Background: Due to proximity to critical structures, the need for spatial awareness during endoscopic sinus surgery (ESS) is essential. We have developed an augmented, real-time image-guided surgery (ART-IGS) system that provides live navigational data and proximity alerts to the operating surgeon during ablation. We wished to test the hypothesis that task workload would be reduced when using this technology.

Methods: A trial involved 8 otolaryngology residents and fellows performing ESS on cadaveric specimens; 1 side in a conventional method (control) and 1 side with ART-IGS. After computed tomography scanning, anatomical contouring, and registration of the head, a three-dimensional (3D) virtual endoscopic view, ablative tool tracking, and proximity alerts were enabled. Each subject completed ESS tasks and rated their workload during and after the exercise using the National Aeronautics and Space Administration (NASA) Task Load Index (TLX). A questionnaire and open feedback interview were completed after the procedure.

Results: There was a significant reduction in mental demand, temporal demand, effort, and frustration when using the ART-IGS system in comparison to the control ($p < 0.02$). Perceived performance was increased ($p = 0.02$). Most subjects agreed that the system was sufficiently accurate, caused minimal interruption, and increased confidence. Optical tracking line-of-sight issues were frequently cited as the main limitation early in the study; however, this was largely resolved.

Conclusion: ART-IGS reduces task workload for trainees performing ESS. Live navigation and alert zones may be a valuable intraoperative teaching aid.

Key Words: image-guided surgery; endoscopic sinus surgery; virtual reality; skull-base surgery; surgical navigation

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Endoscopic sinus surgery (ESS) presents a number of challenges to surgeons of all experience levels. Access through the nose is limited and the restricted operative field requires specific instrumentation for fine dissection. Depth cues are limited by the 2-dimensional monitor. The sinus cavities are a complex 3-dimensional (3D) environment surrounded by critical structures including the eyes, cranial nerves, carotid arteries, and intracranial contents. Orientation during sinus surgery is essential to complete the procedure thoroughly while avoiding complications. As such, ESS can at times be very technically and spatially demanding.

Image-guided surgery (IGS) systems, usually based on preoperative computed tomography (CT) scans, have been employed to aid in navigation during ESS. To date, these systems have mostly been used intermittently to confirm the 3D position of a nonablative tool. If imaging data is continually referenced, surgeons may take advantage of “live” navigation to enhance spatial awareness during the procedure. The Guided Therapeutics program at the University of Toronto has developed an augmented, real-time
image guided surgery (ART-IGS) system that transforms imaging data into an accessible and dynamic display. The endoscope is tracked and when registered to the IGS system allows a 3D virtual view to be shown. Pertinent anatomy and surrounding alert zones are precontoured on the CT scan and then displayed in the virtual endoscopic image. Ablative instruments are tracked and the system provides proximity feedback and alerts. It should be noted that the prototype being tested did not update the virtual view to compensate for ablation or deformation occurring during a procedure. As such the “real-time” description reflects the dynamic update of the virtual view in relation to endoscope tip position in addition to the feedback provided by active proximity alerts. Conventional IGS systems do track in real-time but usually do not provide dynamic feedback in a continuous fashion.

Together, these applications can provide real-time image guidance and potentially increase safety and efficiency while reducing navigational demand. We have previously demonstrated greater precision and a trend toward faster task completion when using this technology. In addition to these advantages, advanced navigational systems used in other industries have been shown to decrease task workload.7

In order to develop the ART-IGS system for clinical implementation we performed a preclinical cadaver trial to collect additional end-user open feedback. Comments on visual display, alarms, and ergonomics were among the topics included for analysis. We hypothesized that using this system would decrease task workload during ESS by providing visual cues to aid spatial awareness and alarms to indicate proximity to critical structures. A trial comparing ART-IGS to conventional ESS was performed to investigate this hypothesis.

**Materials and Methods**

Institutional ethics board approval was gained for a cadaver dissection study investigating the new technology.

Eight otolaryngology residents (postgraduate year 3 [PGY 3] and above) and fellows performed ESS with ART-IGS, as well as in a conventional manner, on cadavers. They were randomized as to which side and which condition they started first.

Prior to dissection, fiduciary markers were attached and each specimen underwent CT scanning. Manual segmentation of important anatomical structures on the scan was then undertaken using ITK-SNAP 2.0 software. Structures contoured included the carotid arteries, optic nerves, pituitary, dura, periorbita, and pterygopalatine fossa. Proximity alert zones of 2 to 4 mm were manually added around critical structures including the periorbita, dura, and carotid arteries (Fig. 1). A real-time 3D virtual view was then created with custom visualization software after registration of the head and a 0-degree endoscope (Hopkins II telescope and IMAGE1 camera; Karl Storz, Tuttlingen, Germany) to an optical IGS system (Polaris; NDI, Waterloo, ON, Canada) with typical registration errors of 1 to 2 mm.

A 4-mm sinus microdebrider (Medtronic, Jacksonville, FL) was tracked in the same fashion and alarms were provided when the tip of the instrument entered a proximity alert zone. A large parallel submonitor provided dynamic navigational assistance by displaying a virtual endoscopic view and the traditional triplanar CT (Fig. 2).

Each subject performed an uncinectomy, middle meatal antrostomy, ethmoidectomy, and sphenoidotomy on each side. Task workload was assessed using a pencil and paper version of the National Aeronautics and Space Administration Task Load Index (NASA-TLX) midway through the dissection (posterior ethmoid dissection) and at the completion of each side. This was followed by a semistructured qualitative interview in which open feedback was encouraged. In addition, some more focused questions on visualization, alerts, and ergonomics were asked. Subjects then completed a 7-point Likert scale questionnaire pertaining to various aspects of the technology (Table 1.)
Augmented image-guidance for sinus surgery

Statistical analysis
Paired NASA-TLX data was analyzed using the Wilcoxon signed rank test with $p < 0.05$ deemed significant. Median (interquartile range [IQR]) values were calculated for Likert questionnaire responses.

Results
Likert questionnaire
Level of agreement with the statements is shown in Table 1. Most subjects agreed with the statements; however, 3 of 8 participants (subjects 1, 3, and 4) did not agree the system was ready for trial. The last 4 subjects, who trialed the system after some feedback-directed changes to the system, all responded more favorably. Most subjects felt they were faster and the system was sufficiently accurate but this was not universal.

Task workload
There was a significant reduction in all NASA-TLX subscales excluding physical demand ($p = 0.38$) (Table 2). There was a significant reduction in mean (standard deviation [SD]) mental demand from 8.5 (4.4) during conventional surgery to 7.0 (3.9) with ART-IGS ($p = 0.007$). Mean (SD) effort was reduced from 8.6 (3.4) down to 5.1 (3.1) with ART-IGS ($p < 0.001$). Similar decreases in workload were seen for temporal demand and frustration while perceived performance was increased with ART-IGS ($p = 0.02$).

Qualitative interview responses
Line-of-sight
Line-of-sight issues with optical tracking were overwhelmingly the most reported dislike or limitation. Three of the first 4 participants believed the technology was not ready for clinical trial and they all cited line-of-sight problems as the principal reason. Reference markers on the head and the endoscope were adjusted to a more oblique angle and this resulted in the remaining 4 participants agreeing that a clinical trial was feasible and resulted in far fewer comments on tracking limitations. Optical tracking was lost when participants rotated the instrument too far and this concerned some participants who adjusted the ablative surface of the microdebrider by turning their wrist. The 3D virtual view and the alarms did not work when reference markers were out of sight and concern in regard to this issue was voiced.

TABLE 1. Results of 7-point Likert scale questionnaire pertaining to various aspects of the technology

<table>
<thead>
<tr>
<th>Results</th>
<th>Subjects who disagreed (0–3), (n)</th>
<th>Subjects who were neutral (4), (n)</th>
<th>Subjects who agreed (5–7), (n)</th>
<th>Median (IQR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statement a: I felt it was faster to perform surgery when aided by the virtual view</td>
<td>2</td>
<td>1</td>
<td>5</td>
<td>5 (3.75–6)</td>
</tr>
<tr>
<td>Statement b: The system appeared to be sufficiently accurate for its intended use</td>
<td>2</td>
<td>0</td>
<td>6</td>
<td>6 (4.5–7)</td>
</tr>
<tr>
<td>Statement c: Dynamic tool tracking allowed me to quickly assess my proximity to critical structures without significantly interrupting dissection</td>
<td>0</td>
<td>2</td>
<td>6</td>
<td>5.5 (4.75–6)</td>
</tr>
<tr>
<td>Statement d: Proximity alerts increased my confidence during ablation close to critical structures</td>
<td>0</td>
<td>2</td>
<td>6</td>
<td>5.5 (4.75–6)</td>
</tr>
<tr>
<td>Statement e: The current technology is ready for clinical trial without significant changes</td>
<td>3</td>
<td>0</td>
<td>5</td>
<td>5 (2.75–5.5)</td>
</tr>
</tbody>
</table>

*Postdissection questionnaire statements: 7 = strongly agree, 1 = strongly disagree.
IQR = interquartile range.
Auditory alerts were used to inform the surgeon when optical markers were not visible by the IGS camera.

**Visual display**

All participants were generally impressed by the navigation system display, remarking that it was near real-time and intuitive. The 3D virtual endoscopic view was preferred over the triplanar image guidance by most. However, 2 subjects mainly used the cross-sectional images. The main limitation with the virtual view, as seen in Figure 3, was the surface mesh, which was described as “busy” and at times “confusing.” Many subjects thought the surface rendering provided too much unnecessary information and suggested altering the mesh to decrease noise. All agreed that the virtual view correlated well with the endoscopic view. It was suggested that the visualization options for surface and anatomical contours should be customized on a case-specific basis, taking into account the desired ablation and potential hazards.

**Tool tracking/auditory alerts**

Tracking the ablative tool allowed navigational assistance without having to change instruments and minimized interruption. Alert zones of around 2 mm were thought to be appropriate. Auditory alerts were the preferred feedback, with most suggesting that visual or tactile alarms would be too distracting. Many participants thought customizing alarms during dissection would be helpful such that alert zones could be reduced or removed after successful identification of the critical anatomy.

**Potential advantages/time**

Most subjects did not feel that the technology significantly saved them time during their initial experience on a cadaver specimen. They did, however, believe that in real cases the technology would increase their confidence and save them time. Many stated that they would perform “more complete” surgery with ART-IGS, particularly around the skull base and especially in “difficult cases,” “around critical structures,” and during “polyposis or tumor cases.”

**Discussion**

Task workload was reduced when using the augmented, real-time IGS system. Despite an explosion of technological advances aimed at safer, easier, and more efficient surgery, operative task workload is still relatively poorly explored. Increased workload has been associated with inferior task performance and higher procedural error rates. Our results suggest that providing live navigational data that can be rapidly and intuitively referenced by the operating surgeon may decrease the cognitive demand required for orientation. Greater spatial awareness could then result in more confident tissue ablation while safely avoiding critical structures.

The use of virtual reality to aid in surgical training is being heavily pursued and is rapidly evolving. It is predicted to make a huge impact on surgical training in the near future and has been shown to improve performance for many skills including temporal bone dissection and laparoscopic tasks. Virtual views have been designed to perceptually match a real model in terms of spatial cues and anatomical relationships. Anatomy that is normally hidden behind tissue can be easily displayed in a virtual view by reducing the

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**TABLE 2. Comparative NASA-TLX scores**

<table>
<thead>
<tr>
<th>NASA-TLX subscale</th>
<th>Conventional, mean (SD)</th>
<th>ART-IGS, mean (SD)</th>
<th>Significance Wilcoxon signed rank test, p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mental demand</td>
<td>8.5 (4.4)</td>
<td>7.0 (3.9)</td>
<td>0.007&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Physical demand</td>
<td>5 (2.4)</td>
<td>4.4 (2.2)</td>
<td>0.38</td>
</tr>
<tr>
<td>Temporal demand</td>
<td>4.6 (2.6)</td>
<td>3.3 (2.2)</td>
<td>0.02&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Performance</td>
<td>6.9 (3.9)</td>
<td>4.8 (2.9)</td>
<td>0.02&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Effort</td>
<td>8.6 (3.4)</td>
<td>5.1 (3.1)</td>
<td>&lt;0.001&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Frustration</td>
<td>7.4 (3.8)</td>
<td>3.6 (2.3)</td>
<td>0.005&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup>Significant improvement with ART-IGS (p < 0.05, Wilcoxon signed rank test).

NASA-TLX = National Aeronautics and Space Administration Task Load Index; SD = standard deviation; ART-IGS = augmented, real-time image-guided surgery.

Auditory alerts were used to inform the surgeon when optical markers were not visible by the IGS camera. The visual display was generally impressed by the navigation system display, remarking that it was near real-time and intuitive. The 3D virtual endoscopic view was preferred over the triplanar image guidance by most. However, 2 subjects mainly used the cross-sectional images. The main limitation with the virtual view, as seen in Figure 3, was the surface mesh, which was described as “busy” and at times “confusing.” Many subjects thought the surface rendering provided too much unnecessary information and suggested altering the mesh to decrease noise. All agreed that the virtual view correlated well with the endoscopic view. It was suggested that the visualization options for surface and anatomical contours should be customized on a case-specific basis, taking into account the desired ablation and potential hazards.

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opacity of surface renderings and highlighting important structures. If such a feature is useful for surgical training in a laboratory, it seems logical that displaying it in the operating room (OR) may also be of benefit. By basing the virtual view on the patient’s CT scan and registering with an IGS system we have been able to provide this feature and we believe that, if safely integrated, it will be an excellent training aid in the OR.

In addition to precise registration, accurate anatomical segmentation is required in order for critical structures to be safely displayed. We performed manual contouring of preoperative CT scans, which is labor-intensive. Although this is 1 barrier to adoption of this technology, we believe that this process may also be a valuable training opportunity. By personally outlining the critical structures on the images and adding personalized alert zones, each surgical trainee will quickly gain a greater understanding of the anatomical relationships and boundaries of the operative field. If a trainee was to perform this exercise for their first 10 ESS procedures and have the data available during the procedure, we foresee a more rapid and thorough appreciation of the 3D relationships encountered. This process would certainly need to be overseen by an experienced surgeon because compounding contouring and registration error may cause miscuing of data and potentially result in disaster. Ongoing research into semiautomatic segmentation of anatomical structures may assist in providing a more efficient and reproducible process to reduce the demands on the surgeon. Given the limited number of participants, we were unable to analyze the data after stratification according to experience level. Despite this, we did observe that although absolute measures of workload were reduced in the more experienced subjects, the relative reduction in workload with ART-IGS remained similar.

Current use of IGS systems is usually intermittent and often requires changing instruments to insert a conventional tracked pointer. Many of our subjects commented on the potential advantages of having the ablative tool tracked in real-time and thus being able to quickly glimpse at the virtual view to confirm their surgical instrument position. Encountering bleeding during posterior ethmoid polypectomy was 1 example given. Many surgeons, particularly those training, find it difficult to get a sense of their proximity to the orbit, skull base, or sphenoid in this situation. If they need to change instruments the field may be obscured by blood. This may have to be repeated multiple times, which slows progress. Live tracking not only allows faster navigational assistance but also can provide alerts when a critical structure is near, leading to more efficient progress by blood. This may have to be repeated multiple times, which slows progress. Live tracking not only allows faster navigational assistance but also can provide alerts when a critical structure is near, leading to more efficient progress through difficult parts of the procedure. We elected to compare the ART-IGS system to standard ESS (without IGS) as this is the standard of care in our institution for routine sinus surgery. Further investigation into the potential benefits of 3D visualization and auditory feedback over conventional IGS is required, especially given the expanding range of instruments that can tracked with commercial systems.

Adjustment of reference marker positions was the most noticeable improvement made to the system during testing. It is essential for the optical reflectors on the endoscope, the head, and the instrument to be in the field of view of the IGS camera for the system to work correctly. It is of particular importance if proximity alerts are expected but not enabled because of a line-of-sight problem. Moving the markers such that they obliquely face the opposite side to the surgeon largely eliminated the line-of-sight issue. This is evidenced by the more favorable responses from the final 4 subjects. Despite these changes, reference markers did occasionally obstruct or interfere with each other. Further offsetting the markers may help to some degree, but this is likely to remain an issue when access is restricted to 1 side of the nose. Pronating the wrist to alter the direction of the ablative surface of the microdebrider was frequently associated with loss of tracking and this problem with “roll” movement is the most difficult to overcome. Electromagnetic tracking may provide 1 potential solution to this problem; however, this method may introduce other issues that may need to be addressed in a clinical setting.

In order to conceptualize the relative position of the critical structure contours, a representation of the surface landmarks seen on the endoscopic view must be present on the virtual view. This was provided by a mesh generated from the preoperative CT scan. As the surface area of the sinuses is large, the framework created was quite busy as it tried to accurately represent all mucosal surfaces. Subjects were a little confused and distracted by this, especially given multiple layers of mesh might be seen between the endoscope and a critical structure not far away, such as the orbit. This occurred even if the surfaces and cells in this area had been removed, because the mesh was not updated according to ablation. Further investigation into overcoming this problem is required and potential solutions include digitally erasing (either manually or automatically) ablated tissue from the virtual view, removing a segment of the nasal anatomy from being represented, decreasing the mesh density, or updating the surface anatomy with intraoperative imaging. We acknowledge that in order to make the system truly “real-time” we need to account for tissue deformation and ablation in the virtual view.

Practical restrictions, including a limited supply of skilled subjects, lack of time for prior experience with the system, and material resources, prevented us from being able to fully evaluate the system in a quantifiable manner. Providing concrete experimental evidence of safer or more efficient surgery using a realistic model is difficult. Critical complications during sinus surgery are relatively rare; thus, the numbers required to prove any safety advantage are too large to practically investigate. Similarly, given each subject had not previously used the system, efficiency was difficult to measure. We soon realized each subject would spend considerable time “playing” with the new system and thus strictly timing the procedure was not going to provide any meaningful assessment of potential time-savings the technology may bring. Task workload was able to be assessed and thus...
we focused on this area to provide some quantitative measure of the performance of our system. Although workload scores reduced significantly in a statistical sense, we are unsure at this stage if this would impact clinical practice and outcomes. Qualitative feedback was extremely helpful in identifying shortfalls of the system and directing improvements. Registration accuracy was maintained throughout the experiments; however, problems with robustness of the IGS tracking and computer processing were found. These issues may not have surfaced without rigorous and practical preclinical testing.

Advanced navigational displays, such as the ART-IGS system we have developed, show great promise as educational tools while potentially making procedures safer, more efficient, and less demanding even for experienced surgeons. The degree of benefit is likely to depend on the experience of the surgeon and the difficulty of the dissection. Further investigation into potential detrimental effects of this technology are required, including the consequences of misusing data through registration or contouring error, as well as issues surrounding reliance, trust, complacency, and attention shifts. Given this, we believe initial clinical trials should be performed in academic centers with surgeons who are very familiar with IGS systems. With careful integration we see these new modes of navigational feedback becoming a valuable adjunct during ESS education and practice.

Conclusion

ART-IGS reduces task workload for trainees performing ESS on cadavers. Live navigation and alert zones may be a valuable intraoperative teaching aid. Further investigation should focus on potential applications for experienced surgeons, display upgrades to account for tissue ablation, and ways to reduce the potential distraction.

Acknowledgments

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References