INTRODUCTION

There have been tremendous advances in information technology over the last decade through improved computer processing speeds and novel user interface systems. The data available from state of the art imaging offers a wealth of potential information to the operating surgeon. Image-guided surgery (IGS) systems are now commonly used in skull base surgery; however, the interface is often poor and the detailed information provided does not aid the surgeon dynamically during ablation.

Accurate co-registration of imaging data to an actual endoscopic view allows virtual views that can move in unison with the endoscope when an IGS system is used. By contouring structures on preoperative imaging, specific anatomical detail can be made available to the operating surgeon through wall down virtual views. These concepts are not new, and these applications have long been recognized as excellent teaching aids.

The integration of this technology into the operating room has been met with numerous difficulties and expert criticism. Computer processing improvements and software development now allow these features to be used in real time, enhancing the clinical potential.

The skull base is a complex three-dimensional (3D) structure close to critical structures such as the eye, brain, and carotid arteries where precise orientation is required. Novice surgeons often have trouble navigating in this area with potentially disastrous effects. Even experienced surgeons can find it stressful dissecting close to critical structures. The task workload on the surgeon is rarely examined in surgical literature when assessing new procedures and technology. Evidence suggests that workload during a procedure has an inverse relationship with surgical performance.

We hypothesize that workload could be reduced by clearly and accurately...
displaying the critical anatomy in real time during difficult endoscopic skull base procedures.

The Guided Therapeutics group at the University Health Network, Toronto, has developed an augmented IGS system that incorporates intraoperative cone-beam computed tomography (CBCT), virtual or augmented displays, and image registration.8–10 In this preclinical cadaver study we aimed to assess the accuracy of otolaryngology residents and fellows in identifying certain anterior skull base and sinonasal structures with endoscopy alone and then with augmented endoscopy. This augmented view included a traditional tri-planer IGS as well as a real-time virtual view coregistered to a postablation CBCT scan with anatomical contours highlighting important structures (Fig. 1a and 1b). We also assessed whether the subjects felt they were more accurate and/or more confident with the added technology. We also aimed to assess the task workload with and without the technology.

MATERIALS AND METHODS

Augmented IGS System

A single cadaver head underwent predissection scanning with conventional multidetector computed tomography (MDCT). Multiple fiduciary markers were fixed to bone prior to imaging. The MDCT images were used for anatomical contouring using ITK-Snap (www.itksnap.org). An overview of the system, including a list of structures contoured, is shown in Figure 1c. Extensive endoscopic dissection was then undertaken with near total ethmoidectomy, wide middle meatal antrostomy, wide sphenoidotomy, and posterior septectomy. After dissection, postablation CBCT images were acquired using a prototype mobile C-arm for intraoperative 3D imaging.8 Deformable registration of the contoured, predissection MDCT data to the postdissection CBCT was performed allowing the contours to be accurately superimposed onto postablation imaging. This was designed to match the clinical process we envisioned, in which contour segmentation would be performed prior to surgery and registered forward into intraoperative scans to avoid the need for direct contouring on intraoperative images.

A registration marker was attached to the head for the IGS. The implanted fiducials were used to calculate fiducial registration error, which was consistently shown to be in the order of 1 mm. The endoscope was tracked by the IGS, and a real-time virtual view was created based on imaging data and relative endoscope tip position. Contour data was then imported and displayed in a wall down mesh as displayed in Figure 1d. This process has previously been described by our group.9

Localization and Workload Study

Twelve subjects (six otolaryngology fellows and six otolaryngology residents) were enrolled in the study after institutional ethics review board approval and informed consent was obtained. The study was divided into two stages. In each stage the subject was asked to identify seven sinonasal landmarks. Each subject was first given time (up to 2 minutes) to examine the

Fig. 1. (a) Image-guided surgery system used for preclinical study, including optical tracking system Northern Digital Inc. (NDI) Polaris; Waterloo, Ontario, Canada), tracked endoscope and pointer, and custom three-dimensional visualization software. (b) Real endoscopic view of cadaveric anterior skull base region. (c) Surgical contours of critical anatomical structures in intraoperative cone-beam computer tomography (CT) image. (d) Real-time endoscope tracking and endoscopy-CT registration enables wall down perspective views of contoured structures aligned with real endoscopic view.
preoperative computed tomography (CT) scan. During stage 1, the participant was asked to localize each landmark to the best of their ability using conventional endoscopy alone (Karl Storz Hopkins II 0° telescope and IMAGE1 camera; Karl Storz, Tuttingen, Germany). Landmark localization was achieved using a tracked probe to record precise 3D coordinates. In stage 1 the subject could not see the virtual view, tracked probe, or the IGS screen. Subjects then completed the pencil and paper version of the NASA task load index (NASA-TLX).11

The same exercise was performed in stage 2; however, on this occasion each subject was provided with triplanar image guidance and a virtual view with visible anatomical contours in addition to conventional endoscopy (Fig. 1a). The probe positions for each landmark were again recorded. No time limits were placed on either stage. After the exercise the participant again completed the NASA-TLX assessment and a short questionnaire asking whether the additional IGS technology aided and/or increased confidence in locating each landmark (Table I). Questionnaire responses were placed on a seven-point Likert scale with 7 = strongly agree and 1 = strongly disagree.

### Statistical Analysis

Paired, nonparametric data comparing stage 1 and 2 NASA-TLX scores were analyzed using the Wilcoxon signed rank test, with P < .05 deemed significant. The mean and standard deviation (SD) were calculated for questionnaire responses, with percentage of respondents who agree (seven-point Likert scale score 5 or greater) with statement A and B also displayed.

The localized anatomical points were used to compute the 3D mean and SD across all subjects. The 3D standard deviation was the quadrature sum of the SDs computed along the three coordinate axes. The effect of augmented endoscopy on navigation precision was evaluated at each anatomical site by comparing the 3D standard deviations from stage 1 and stage 2.

### RESULTS

#### 3D Localization Precision

The 3D standard deviation in localized position was reduced by factors ranging from 1.9 (right optic nerve) to 8.9 (vidian nerve). Figure 2 graphically depicts the reduction in response variability across the cohort of residents for the case of the left carotid artery landmark. As shown in Figure 3, navigation precision across subjects improved for all anatomical landmarks with the addition of augmented endoscopy (stage 2).

#### Surgical Assistance and Confidence Questionnaire

The subjects agreed (response 5 or greater) that the augmented endoscopy displayed in stage 2 aided the localization (statement A) of anatomical structures on 51 of 60 occasions (85%). The response was most positive for the vidian nerve, carotid artery, and optic nerve with 11/12 (92%) agreeing. The mean (SD) overall rating was 5.75 (1.33).

The positive response was even greater when confidence in localization (statement B) was assessed with an overall mean response of 6.35 (SD 0.99) and 58/60

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**TABLE I.** Each Landmark Identified Was Graded for Both Statements on a Seven-Point Likert Scale

<table>
<thead>
<tr>
<th>Statement A</th>
<th>Statement B</th>
</tr>
</thead>
<tbody>
<tr>
<td>The 3D virtual view aided in identifying the following structures.</td>
<td>I was more confident in my localization with the 3D virtual view.</td>
</tr>
</tbody>
</table>

*7 = strongly agree; 1 = strongly disagree.
3D = three-dimensional.

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![Fig. 2. Localized three-dimensional (3D) positions for the right carotid artery using (a) endoscopy alone and (b) augmented endoscopy. (c, d) Subject response variability is graphically represented using an ellipsoid centered at the 3D mean with principal axes lengths of 2 standard deviations in each direction. (e) Direct overlay of the ellipsoids for endoscopy alone and augmented endoscopy illustrates a factor of 3 reduction in the 3D standard deviation.]
responses in agreement (97%). There was 100% agreement that the augmented endoscopy increased confidence in identification of the vidian nerve, carotid artery, and optic nerve (Table II).

**NASA-TLX Workload Assessment**

NASA-TLX response scores displayed a highly significant reduction in workload in four of the six subscales (mental demand, performance, effort, and frustration) (Table III). Mental demand was reduced from a mean score of 7.96 (SD 4.38) to 4.58 (SD 3.60) with the addition of augmented endoscopy ($P = .006^*$). There was a >50% mean reduction in workload for effort ($P = .004$) and frustration ($P = .003$), whereas perceived performance was also improved ($P = .025$). There was no statistically significant difference in physical demand or temporal demand (Fig. 4).

**DISCUSSION**

The need for accuracy in skull base surgery is absolute. Serious complications such as orbital injury, blindness, cerebrospinal fluid leak, and intracranial hemorrhage result from surgical misadventure in this region. Sound anatomical knowledge is required for dissection at the skull base, but when orientation is difficult and issues such as bleeding, anatomical variations, and tumor distortion occur, confidence can plummet and operative progress can slow considerably. This is especially a problem with endoscopic approaches, as a clear orientated view is essential. Progress may be slowed unnecessarily when one is convinced they may be closer to a critical structure when in fact they are safely clear. In this situation, precise real-time image guidance could potentially help a surgeon continue ablation confident that they are safe and reduce operating time and stress.

It stands to reason that precise, precontoured navigational assistance increases accuracy in a subgroup with limited experience and knowledge. However, in addition to this, the current study has also shown that operator confidence is significantly increased with a decline in workload when aided by augmented image guidance. These aspects are frequently overlooked in surgical skills teaching, assessment of new technology, and procedures and in the operating room. A recent study

TABLE III.
Mean Scores for Endoscopic Navigation With Endoscopy Alone and Augmented Endoscopy.

<table>
<thead>
<tr>
<th>NASA-TLX Domain</th>
<th>Endoscopy Alone, Mean (SD)</th>
<th>Augmented Endoscopy, Mean (SD)</th>
<th>Ratio</th>
<th>$P$ Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mental demand</td>
<td>7.96 (4.38)</td>
<td>4.58 (3.60)</td>
<td>0.58</td>
<td>.006*</td>
</tr>
<tr>
<td>Physical demand</td>
<td>4.67 (2.90)</td>
<td>4.13 (3.13)</td>
<td>0.88</td>
<td>.461</td>
</tr>
<tr>
<td>Temporal demand</td>
<td>5.29 (3.56)</td>
<td>4.67 (3.66)</td>
<td>0.88</td>
<td>.758</td>
</tr>
<tr>
<td>Performance</td>
<td>10.12 (3.22)</td>
<td>6.46 (5.85)</td>
<td>0.63</td>
<td>.025*</td>
</tr>
<tr>
<td>Effort</td>
<td>9.08 (4.54)</td>
<td>3.67 (2.06)</td>
<td>0.40</td>
<td>.004*</td>
</tr>
<tr>
<td>Frustration</td>
<td>7.67 (3.66)</td>
<td>3.38 (2.88)</td>
<td>0.44</td>
<td>.003*</td>
</tr>
</tbody>
</table>

*$P$ values derived from Wilcoxon signed-rank test for paired, non-parametric data with significant results ($<.05$).

NASA-TLX = NASA task load index; SD = standard deviation.
on laparoscopic surgical performance showed that performance was lower when there was a higher mental workload. They postulated there may be a detrimental impact of increased workload, not only on performance but also on safety. This does not account for the possibility that one may report a higher workload when they perceive they are performing poorly, and thus the performance affects the workload rather than vice versa. Performance errors may increase when a task is mentally demanding, as attention may be fixed on a certain task decreasing the capacity to deal with unexpected events. Strategies employed to reduce workload and fatigue have been shown to increase performance without prolonging surgical time.

Subjects reported decreased mental demand, effort, and frustration when using the augmented endoscopic view. These parameters have been poorly explored in surgical literature, and the significance of task workload has probably been under-rated in the past. Integration of key technology and an efficient ergonomic interface with the surgeon is a crucial area of development as less invasive minimal access surgery continues to expand.

Although the evidence for increased accuracy and reduced workloads in this study is compelling, it must be kept in mind that the sample size was small (12 subjects) and only one cadaver head was used for navigation. Additionally, the protocol could only be practically performed if the augmented navigation followed the conventional. It is possible that part of the reduced workload might be due to a test-retest phenomenon rather than the impact of the technology. This system does not replace sound anatomical knowledge or the need for surgeons to be able to conceptualize 3D anatomy based on cross-sectional imaging. Although we believe that navigation may be more efficient and intuitive with augmented endoscopy, standard triplanar IGS systems may provide equally precise assistance, and further comparison between these modalities is warranted.

Experienced surgeons were used to define gold standard zones for data analysis but were not formally tested. The landmarks tested were easily accessible, and the view of the carotid arteries, optic nerves, and the pituitary fossa was excellent with endoscopy alone. Given this, we predict that an experienced surgeon used to operating in this area would not find the technology to be of any benefit during this exercise. Further investigation is required to see if during more advanced ablative procedures these applications may be of use to expert skull base surgeons. Factors such as tumor, bleeding, or anatomical variations can make navigation more difficult and slow operative progress, and it is in this setting that we foresee this technology being used clinically.

CONCLUSION
Augmented endoscopy, including virtual views and critical structure contouring, is an exciting development that has the capacity to increase accuracy and safety while reducing operator workload. Further investigation is required to assess its utility for advanced ablation by skull base surgeons. This may support the introduction of such technology into the operating room. Research should also include development of the optimal user interface with consideration of distraction and other potentially detrimental effects.

Acknowledgments
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BIBLIOGRAPHY