Virtual Surgical Planning in Endoscopic Skull Base Surgery

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Objectives/Hypothesis: Skull base surgery (SBS) involves operative tasks in close proximity to critical structures in a complex three-dimensional (3D) anatomy. The aim was to investigate the value of virtual planning (VP) based on preoperative magnetic resonance imaging (MRI) for surgical planning in SBS and to compare the effects of virtual planning with 3D contours between the expert and the surgeon in training.

Study Design: Retrospective analysis.

Methods: Twelve patients with manually segmented anatomical structures based on preoperative MRI were evaluated by eight surgeons in a randomized order using a validated National Aeronautics and Space Administration Task Load Index (NASA-TLX) questionnaire.

Results: Multivariate analysis revealed significant reduction of workload when using VP \((P<.0001)\) compared to standard planning. Further, it showed that the experience level of the surgeon had a significant effect on the NASA-TLX differences \((P<.05)\). Additional subanalysis did not reveal any significant findings regarding which type of surgeon benefits the most \((P>.05)\).

Conclusions: Preoperative anatomical segmentation with virtual surgical planning using contours in endoscopic SBS significantly reduces the workload for the expert and the surgeon in training.

Key Words: Skull base surgery, contouring, image guidance, surgical planning.

Level of Evidence: 4.

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INTRODUCTION

Skull base surgery involves operative tasks in close proximity to critical structures in a complex three-dimensional (3D) anatomy. Furthermore, the anatomical structures are subject to variations across different patients and morphological changes due to the extent of the disease. Thus, there is a need for significant exposure of the surgical target and planning to safely and precisely remove the tumor. To fulfill such need, integrated systems for intraoperative surgical guidance have been actively investigated over the past several years, including systems that provide virtual and augmented reality surgical views in addition to standard planning (SP)\(^1\)–\(^4\).

In analogy of the radiation oncologist outlining and contouring the target volume, virtual planning (VP) for surgical guidance requires accurate methods for anatomical contour delineation by using manual and/or automatic methods based on preoperative volumetric imaging. Contouring makes use of a dedicated software program that allows the surgeon to manually (or semiautomatically) contour anatomical structures within preoperative 3D images. This typically involves the surgeon contouring structures slice by slice and assigning distinct color codes for each anatomical entity (e.g., carotids in red, nerves in yellow). Combinations of different imaging modalities in delineation is not uncommonly used. The resulting contours can be presented to the surgeon in a 3D view for preoperative surgical planning as well for intraoperative surgical guidance. Thus, VP can help to visualize the surgical process and support the surgeon with intratreatment imaging and surgical guidance.\(^4\)

There are reports incorporating pre- and/or intraoperative computed tomography displaying the location of a tracked instrument in endoscopic image guidance systems finding its way through a mainly bony complex anatomical formation.\(^5\)–\(^7\) When visualization of the primary tumor and its relevant surrounding structures, such as carotid arteries and optic nerves, is required, a preoperative magnetic resonance imaging (MRI) is usually performed. Earlier reports describe contouring on preoperative MRI and integrate it into surgical planning and guidance.\(^4\),\(^5\),\(^6\) Nevertheless, the reported benefit on preoperative contoured imaging has never found its way into the routine operating room setup.
The overlay of imaging contours on an anatomical background results in an augmented or virtual reality view. A recent review published by Alaraj et al. concluded that detailed virtual reality neurosurgical modules will evolve to be an essential part of the curriculum of the training of neurosurgeons.10

The aim of this study is to investigate the value of 3D anatomical segmentation based on preoperative MRI for surgical planning in endoscopic skull base surgery by using a validated quantification tool, and to initiate its use in clinical routine. Further, the study includes both surgeons in training and experienced skull base surgeons, to compare the effect of surgical planning with 3D contours between these two groups.

MATERIALS AND METHODS

Twelve patients undergoing endoscopic skull base surgery at the University Health Network, Toronto, Ontario, Canada were retrospectively enrolled in this study. The study protocol was approved by the institutional review board. All patients were referred to our institution for further management of their pituitary lesions, including macroadenoma (n=6), craniopharyngioma (n=3), meningioma (n=1), chordoma (n=1), and angiosarcoma (n=1). Preoperative MRI scans were obtained on the same day as surgery using a General Electric (Milwaukee, WI) Signa Excite 1.5-T scanner with MRI compatible registration fiducial markers (n=8) attached to the patient for use with a commercial surgical navigation system (StealthStation; Medtronic Navigation, Louisville, CO). According to the institutional head and neck MRI scanning protocol, the acquired guidance images have a pixel size of 1×1 mm2 and a slice thickness of 2 mm. For retrospective anatomical segmentation, T1-weighted images acquired after intravenous gadolinium were used to best differentiate between the structures of interest, such as the primary tumor, cavernous sinus, carotid arteries, and optical nerves.

Manual contouring was performed on the triplanar views (axial, sagittal, and coronal) by an experienced skull base surgeon and approved by a neuroradiologist with >20 years experience in reviewing neuroimages (W.K.). ITK-SNAP 2.2 (University of Pennsylvania, Philadelphia, PA), an open-source 3D segmentation software package, was used to delineate the tumor and surrounding critical structures.11 The carotid arteries, optic nerves, cavernous sinuses, pterygopalatine fossae, dura, and tumor were selected as critical structures for contouring (Fig. 1). The contouring time for each case was between 30 and 60 minutes, depending on the lesion’s size, location, and relationship to critical anatomical structures (Fig. 2).

In all cases, the original SP and VP images were presented to the surgeon in a manner consistent with standard preoperative surgical planning. The surgeon was free to scroll through images and adjust window/level, and there were no time constraints. The MRI sequences, SP and VP, were shown to four experts (senior staff members) in skull base surgery and...
to four novices (fellowship-trained skull base surgeons). The order of the 24 image sets (VP and SP for 12 patients) was randomized, and a new randomization order was generated for each surgeon using Excel (Microsoft, Redmond, WA). The eight subjects were free to select any endonasal surgical approach described by Cavallo et al. and Kassam et al. After defining a surgical approach, the subjects assessed the SP and VP images quantitatively using the validated National Aeronautics and Space Administration Task Load Index (NASA-TLX) for each case. The standard questionnaire includes subscales for effort, frustration, mental, physical, and temporal demand, and performance rated on a visual analog scale from 0 to 20. In our study, physical demand was excluded, because there was no physical task to complete. Each subject reviewed 12 patients’ MRI data with SP or VP view of critical structures and tumor. In total, 24 questionnaires were collected from each subject for statistical analysis.

**Statistical Analysis**

Paired NASA-TLX scores for each 2D and 3D augmented view were analyzed using a paired t test, after confirming the normality assumption on the data using a quantile–quantile plot. P values of less than .05 were considered significant. A multivariate analysis was performed using a repeated measures test to evaluate which factors—planning data (2D or 3D), selected surgical approach (e.g., trans-sphenoidal, transplanum) and experience level (expert or novice)—had a significant effect on the differences in NASA-TLX scores. All statistical analysis was performed using SAS 9.3 (SAS Institute, Cary, NC).

**RESULTS**

Analyzing the effect of the level of expertise (expert vs. novice) on the workload for each subscale, multivariate analysis demonstrated a significantly reduced workload for the expert compared to the novice irrespective of the planning view or surgical approach for each subscale (effort: $P=.004$; frustration: $P=.0001$; mental and temporal demand: $P=.002$ and $P=.006$, respectively; performance: $P=.04$). The overall multivariate analysis for the difference between SP and VP, after adjustment for different surgical approaches and for different surgical expertise (expert vs. novice), revealed a significant effect of VP on differences in NASA-TLX scores as shown in Figure 3 ($P<.0001$ for all NASA-TLX subscales). Analyzing the choice of surgical approach, the NASA-TLX subscales were not significantly influenced, showing $P>.05$.

Figure 4 illustrates a statistically significant reduction of workload for both novice and expert when adding VP. With application of the NASA-TLX, the performance subscales demonstrate a significantly higher performance with available VP irrespectively of the level of expertise. The paired t test analysis is demonstrated in Table I. Table II shows which surgical level of expertise (expert vs. novice) is most affected by the VP views.

**DISCUSSION**

In this study, we revealed a significant effect in terms of reduced workload for both the expert and the
surgeon in training when VP on preoperative MRI is available. The reduced workload subsequently implies a surgical planning benefit. Thus, although advances in endoscopic image-guidance provide additional information during the surgical procedure itself, this study suggests a future role for VP prior to surgery during the routine planning workflow of skull base surgeons.

An important first result in the study was the multivariate analysis showing an overall reduced workload in all subscales for the expert compared to the surgeon in training irrespective of the planning view (SP vs. VP) or surgical approach. The analysis proves the NASA-TLX questionnaire is able to differentiate between different levels of expertise. The statistical comparison between SP and VP views revealed a statistically significant reduction in workload afforded by the VP view irrespective of the level of expertise (novice or expert) and the surgical approach chosen. The multivariate characteristic of this analysis is important, because the type of surgical approach may influence the workload scores, as well does the level of surgical education. Nevertheless, it is the VP view of preoperative contoured MRI sequences that made the difference in our analysis.

Subjectively, the most beneficial addition of VP compared to SP was the depth perception in large tumor cases, as well as the clival anatomy. If the sphenoid is not well pneumatized, the VP approach is of subjective benefit also. For an educational purpose, the expert surgeons suggest adding the middle turbinate in the segmentation process as well as the floor of the third ventricle.

Because some authors demonstrate the value of endoscopic training simulation in terms of flattening the learning curve in new skill acquisition, we have included both experts and novices in our analysis to elucidate who is affected the most from surgical planning using virtual anatomical segmentations. The subanalysis of the two different experience-leveled surgeons revealed no significant difference between the expert and the surgeon in training regarding reduced NASA-TLX workload scores with VP available. This is most probably related to the limited number of subjects participating in the study (four experts and four novices). Interestingly, when looking at the performance status, the difference between SP and VP was more substantial in the novice group, indicating that novices may have a higher overall benefit from the VP view. In future studies, it would be interesting to investigate whether our results reveal a change in potential for surgical errors. A recently published article by Yurko et al. describes the relationship of workload and performance during simulator training for novices on a complex laparoscopic task. They found increased workload is associated with inferior task performance and higher likelihood of errors.

Preoperative contouring in this study was performed manually on MRI data. The average time spent contouring per case was 45 minutes. This is additional time the surgeon would need to spend in an already time-constrained workflow, which likely reflects the absence of contouring in routine clinical practice. There are reports of automated segmentation showing a reduced time of segmentation compared to the manual contouring. However, the skull base and its small, complex 3D structures is not an ideal candidate for these semiautomated or fully automated methods. More clinical and fundamental research needs to be completed before an automated segmentation process can be applied to these delicate structures. In addition, the specific role of clinicians (e.g., radiologists, surgeons, surgical fellows, and residents) in the generation and validation of surgical contours needs to be addressed in more detail.

The benefit of surgical contouring is not necessarily limited to surgical planning. There has been significant work done on the use of virtual anatomical segmentations in virtual and augmented reality views within intraoperative image guidance systems. In a recent study, Dixon et al. showed that augmented endoscopy, including virtual views and critical structure contouring using the same methods described in this study, demonstrated increased accuracy and safety while reducing operator workload. As such, the benefits and corresponding workflow considerations of virtual contouring should be

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**TABLE I.**

<table>
<thead>
<tr>
<th>Subscale</th>
<th>Group</th>
<th>ΔNASA-TLX</th>
<th>SD</th>
<th>Lower</th>
<th>Upper</th>
<th>(P)</th>
</tr>
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<tbody>
<tr>
<td>Effort</td>
<td>Expert</td>
<td>3.3</td>
<td>4.3</td>
<td>2.0</td>
<td>4.5</td>
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<td></td>
<td>Novice</td>
<td>2.4</td>
<td>3.6</td>
<td>1.3</td>
<td>3.4</td>
<td>(&lt;.0001)</td>
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<tr>
<td>Frustration</td>
<td>Expert</td>
<td>2.5</td>
<td>3.3</td>
<td>1.5</td>
<td>3.4</td>
<td>(&lt;.0001)</td>
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<tr>
<td></td>
<td>Novice</td>
<td>2.5</td>
<td>4.5</td>
<td>1.2</td>
<td>3.8</td>
<td>(0.004)</td>
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<tr>
<td>Mental</td>
<td>Expert</td>
<td>3.4</td>
<td>4.7</td>
<td>2.0</td>
<td>4.7</td>
<td>(&lt;.0001)</td>
</tr>
<tr>
<td></td>
<td>Novice</td>
<td>2.1</td>
<td>3.8</td>
<td>1.0</td>
<td>3.2</td>
<td>(0.003)</td>
</tr>
<tr>
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<td>3.1</td>
<td>0.5</td>
<td>2.3</td>
<td>(0.031)</td>
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<td>Novice</td>
<td>2.2</td>
<td>3.9</td>
<td>1.1</td>
<td>3.3</td>
<td>(0.003)</td>
</tr>
<tr>
<td>Performance</td>
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<td>2.2</td>
<td>1.7</td>
<td>0.5</td>
<td>(0.009)</td>
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<tr>
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<td>Novice</td>
<td>1.3</td>
<td>3.0</td>
<td>2.2</td>
<td>0.4</td>
<td>(0.051)</td>
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CI=confidence interval; NASA-TLX=National Aeronautics and Space Administration Task Load Index; SD=standard deviation.

**TABLE II.**

<table>
<thead>
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<th>Subscale</th>
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<th>(P)</th>
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<tr>
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<td>Novice</td>
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CONCLUSION

Preoperative anatomical segmentation for surgical planning in endoscopic skull base surgery is significantly associated with less workload on scales, which evaluate effort, frustration, and performance in addition to mental and temporal demand. The same virtual planning contours can be used for intraoperative image guidance and assist the surgeon throughout the procedure. Further research needs to be undertaken to address the workflow efficiency of contour segmentation (e.g., semi-automated methods) for it to be routinely incorporated in skull base surgery. Current clinical studies are investigating the benefits of preoperative virtual contouring on planning and execution during surgery.

BIBLIOGRAPHY