomy planning must be performed at the time of surgery. This is not the case for the methodology proposed in this paper. In addition, the texture provides a real physical space representation of the actual patient to the projected craniotomy plan provided by the aforementioned steps. Figure 4(a) shows the textured pattern of our mock patient scanned by a 3-D-structured light scanner. This represents the mock physical patient with physical pattern overlaid on the patient's head. Figure 4(b) shows the segmentation and mesh reconstruction of the head, brain, and tumor from MRI. Figure 4(c) shows the registration result of

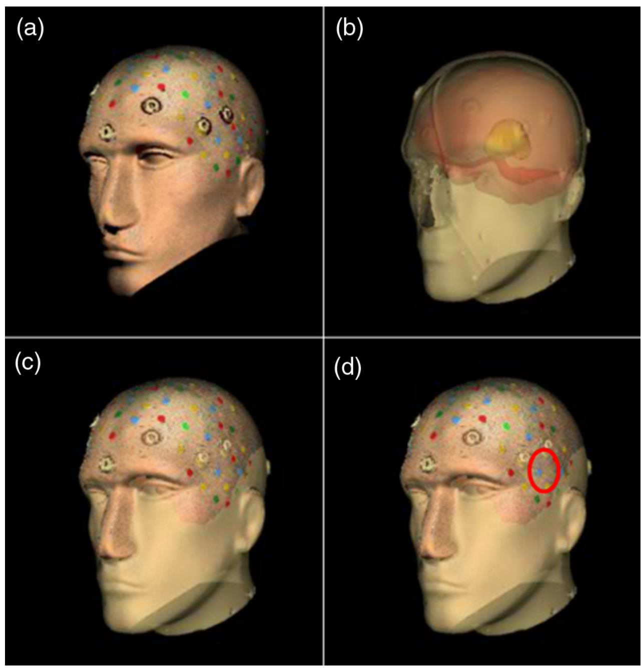

Fig. 4 (a) Textured scan model from a 3-D structured light scanner. (b) Mesh segmentation reconstruction from MRI. (c) Register textured scan model and mesh reconstruction together. (d) Overlay of the virtual planning contour onto the registered head surface model.

the 3DTPC scan of the head and head surface derived from MR. Figure 4(d) overlays an example of a virtual planning craniotomy contour onto the head surface model. This is an example of a 3DTPC-to-MR reference display that the surgeon could use as a reference to mark the physical patient's craniotomy in the OR without tracking technology. More specifically, within the OR, the reference shown in Fig. 4(d) display could be provided to the surgeon while the patient's head is fixed. The patient's head would still have all textured information. Using Fig 4(d) display, the surgeon could then use the texture landmarks as a reference to transfer the virtual craniotomy to the physical patient, all performed without conventional tracking. In summary, rather than the conventional tracking providing the link, texture references become the link.

2.2 *Experiments*

We designed an experiment to test the proposed trackerless craniotomy planning versus conventional craniotomy planning. The experimental system involves a head-shaped phantom with real clinical MR preoperative brain scans appropriately scaled and positioned within the head representing a surgical candidate. 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. Note that the surgeon performed the conventional and trackerless approaches on different days and with at least a week in between visits. This was done to avert possible bias associated with the order of performed planning type, i.e., conventional or trackerless.

2.2.1 *Conventional approach description*

As a control to compare, we recreated conventional plans with our mock OR. In this approach, the neurosurgeon begins by examining a given patient case on the 3D Slicer to visualize the 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[17]), OpenIGTLinkIF,[18] and the PLUS toolkit[19] (an application that streams live tracking data to the 3D Slicer). This point-based registration begins by selecting the center points of the attached MR-visible fiducials on the mock head surface and virtual image volume. Within the mock OR, the corresponding fiducials are digitized using a Northern Digital Polaris Spectra (NDI, Waterloo, Ontario, Canada). These fiducial centers are also digitized in the 3D Slicer on the virtual image 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 physical head. The neurosurgeon then draws the craniotomy contour on the surface of the head with a marker using the traditional guidance display to assist. Then, the neurosurgeon uses the digitizing stylus to trace the craniotomy contour drawn with the marker to quantify the planned craniotomy size and location for comparison with trackerless approach. Our custom OpenIGT extension collects the digitized points in physical space and transforms them to image space providing a contour that represents a conventional craniotomy approach in image space. This is done for all five patient cases (Fig. 5).

2.2.2 *Trackerless approach description*

For every case (total five), the neurosurgeon is also asked to plan a tumor resection procedure using our 3D Slicer module on a day other than the conventional planning. This procedure starts with the case being uploaded into the 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 (Fig. 1) is used by the neurosurgeon to virtually plan the patient's craniotomy. The neurosurgeon uses the record function to trace a contour for the craniotomy using the cross-sectional display and landmarks as a guide. After craniotomy planning is achieved, the 3-D scan of the physical head with a physical pattern [Fig. 4(a)] is registered to image space [Fig. 4(b)] using a surface-based registration and the head geometries [Fig. 4(c)]. Figure 4(d) shows the registered overlay of the 3-D physical

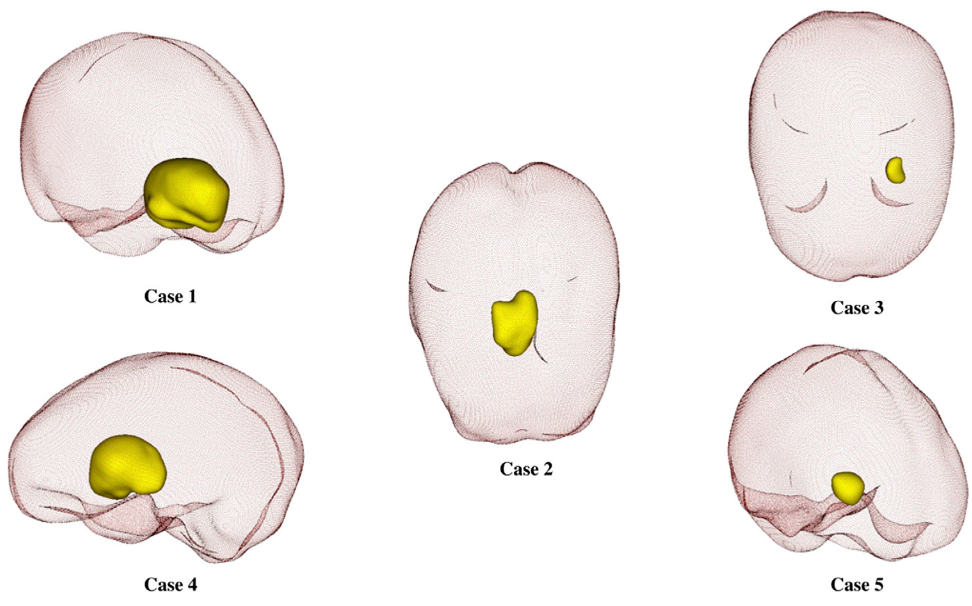

Fig. 5 Five cases of clinical patient data for experiment showing different tumor presentations.

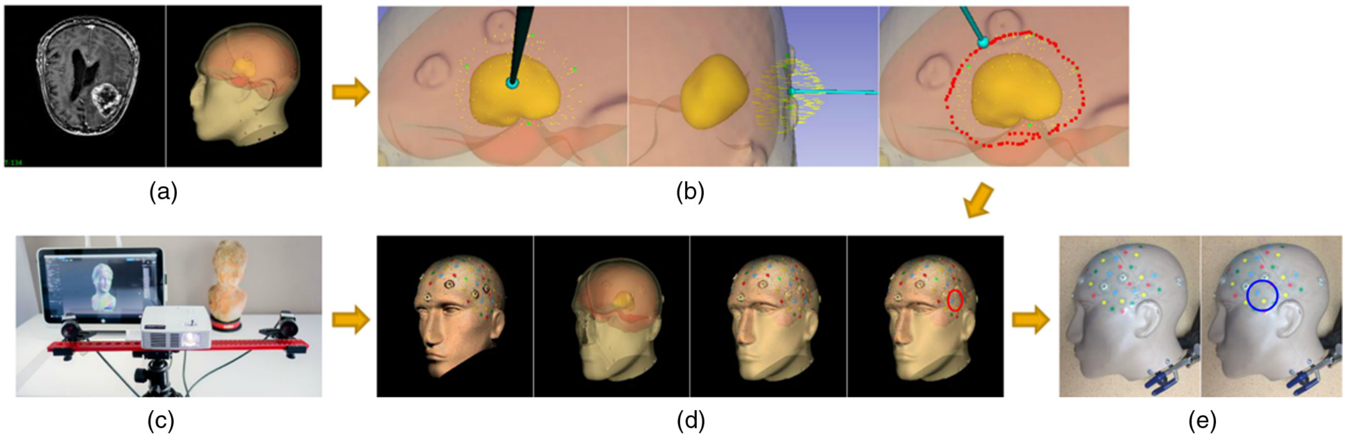

Fig. 6 Trackerless experiment workflow. (a) Segmentation and mesh reconstruction from MRI data. (b) Virtual plan using our trackerless planning system. (c) Scanning head phantom using structured light scanner.[20] (d) Register textured 3-D scan model and head surface model from MRI together, and overlay of virtual plan contour onto the texture. (e) Neurosurgeon translates the virtual plan onto the physical head by referencing the texture dots.

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 at the time of a freehand designation of the craniotomy in physical space. More specifically, the neurosurgeon can then, without the utilization of a conventional tracker, use the visible physical pattern on the physical patient head 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. This trackerless experiment workflow is summarized in Fig. 6.

3 Results

Using imaging data from five clinical cases (shown in Fig. 5) that underwent resection at Vanderbilt University Medical Center, retrieved under Institutional Review Board approval, the framework could be challenged under conditions involving different tumor sizes and located positions. All four experienced neurosurgeons completed conventional and virtual craniotomy planning on the phantom manikin head. Of note, the five patient MRIs from these real surgical cases were scale-adjusted and merged into the manikin head image set and in appropriate anatomical locations for the purpose of integrating real brain and tumor presentations. Using the digitized craniotomies, the results across surgeons and cases were compared. Figure 7 shows the results from each trial. The green area patch is the craniotomy planned using the conventional guidance approach. The red contour represents the planned craniotomy using the virtual stylus approach. Recall that this approach is essentially equivalent to the conventional approach but is performed completely in the virtual environment. The blue contour represents the surgeons' attempt to designate the craniotomy in its true physical space using our 3DTPC-to-MR overlay [e.g., Fig. 4(d)] as the only guiding reference (trackerless), i.e., the freehand transfer of an observed virtual craniotomy onto the mock physical patient. It should be noted that after the surgeon created the freehand contour, the contour was digitized with a conventional tracking technology to facilitate the comparison, as shown in Fig. 7. The quantitative metrics of comparison were the difference between centroid positions of the trackerless and conventional craniotomy and area percentage differences (calculated by $(|A_{\text{trackerless}} - A_{\text{conventional}}|)/A_{\text{trackerless}}$, where A is the area of each respective craniotomy region) of each case from all four neurosurgeons. The purpose of the first metric is to quantify the degree of colocalization between trackerless and conventional craniotomy placement. The purpose of the second metric is to quantify the percentage difference in planned conventionally derived craniotomy size relative to the trackerless realized. These metrics are plotted in the bar graphs of Figs. 8 and 9, respectively, which demonstrate the virtual-to-physical craniotomy contour fidelity. The clinical contour fidelity can be evaluated by comparing virtual craniotomy planning and conventional craniotomy planning.

4 Discussion

The goal of this work is to allow the surgeon to plan a craniotomy for neurosurgery without using conventional guidance in current clinical practice. From observing Fig. 7, we see qualitative agreement between red (virtual craniotomy using our display) and blue contours (designation of craniotomy plan freehand on mock physical subject using our 3DTPC-to-MR display). This demonstrates that the trackerless platform can be used to translate a virtual plan to a physical outcome of craniotomy designation effectively. The difference between that plan and the conventional approach (compare red/blue contour to the conventionally determined green region) is relatively consistent among cases 2, 3, and 4. However, cases 1 and 5 are less consistent. Our initial hypothesis to explain the disagreement was that when surgeons perform the virtual planning on a two-dimensional screen, they may have lost the sense of the 3-D nature of the physical head [see Fig. 10(a)]. As a consequence of the results, we simulated a real OR in the virtual planner and added a clamp and surgical bed, allowing the head to rotate in the range of the clamp [see Fig. 10(b)]. We performed another round of virtual experiment with this version of virtual interface. Since one of the surgeons left our hospital during the experiment, the other three neurosurgeons were asked to perform this experiment. Figure 11 shows the comparison results of virtual planning contour with and without the clamp and surgical bed in the same five clinical cases. The red contour is the craniotomy plan with the virtual planning system. The purple contour is the craniotomy plan with the virtual planning system

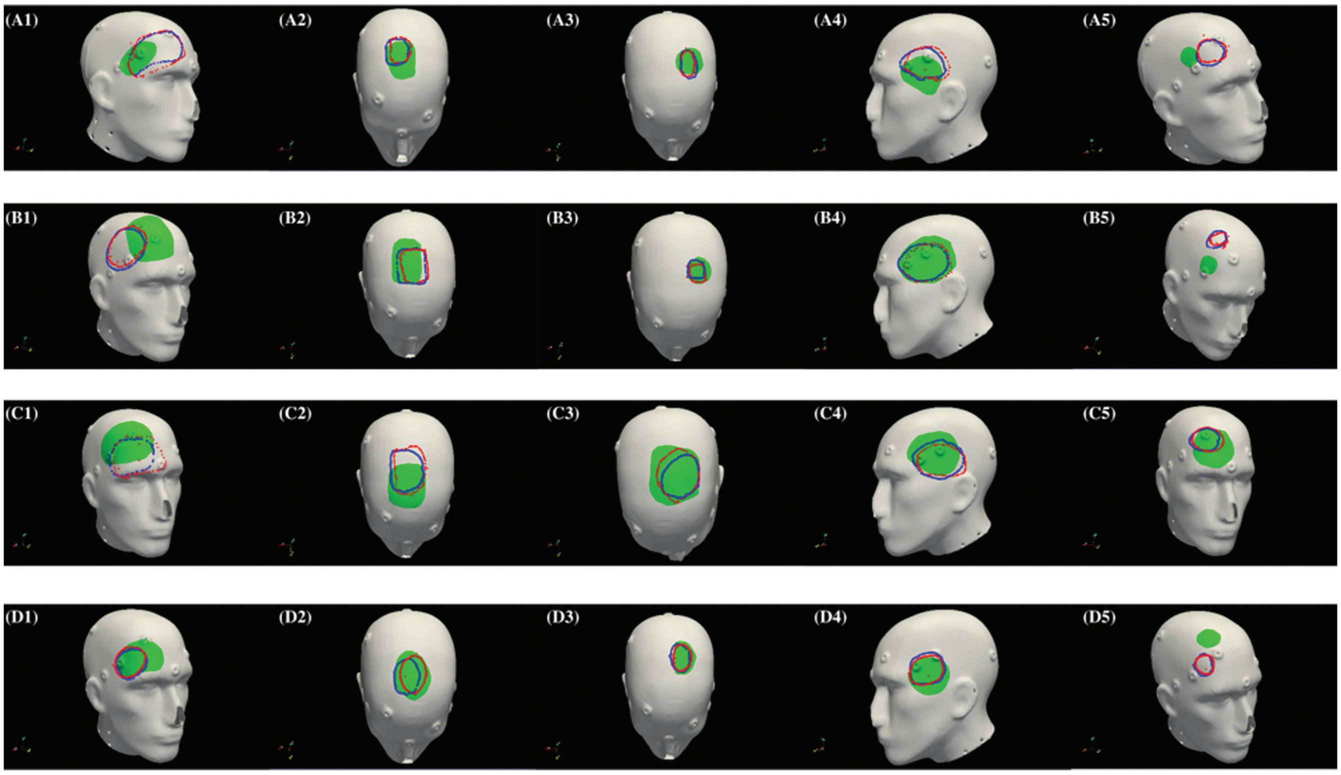

Fig. 7 Comparison results of our approach and conventional localization method in five clinical cases integrated with head phantom performed by four experienced neurosurgeons (A)–(D). The green patch represents craniotomy planned with conventional approach. The red contour is the craniotomy plan with virtual stylus planner. The blue contour is the transfer of that craniotomy plan to the physical mock subject using 3DTPC-to-MR display and freehand designation.

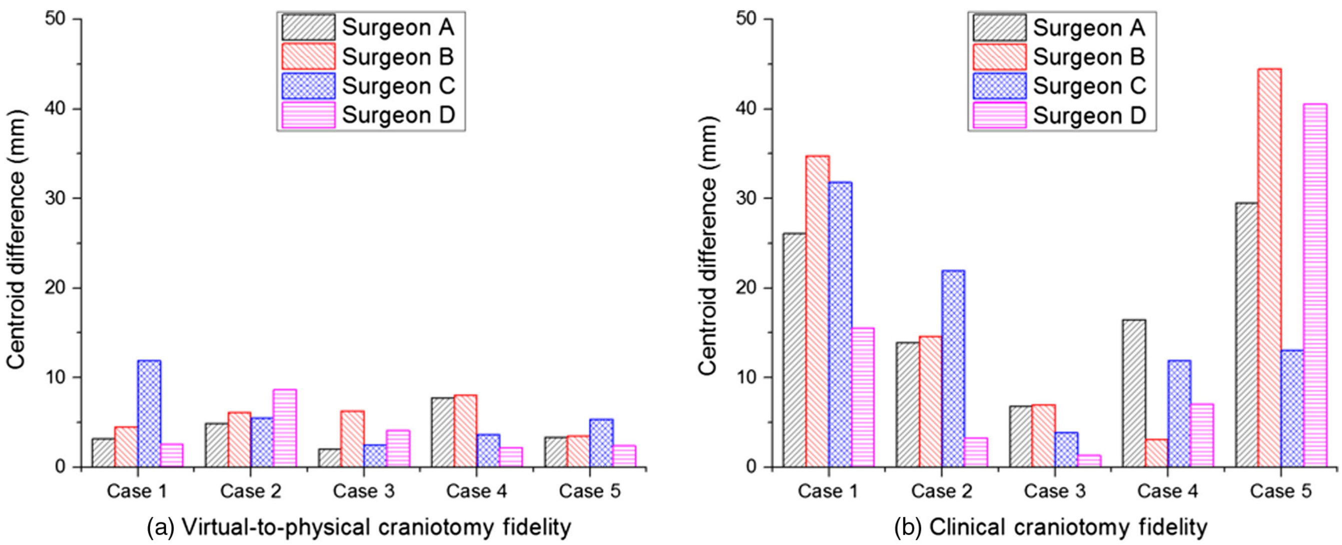

Fig. 8 Bar plot of craniotomy planning regarding differences in centroid location expressed as a distance for each case with each neurosurgeon. (a) Virtual-to-physical craniotomy centroid location difference between virtual planned contour and the translation of that contour on the physical head. (b) Clinical craniotomy centroid location difference between virtual planned contour and conventionally planned contour.

with the clamp and bed. Notice that the purple contour is once again consistent with the red except for cases 1 and 5, suggesting that adding clamp and surgical bed was not a strong influence. As additional investigation into this behavior of these two cases, neurosurgeons were asked to perform one more round of virtual and conventional planning only on cases 1 and 5. Figure 12 compares three different rounds of virtual and conventional planning of cases 1 and 5 by three of the surgeons. The conventionally planned craniotomy size and location (green patch) of case 1 is relatively consistent, but it is somewhat less consistent

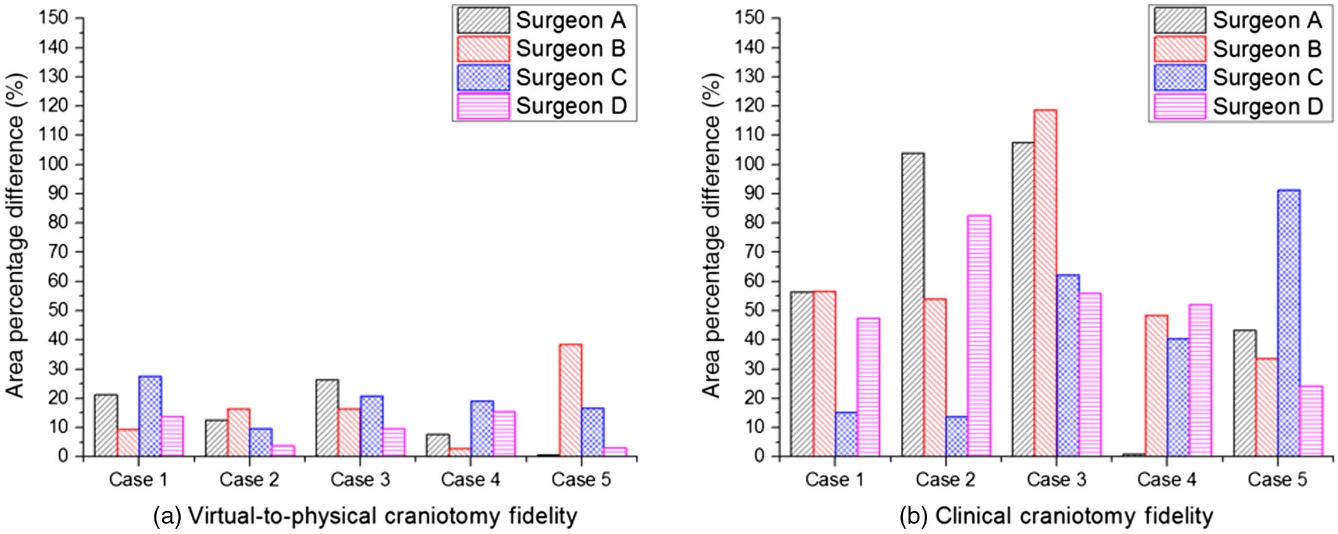

Fig. 9 Bar plot of craniotomy planning area percentage difference for each case with each neurosurgeon. (a) Virtual-to-physical craniotomy area percentage difference between area enclosed by virtually planned contour and the area enclosed by physical head counterpart. (b) Clinical craniotomy area percentage difference between area enclosed by virtually planned contour and conventionally planned counterpart.

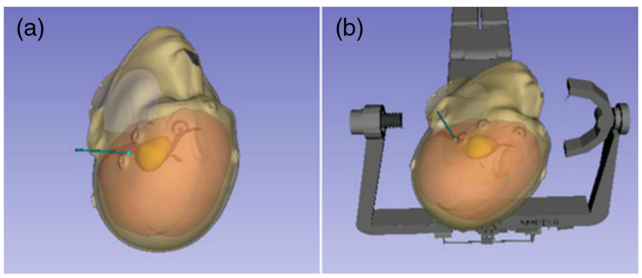

Fig. 10 (a) Virtual planning system interface. (b) Virtual planning system with the addition of clamp and bed to simulate real OR.

in case 5. With respect to the correlation with the virtual craniotomy plan, there is certainly more overlap between virtual and conventional plans for case 1. Case 5, however, has considerably more discrepancies [for example, Figs. 12(A5c), 12(D5a), and 12(D5b)].

To further analyze, follow-up interviews were conducted with physicians to discuss the choices made with respect to their planning results. In the preliminary experiment,[21] the conventional approach was from a previous study conducted approximately one year prior,[22] and the neurosurgeon claimed that his preferred surgical approach had since changed with respect to that presentation. In the extended experiment presented here, all the surgeons repeated the conventional planning. However,

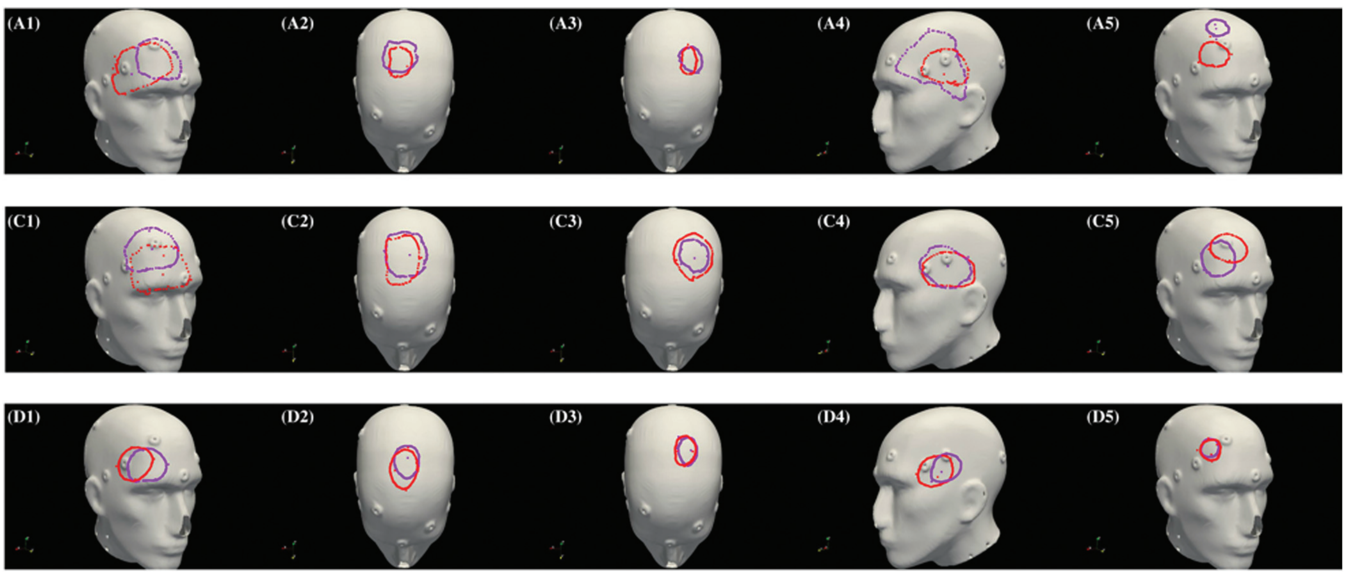

Fig. 11 Comparison results of virtual planning contour with and without clamp and surgical bed in five clinical cases integrated with head phantom performed by three experienced neurosurgeons A, C, and D (neurosurgeon B has left). The red contour is the craniotomy plan with virtual planning system. The purple one is the craniotomy plan with virtual planning system that adds clamp and bed.

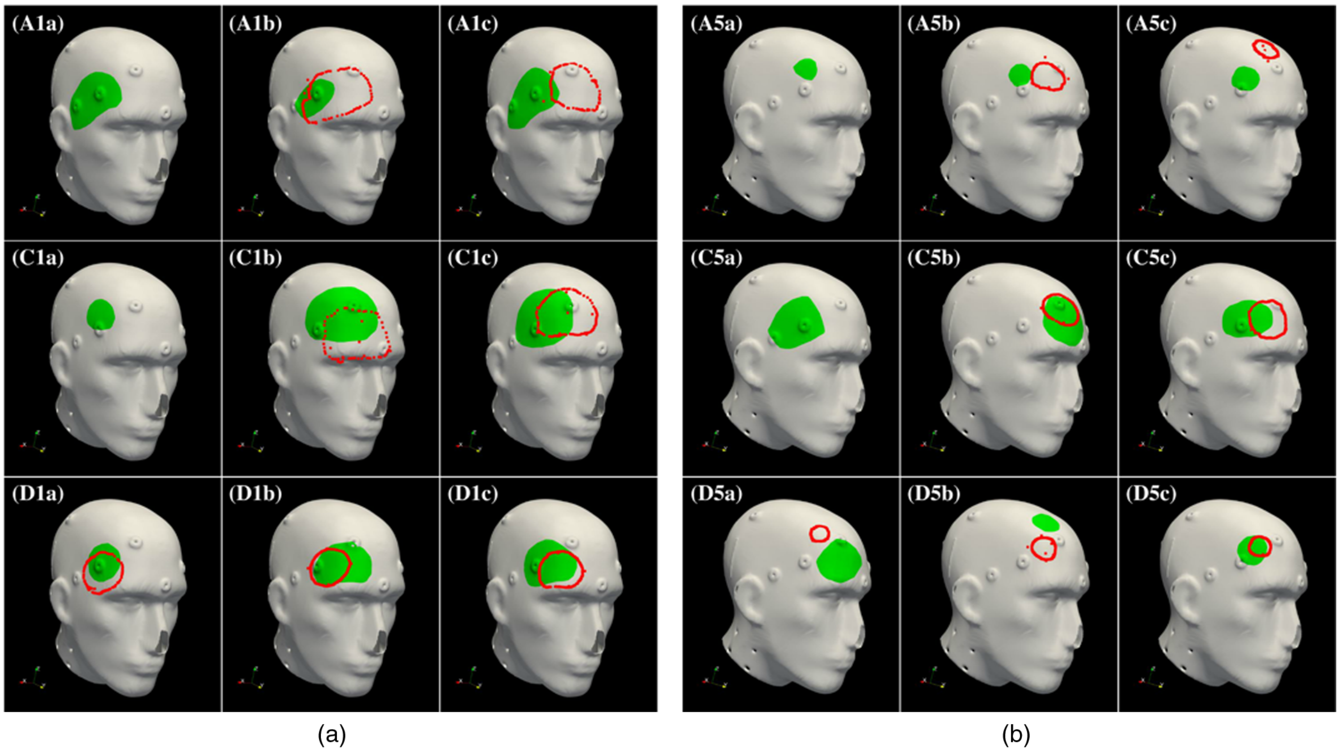

Fig. 12 Comparison between different results of conventional planning (green area) and virtual planning (red contour). (a) Three plans of case 1 from neurosurgeons A, C, and D. (b) Three plans of case 5 from neurosurgeon A, C, and D. [Note that surgeons A and C did not plan virtually on the first round, so there are no red contours in (A1a), (A5a), (C1a), and (C5a).]

despite the explanation for the discrepancy and the repeating of the conventional planning, the results still appeared to undergo a similar discrepancy. One of the senior neurosurgeons, with more than 20 years of experience, provided his interpretation of the results of cases 1 and 5. The tumor positions of cases 1 and 5 make the tumor localization difficult. Case 5, specifically, will not appear on all three planar views of the MRI. The neurosurgeon indicated that seeing the tumor on at least two planar views improved the craniotomy planning. This may have contributed to the differences in the planning for case 5. In case 5, the tumor was often only visible on one or two of the MRI planes. Figure 13 shows two examples of the virtual stylus positions in case 5. When the virtual stylus is placed on the right side, the tumor is only shown on sagittal view [see Fig. 13(a)]. However, moving the virtual stylus to the bottom left, the tumor is only visible in the axial slice [Fig. 13(b)]. As a result of this variability in determining tumor extent from imaging data, there is increased variability when planning on a small tumor when compared to planning with a larger tumor (compare case 1 and 5 in Fig. 12). The surgeon's conclusion was that the discrepancies in cases 1 and 5 are due to a lack of anatomical landmarks (dural septa, tissue, ventricles, etc.) near the two tumors. As a result, the plan for the craniotomy varied. This contrasts with cases 2 and 3 that have a dural septa reference and have a distinct trajectory for resection. What is clear is that neurosurgeons take into account various anatomical landmarks to optimize patient outcomes. In addition, a craniotomy position is selected to achieve the best tumor exposure for resection while minimizing patient harm. In cases 1 and 5, there were multiple trajectories that could do this and perhaps multiple safe and effective approaches to these tumors.

There were other observations as well. Figure 7 also shows that some surgeons prefer different sizes of craniotomy. For example, surgeon C always plans a bigger craniotomy as compared to other surgeons. There is considerable debate in the neurosurgical literature about the appropriate size of a craniotomy. The general consensus is that the opening should allow the entire tumor to be safely visualized and resected. However, different surgeons may have specific preferences beyond this practice. For example, some tumor surgeons may prefer to identify margin by separating along surgical tissue planes between the tumor and healthy brain wherever possible before removing the bulk of the tumor. Others may prefer to make a smaller approach and internally debulk the tumor before altering the surgical angles and visualizing each margin.

Another interesting finding in the preliminary experiment is that the conventional guidance method consistently provided a larger craniotomy plan. However, with the extended experiment results in Fig. 7, this finding is not repeated. Overall, the size of virtual planning and conventional contour is quite consistent. The main drawback of the proposed virtual planning system is that the anatomical structure is not obvious, compared with conventional planning. In addition, it should also be stated that, as this is a new technology, undoubtedly there are still training effects as the platform itself represents a very different means of planning as well as interacting with the physical anatomy. However, in consideration of its advantages such as consistent planning contours, intraoperative workflow efficiencies, and the trackerless planning strategy, the participating surgeons were enthusiastic that this virtual planning method could be an alternative to conventional planning, with perhaps a noted strength for junior resident training.

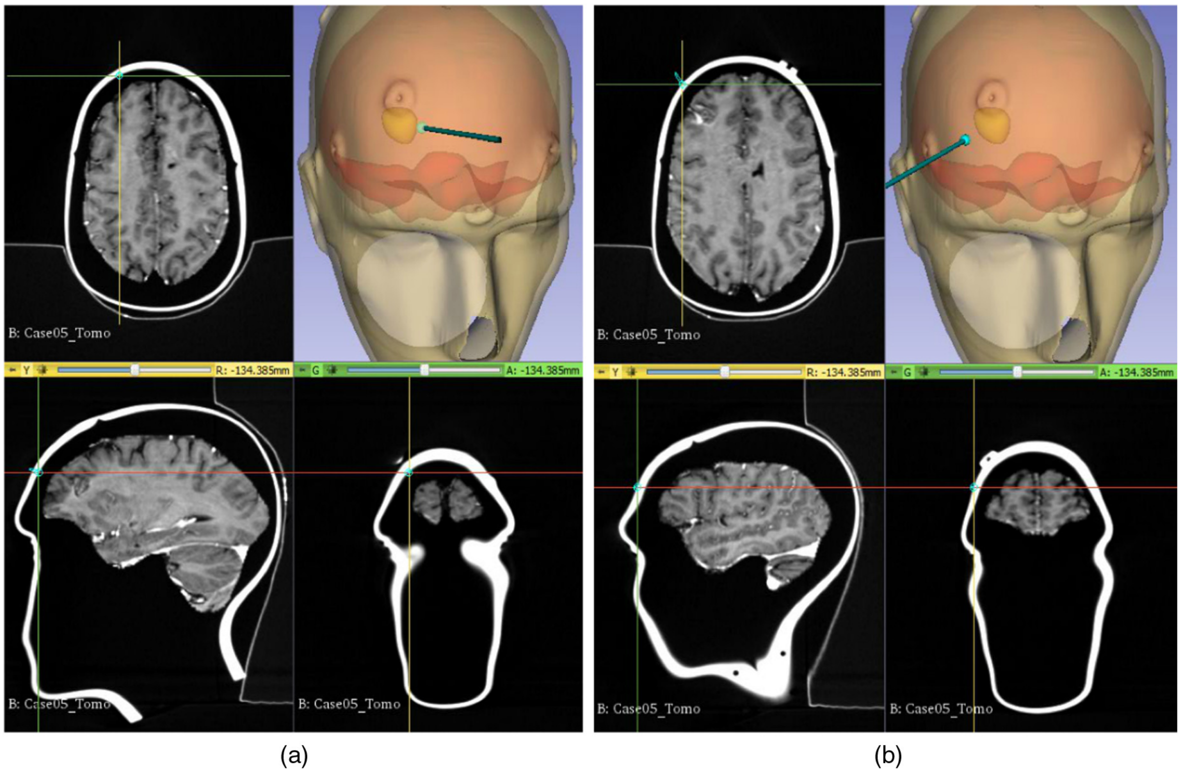

Fig. 13 Three image views (axial, sagittal, and coronal) and 3-D view of case 5 with different location of virtual stylus. (a) When the virtual stylus is placed at the right side of the tumor, then the tumor is only shown on the sagittal view. (b) When the virtual stylus is placed at the bottom left of the tumor, then the tumor is only shown on the axial view.

While the above discussion is quite encouraging, there are certainly limitations to the study that must be acknowledged as well as considerations from the perspective of clinical utility. Beginning with the former, it must be acknowledged that while each of the five cases utilized represent real pathologies and involve patients who underwent neurosurgical resection, the impact of the experiments of scaling these neuroanatomical presentations within our phantom head cannot be ascertained. For example, if the scalp-to-brain distance became too excessive in the scaling process such that it was not realistic, the effect of such a variation on the fidelity of our results or its potential effect on clinical translation are unknown. Similarly, the phantom head is rigid as compared to the deformable patient scalp. The influence that deformability has on digitization in either the conventional or the trackerless method is unknown. Finally with respect to the study reported herein, it must be noted that our head presentation mock surgery setup, while similar to the OR, still represents a considerable difference when compared to head fixation with the Mayfield clamp, which is routinely used in the neurosurgical theater. It should be noted that none of our participating surgeons complained of these aspects, once the final mock system for testing was realized. Moving on to clinical considerations, there are several to contemplate. First, the approach would likely require a considerably shaved scalp in the region of the craniotomy and could potentially be more extensive. From a cosmetic perspective, this could be a concern. Second, presentations that require a prone patient may be more challenging. Third, with respect to the task of creating textures to allow planning, the best practices are uncertain (e.g., optimal distribution of texture and method of applying). A fourth and more intriguing aspect to consider is altering of workflow with the approach, with the trackerless potentially being an improvement. More specifically, the trackerless planning could be initiated at almost any time prior to surgery (assuming preoperative/diagnostic MRIs are available). Theoretically, a structured light scanner is highly portable and could be used in the patient's room. Assuming a prepared scalp, textured fiducials could be applied on visible scalp areas or even inked as is commonly done. The image-to-physical registration (as shown in Figs. 4 and 6) could be done immediately. The physician could plan the craniotomy in the patient's room and even share with the patient their decisions. The only requirement would be that the craniotomy texture on the patient could not be removed prior to presentation in the Mayfield clamp to preserve the plan. This should not be a problem as conventional craniotomies are planned with the scalp intact and before constructing the sterile site. It is reasonable to assert that the trackerless approach would result in a better workflow and can be less encumbered for three reasons: (1) registration between patient-textured surface and MR could be done before the patient gets to the OR, (2) similarly, the craniotomy plan could be done prior to the OR, and (3) if done prior to the OR, no registration process with a stylus has to be performed at all in the OR, thus saving considerable time. If found acceptable, it would be intriguing to compare these approaches.

5 Conclusions

The paper demonstrates the feasibility of using a trackerless surgical image-guided system to plan and execute a craniotomy for neurosurgery. Overall, the virtual craniotomy plan provided by the approach was consistent with the conventional one. The interactive extension of the 3D Slicer shown here can simplify the procedure of preoperative planning by removing the need for conventional tracking and provide a reliable craniotomy contour. The work herein, when combined with our cortical surface registration,[1] cortical deformation measurement methods,[2,23] and finally computational brain shift prediction framework,[24] 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.

Disclosures

No conflicts of interest, including financial or others, are declared by the authors.

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