Intraoperative surgical navigation for endoscopic sinus surgery: rationale and indications

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Purpose of review
The present review discusses the rationale and indications for image-guided surgery through a critical discussion of registration concepts as well as clinical reports.

Recent findings
The surgical navigation accuracy achieved by commercially available image-guided surgery systems is best reported as target registration error. Clinically achievable target registration error is probably in the 1.5–2.0 mm range. Dry lab studies of registration serve to highlight the principles of registration, the process through which image-guided surgery systems calculate the one-to-one mapping relationship between the preoperative imaging data and the intraoperative surgical volume. Reports on image-guided surgery have highlighted its usefulness in primary and revision endoscopic sinus surgery, osteoplastic frontal sinusotomy, transsphenoidal hypophysectomy, endoscopic cerebrospinal fluid leak repair and endoscopic pterygomaxillary fossa biopsy. Both three-dimensional computed tomography angiography and computed tomography–magnetic resonance fusion images have been incorporated into IGS for advanced minimally invasive endoscopic skull base procedures. The American Academy of Otolaryngology–Head and Neck Surgery policy statement accurately summarizes the current consensus for image-guided surgery applications.

Summary
Image-guided surgery has emerged as an important technology, which both general otolaryngologists and subspecialty rhinologists can employ for a wide variety of procedures.

Keywords
computer-aided surgery, endoscopic sinus surgery, endoscopic skull base surgery, image-guided surgery, surgical navigation, target registration error

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Abbreviations

3DCTA	three-dimensional computed tomography angiography
CBR	contour-based registration
CSF	cerebrospinal fluid
CT	computed tomography
ICA	internal carotid artery
IGS	image-guided surgery
MR	magnetic resonance
PPR	paired-point registration
TRE	target registration error

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Introduction

Over the past decade, sinus surgeons have accepted intraoperative surgical navigation (also known as image-guided surgery, or IGS) as a technological means to improve surgical outcomes and reduce surgical morbidity. Initial applications were primary and revision functional endoscopic sinus surgery, but more recently rhinologists have used surgical navigation for a wide variety of minimally invasive endoscopic approaches to the anterior and middle cranial fossa skull base. Although the core technology has not changed meaningfully since its introduction, clinical experiences have grown considerably, and a few new applications [such as computed tomography–magnetic resonance (CT-MR) fusion] have been introduced. In addition, a few reports have highlighted the principles of registration protocols, the initial step that supports all surgical navigation.

Limitations of endoscopic visualization

Within the specialty of otorhinolaryngology, rhinologists were the first to express meaningful interest in IGS for a variety of reasons. Mosher [1], who widely reported on ethmoidectomy in the preendoscopic era, described a variety of measurements within the paranasal sinuses; in many ways, these efforts represent a primitive form of surgical navigation. Paranasal sinus surgery languished until the mid-1980s, when surgical nasal endoscopy was introduced. In the early endoscopic era, the rate of major complications was approximately 0–8%, and the steep learning curve was widely acknowledged [2–4]. The technical challenges of endoscopic sinus surgery reflect a variety of issues (including anatomic complexity); it is important not to discount the intrinsic limitations of surgical nasal endoscopy. Although the telescopes provide bright illumination and brilliant images, the view provided by the telescopes is only a two-dimensional representation of a complex three-dimensional space. Furthermore, the telescopes provide a wide-angle perspective, which intrinsically introduces a fish-eye effect (analogous to spherical aberration). The potential for perceptual distortion and secondary surgical error during these procedures is considerable. Thus, surgical rhinologists were very interested in intraoperative surgical navigation, as it was felt that this technology should reduce surgical complications and fit well with endoscopic techniques.

Registration error theory and applications

Registration is the process of aligning corresponding fiducial points in the preoperative imaging data set and the intraoperative surgical field volume. Before surgical navigation can commence, the IGS system must calculate this mapping relationship between the image space and the physical space. The intrinsic properties of the registration process, regardless of the specific registration protocol, carry limitations affecting surgical navigation accuracy.

Target registration error (TRE) is the best estimate of navigational accuracy, as it alone addresses the relationship between the instrument tip and its measured position [5••,6••]. Although anecdotal reports suggest submillimetric TRE for commercially available IGS systems, more rigorous analyses suggest that TRE is within the 1.5–2.0 mm range (Table 1) [7,8•,9–12]. Many publications describe IGS applications; however, relatively few publications present TRE data. Furthermore, when TRE data are presented, they tend to be specific for a specific IGS platform and registration protocol. In actuality, the principles that guide registration should be considered independent of the IGS hardware; thus, publications have increasingly focused on registration concepts, rather than devices for registration.

Recent publications have used dry lab models to demonstrate the limitations of registration and surgical navigation. Berry *et al.* [13] have explored the relationships between fiducial placements and surgical navigation target accuracy for a variety of skull base targets in a dry lab model for registration with external fiducial markers. The authors concluded that appropriate selection of fiducial location has a direct impact on measured surgical navigation accuracy. More recently, Knott *et al.* [8•] presented a dry lab model for registration in which they compared paired-point registration (PPR) and contour-based registration (CBR) protocols. They noted that TRE for PPR was significantly less than the corresponding TRE for the best CBR (0.5 mm vs. 1.5 mm at the anterior ethmoid target, $P < 0.0001$ and 0.8 mm. vs. 1.5 mm at the sphenoid face target, $P < 0.0001$). In a series of statistical comparisons examining the relationships between numbers of fiducial points used for CBR and TRE, the authors concluded that CBR with 125 points (and perhaps as few as 50 points) yields clinically acceptable TRE values. In an earlier publication, Knott *et al.* [14] calculated theoretical TRE for fiducial-bearing headsets and concluded that because theoretical TRE was much less than clinically observed TRE for headset-based registration, other factors, including errors in repositioning the headset, account for much of the inaccuracy observed during surgical navigation after headset-based registration.

Published comparisons among registration protocols for a specific IGS platform are rare. Hardy *et al.* [15•] compared registration accuracy for registrations performed with external fiducial markers, anatomic fiducial points and surface contours in a series of ten cadaveric specimens. Registration with external fiducial markers and with surface contours produced similar TRE values, but registration with external fiducial markers yielded a statistically smaller TRE in comparison with the TRE produced by registration with anatomic fiducial points. Registration with surface contours was deemed more accurate than registration with anatomic fiducial points at the surgical targets of middle turbinate, posterior maxillary wall and carotid artery, but not at the sella tursica and optic nerve.

Clinical impact of IGS

Intuitively, IGS should improve surgical outcomes. Numerous reports have presented case series in which

Table 1 Reported target registration error for commercially available image-guided surgery platforms

System (vendor)	Tracking system	Registration type	Reported accuracy
InstaTrak, (GE Navigation & Visualization, Lawrence, MA)	Electromagnetic	Automatic	2.28 mm (95% CI 2.02–2.53) [7]
		PPR	1.97 mm (95% CI 1.75–2.23) [7]
		CBR with touch	1.5 ± 0.3 mm (laboratory model) [8•]
LandMarx, (Medtronic Xomed, Jacksonville, FL)	Optical	Automatic	N/A
		PPR	1.69 ± 0.38 mm [9]
		CBR	No report
Stryker Navigation System, (Stryker-Leibinger, Kalamazoo, MI)	Optical	Automatic	N/A
		PPR	1.6 mm (range 0.6–3.7) [10]
		CBR ('Mask')	No report
VectorVision, (BrainLAB, Hemstetten, Germany)	Optical	Automatic	No report
		PPR	1.57 ± 1.1 mm [11]
		CBR with laser	2.4 ± 1.7 mm [12]

Adapted from Knott, *et al.* [6••]. CBR, contour-based registration; N/A, registration protocol not available for the specific system; PPR, paired-point registration.

the surgeons deemed IGS helpful. In fact, only one report has shown a statistically significant benefit for IGS. Fried *et al.* [16] confirmed a lower major complication rate for sinus surgery incorporating IGS. Although numerous rhinologists have suggested the need for a prospective clinical trial of IGS, both logistical and ethical issues probably constitute insurmountable obstacles for initiating such a project.

In an attempt to evaluate the clinical impact of IGS, Strauss *et al.* [17••] proposed a rather complex, but nonetheless informative methodology for quantifying the clinical impact of IGS during surgery. They developed a level of quality index that compared the available information before and after IGS application, and they measured change of surgical strategy as a result of IGS application. Their data confirm that IGS provides additional relevant information. Information provided by the IGS system was deemed 'detrimental' in only three out of 792 IGS applications, and even in these instances, no adverse outcomes were noted. In addition, 47.9% of IGS applications yielded a change of surgical strategy. Less experienced surgeons adjusted their strategies more frequently as a result of IGS, and IGS was more commonly associated with adjustments in surgical strategy among endoscopic biopsies and tumor resection cases.

Clinical reports

In this section, recent reports on the clinical applications of IGS are presented. It should be noted that this summary is not exhaustive, as it excludes many older publications that are still relevant today.

Primary and revision endoscopic sinus surgery

Metson [18] reported on the first 1000 image-guided sinus surgery cases performed by 42 surgeons at an academic medical center. IGS utilization, as measured by the numbers of cases and surgeons, dramatically increased during the initial 2 years of the technology's availability. It was felt that the technology enhanced anatomic localization during sinonasal procedures with the potential for improved surgical efficacy and safety. Tabaee *et al.* [19] reported on the utility of IGS in a cohort of 120 patients over a 5-year period. Indications included revision surgery (85 patients), sphenoid sinus disease (12 patients), isolated frontal sinus disease (four patients) and cerebrospinal fluid (CSF) leak repair (seven patients). No major complications were reported, although 15 (16.5%) patients required revision surgery. The rationale for use of IGS was the loss of surgical landmarks from previous surgery or disease processes (including nasal polyposis, mucocele, fungal disease and CSF leak).

Osteoplastic frontal sinusotomy

Although endoscopic techniques are the preferred modality for surgical approaches to the frontal sinus and frontal recess, osteoplastic frontal sinusotomy may still be required in selected cases. Traditionally, a 6-ft plain sinus X-ray has been used as a template to outline the boundaries of the frontal sinus. Admittedly, this technique is imprecise, and it carries the risk for entry into the anterior cranial fossa with consequent intracranial injury. IGS may allow for more accurate delineation of the frontal osteoplastic flap and allow for safer entry into the frontal sinus. Melroy *et al.* [20] compared the extent of the frontal sinus for osteoplastic flap surgery using transillumination, 6-ft Caldwell films, and IGS in ten human cadaveric heads. They noted that IGS generated the smallest difference between measurements and actual values and was statistically superior to Caldwell films and transillumination. Innis *et al.* [21] reported on three cases of image-guided osteoplastic frontal sinusotomy and noted that an infrared image guidance system allowed for accurate placement of the osteoplastic flap for management of frontal sinus osteomas (two cases) and recurrent inverted papilloma (one case).

Transsphenoidal hypophysectomy

IGS is attractive for pituitary surgery in light of the proximity of the sella to the internal carotid artery, optic nerve, cavernous sinus, various cranial nerves and brain parenchyma. This need is further underscored in patients with residual or recurrent masses in the setting of previous transsphenoidal surgery, which inevitably results in alterations of the normal anatomic landmarks of the paranasal sinuses and the skull base. Jagannathan *et al.* [22] reported that computer-assisted frameless stereotaxy in management of 176 sellar lesions resulted in increased accuracy of the approach, with simultaneous reduction in operative time and preoperative planning. Furthermore, in the face of previous unsuccessful transcranial or transsphenoidal operations, frameless stereotaxy enabled reduction of the tumor burden with minimal adverse effects related to the approach.

Endoscopic management of cerebrospinal fluid rhinorrhea

Data supporting the utility of image guidance for CSF leak repair are sparse. Potential advantages include more precise localization of the skull base defect and/or the meningoencephalocele, especially in the setting of anatomic alteration from previous surgery. Additionally, IGS theoretically may decrease the rate of complications when associated critical structures, including the optic nerve, carotid artery and orbit, may be at risk in the surgical field. Tabaee *et al.* [23] compared patients undergoing CSF leak repair with and without IGS and did not confirm a statistically significant difference in the success rates.

Endoscopic pterygomaxillary fossa biopsy

IGS may also be useful in cases with pathology originating from or extending into the pterygomaxillary fossa. As

IGS facilitates precise localization of the lesion, IGS increases the likelihood of a positive biopsy with minimal exposure of the pterygopalatine fossa contents and thus decreases the risk of neurovascular injury. In addition, IGS may avoid external facial incisions and shortens the anesthetic and operative time. Aronsohn *et al.* [24] utilized IGS for tissue biopsy of melanoma, squamous cell carcinoma, and schwannoma arising in the pterygomaxillary fossa. Indeed, IGS may even facilitate resection of similar lesions of the pterygomaxillary and infratemporal fossa in selected cases.

Three-dimensional computed tomography angiography

Three-dimensional computed tomography angiography (3DCTA) combines features of angiography with CT for management of complex skull base lesions. Angiography helps establish patency, location and relationship of major blood vessels to the lesion. Leong *et al.* [25•] utilized 3DCTA in 22 instances for preoperative planning and in 18 cases for intraoperative navigation to define the relationship of the internal carotid artery (ICA) and the various skull base lesions. Indications for the studies included neoplasm, CSF leak, fibro-osseous lesion, and mucocele. In all cases, the 3DCTA provided critical information about the ICA and adjacent skull base anatomy. In this manner, the path of the ICA can be directly appreciated without actual exposure of the ICA in the operative field.

CT-MR fusion

CT and MRI provide complementary information for skull base lesions, as CT depicts bony anatomy well and MRI demonstrates the intracranial and extracranial soft-tissue structures. Image fusion creates composite images with both CT and MRI characteristics; these hybrid images give better definition of the lesion and the surrounding bony and soft tissue anatomy. In 2005, Chiu *et al.* [26] presented an initial report, and in 2006, Leong *et al.* [27•] reported on this technology in 25 cases. The most common indications for CT-MR fusion included multiloculated mucoceles and neoplasms. CT-MR fusion image data sets were loaded into the IGS system and used for intraoperative surgical navigation. In this way, CT-MR facilitated more comprehensive, minimally invasive endoscopic surgery with low overall morbidity.

AAO consensus statement

The American Academy of Otolaryngology–Head & Neck Surgery [28] has published an official policy statement of the appropriate use of IGS:

> The American Academy of Otolaryngology–Head and Neck Surgery endorses the intraoperative use of computer-aided surgery in appropriately select cases to assist the surgeon in clarifying complex anatomy during sinus and skull base surgery. There is sufficient expert consensus opinion and literature evidence base to support this position. This technology is used at the discretion of the operating surgeon and is not experimental or investigational. Furthermore, the American Academy of Otolaryngology–Head and Neck Surgery is of the opinion that it is impossible to corroborate this with Level 1 evidence. These appropriate, specialty specific, and surgically indicated procedural services should be reimbursed whether used by neurosurgeons or other qualified physicians regardless of the specialty. Examples of indications in which use of computer-aided surgery may be deemed appropriate include: (i) revision sinus surgery; (ii) distorted sinus anatomy of development, postoperative, or traumatic origin; (iii) extensive sino-nasal polyposis; (iv) pathology involving the frontal, posterior ethmoid and sphenoid sinuses; (v) disease abutting the skull base, orbit, optic nerve or carotid artery; (vi) CSF rhinorrhea or conditions where there is a skull base defect; (vii) benign and malignant sino-nasal neoplasms.

Conclusion

IGS has gained wide acceptance for a variety of endoscopic procedures of the paranasal sinuses, including primary and revision endoscopic sinus surgery, as well as more complex minimally invasive endoscopic skull base procedures. Rhinologists have been eager to explore this technology, because of the intrinsic limitations of endoscopic visualization and the anatomic complexity of paranasal sinuses and adjacent skull base. Reliable surgical navigation requires a robust and reliable method for registration, the process through which the IGS computer aligns the preoperative imaging with the intraoperative surgical volume. Target registration error best encapsulates surgical navigation accuracy. Most published reports suggest that the achievable TRE is in the 1.5–2.0 mm range. Recent reports have highlighted the principles of registration; these publications provide important information for clinicians who have come to incorporate IGS into their surgical procedures. Although the consensus suggests that IGS has become indispensable for the advanced procedures in contemporary surgical rhinology, objective data to support that conclusion have been limited; however, one publication confirms the impact of IGS on clinical decision making. Recent IGS reports have presented clinical series, which together summarized current IGS applications, including primary and revision endoscopic sinus surgery, osteoplastic frontal sinusotomy, transsphenoidal hypophysectomy, endoscopic CSF leak repair and endoscopic pterygomaxillary fossa biopsy. Both 3DCTA and CT-MR fusion have been incorporated into IGS for even more advanced skull base applications. The policy statement by the American Academy of Otolaryngology–Head and Neck Surgery on IGS emphasizes the broad application of IGS for a wide range of procedures; thus, this statement encapsulates well the current consensus on IGS indications.

References and recommended reading

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