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Initial experience with image-guided surgical navigation in trans-oral surgery

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Abstract

Background—Surgical navigation using image guidance may improve the safety and efficacy of trans-oral surgery (TOS); however, pre-operative imaging cannot be accurately registered to the intra-operative state due to deformations resulting from placement of the laryngoscope or retractor. This proof of concept study explores feasibility and registration accuracy of surgical navigation for TOS by utilizing intraoperative imaging..

Methods—Four patients undergoing TOS were recruited. Suspension laryngoscopy was performed with a CT-compatible laryngoscope. An intraoperative contrast enhanced CT scan was obtained and registered to fiducials placed on the neck, face and laryngoscope.

Results—All patients were successfully scanned and registered. Registration accuracy within the pharynx and larynx was 1 mm or less. Target registration was confirmed by localizing endoscopic and surface structures to the CT images. Successful tracking was performed in all four patients.

Conclusions—For surgical navigation during TOS, although a high level of registration accuracy can be achieved by utilizing intra-operative imaging, significant limitations of the existing technology have been identified. These limitations, as well as areas for future investigation, are discussed.

Keywords

trans-oral surgery; image-guided surgical navigation; laryngoscopy; 3D printing; intra-operative imaging; trans-oral laser microsurgery; trans-oral robotic surgery

Introduction

Trans-oral surgery (TOS), specifically trans-oral laser microsurgery (TLM) and trans-oral robotic surgery (TORS), provides a minimally invasive approach for the management of laryngeal and pharyngeal cancers, thereby reducing treatment morbidity and improving functional outcomes when compared to open approaches^{1,2}. However, determining tumor

extent and localization of critical structures deep to the mucosal surface is hampered by the “inside-out” nature of this approach. A technology that could conceivably improve margin control and reduce complications in TOS is image-guided surgical navigation.

One of the main challenges of studying image-guided surgical navigation in TOS is the fact that preoperative cross-sectional imaging does not reflect the intraoperative state. Preoperative CT and MRI scans are obtained with the patient in repose without any instrumentation; intraoperatively, the patient’s neck is usually extended, and a laryngoscope or surgical retractor is in place resulting in deformation and displacement of the tumor and critical anatomy from their expected locations. This in turn renders the preoperative imaging unusable for image registration during surgery^{3,4}.

In order to better study this complex problem, we have developed a CT and MRI-compatible 3D-printed polymer laryngoscope, described previously⁵. This laryngoscope allows for intraoperative imaging with the scope in suspension, potentially allowing for more accurate image registration. In this report, we present our initial experience with image-guided surgical navigation in trans-oral surgery utilizing intraoperative CT imaging and our CT-compatible laryngoscopy system. There were two objectives for this study: first, to conduct a proof of concept to explore the feasibility of obtaining intraoperative imaging for surgical navigation and determining registration accuracy; and second, to determine the limitations of current technology as a basis for further investigation

Methods

This report is part of a larger pilot study approved by the Dartmouth-Hitchcock Institutional Review Board (IRB) examining upper aerodigestive tract soft tissue deformation during laryngoscopy utilizing intraoperative CT imaging. All patients signed a research consent approved by the IRB. The cases were performed at the Dartmouth-Hitchcock Center for Surgical Innovation, which houses an intraoperative CT and MRI and is equipped for surgical navigation utilizing the Medtronic StealthStation S7 System (Medtronic, Minneapolis, MN, USA) providing both optical and electromagnetic tracking.

Protocol

After intubation, laryngoscopy was performed with a CT-compatible polymer laryngoscope. The laryngoscope was placed in suspension using a custom CT-compatible suspension system designed to fit within the bore of the CT scanner. Ten multi-modality markers were placed in a variety of locations including the chin, over the thyroid cartilage, lateral neck, angle of mandible, pre-auricular region, mastoid tip, clavicle, sternal notch, and the laryngoscope itself (see Figure 1A). Contrast enhanced images were acquired using a Siemens SOMATOM Definition 64-detector row CT scanner (Siemens AG, Munich, Germany). Images were obtained with a .625-mm section thickness and the axial images were reconstructed at 1-mm overlapping sections using B31’s medium smooth kernel in larynx windows. Images were reconstructed into the coronal and sagittal planes with 1 mm thickness at 5mm intervals.

Registration process

The “Cranial” software package on the StealthStation S7 was used to register the surface fiducials using the “PointMerge” method in which individual fiducials are registered to the corresponding points on the 3D-reconstructed CT image. A “Registration Error Metric” is computed by the navigation system once there are enough matched fiducial landmarks. This is the predicted registration accuracy, in millimeters, within a 10 cm radius sphere centered on a point corresponding to the center of the individual fiducials. If this metric is greater than 5 mm, the system will not proceed to navigation and repeat registration is required. Another sphere based on the center of the individual fiducials is referred to as the “Sphere of Predicted Registration Accuracy”. The estimated registration error within this sphere is at most 1.0 mm⁶. During the registration process, the goal is to ensure that the anatomy of interest is within this sphere of predicted registration accuracy. Registration time, defined as the time in minutes involved with inserting and placing the laryngoscope in suspension, applying the fiducials, obtaining the CT scan, and registering the patient was recorded for each patient.

Navigation

Surgical navigation was performed using either the optical tracking system or the electromagnetic tracker (Figure 1B). For optical tracking, the Medtronic Passive Planar Registration Probe was used as well as a universal tracker attached to a laryngeal suction. For electromagnetic tracking, the Medtronic Malleable Suction and the Medtronic StealthStation EM Flexible Stylet were used (Figure 2). Target registration was visually determined by probing immobile surface and laryngeal landmarks. It should be noted that the patient was registered only at the beginning of the case and the scope was not repositioned during the navigation portion of the procedure.

Resection

For the resection portion of the procedure, a standard CO₂ laser attached to a micromanipulator was used. The CT/MRI-compatible laryngoscope has not been tested or approved for use in laser applications and therefore during this portion of the procedure, the scope was switched over to a standard laser-compatible Lindholm operating laryngoscope.

Results

Four patients were enrolled in the study, all of whom were male. Their ages ranged from 57 – 70 (mean 64 years). Indication for surgery, tumor stage, type of surgery, and complications are listed in Table 1. There were no intraoperative complications, specifically none associated with the navigation portion of the procedure. One patient did have a positive margin requiring laser re-excision to negative margins during a subsequent operation. Table 2 provides a summary of tracking method, registration setup time, registration error, type of tracker used, and subjective benefits gained from navigation.

Registration

Use of all ten fiducial markers resulted in a “Registration Error Metric” of 1.5 mm or less for all 4 patients. More importantly, for all 4 patients, the pharynx and larynx were within the

sphere of registration accuracy indicating that registration error in this region was no more than 1 mm. Figure 3 illustrates the registration sphere in Patient #4. Accuracy of registration was visually confirmed by placing the navigation probe on rigid surface anatomic points such as the thyroid notch and internally at the anterior commissure (Figure 4). Registration setup time on average was 76 minutes decreasing with the latter two cases.

Tracking and navigation

Successful tracking was performed in all four patients. Several tracking probes were trialed as shown in Table 2. For optical navigation, the passive planar registration probe and universal optical tracker were trialed. The passive planar registration probe was not of sufficient length to allow navigation of all areas within the laryngoscopic field of view. A universal optical tracker attached to the proximal end of a #7 Jako laryngeal suction provided sufficient length; however, any slight bend in the suction resulted in diminished tracking accuracy. The EM malleable suction provided excellent tracking at the tip and could be bent to track around corners. Given that it is designed for endoscopic sinus surgery, it was also not of sufficient length to be easily manipulated through the laryngoscope. Finally, the EM flexible stylet provided sufficient length; however, the flexibility and lack of malleability made it difficult to probe around corners.

Subjective benefits

Image-guidance was not employed during the resection portion of the procedure since our CT compatible laryngoscope is not currently approved for use with the CO2 laser. However, we found that the initial navigation feedback pertaining to the location of critical structures such as the hyoid bone, pre-epiglottic fat, and tumor edge with respect to the position of the laryngoscope was beneficial during the planning phase of the resection (Figures 5 – 8).

Discussion

Trans-oral surgery in the form of TLM and TORS has been shown to be an oncologically sound approach for management of cancers of the pharynx and larynx^{7–9} with decreased surgical morbidity when compared with open approaches^{1,10}. Given the low long-term morbidity associated with TOS when compared with radiation and chemoradiation therapy, several authors have advocated this approach as primary treatment for oropharyngeal squamous cell carcinoma in select patients and stages^{11–13}. However, since this is a natural orifice “inside-out” approach, the ability to intraoperatively assess the extent of tumor and locate critical vascular and other anatomic structures beneath the visible mucosal surface is limited. Image guidance could provide the necessary information regarding tumor depth and location of critical structures and potentially improve the safety and efficacy of these operations.

Image-guided surgery is an area of considerable interest and investigation¹⁴. Surgical navigation through use of image guidance has proven effective in sinus^{15,16}, skull base¹⁷, and neurosurgery¹⁸, reducing complications and surgical morbidity. This technology has also been examined in thoracic¹⁹, hepatic²⁰, and urological surgery^{21–23}, among others. It

stands to reason that surgical navigation with image guidance would also be beneficial in TOS.

There have been some attempts to incorporate surgical navigation in head and neck cancer surgery. Feichtinger et al. reported on the use of PET/CT image fusion performed on a commercially available surgical navigation workstation. In this pilot study with 6 patients requiring open resections of the maxilla and parapharyngeal space, the authors found that intraoperative margin control using surgical navigation with the fused images was feasible²⁴. Desai et al. examined the use of a commercially available intraoperative image guidance system with the da Vinci Surgical System to safely perform TORS resection of parapharyngeal space tumors in three patients²⁵. These two studies relied on preoperative imaging for image guidance. Given the location of the tumors and surgical approach, significant intraoperative tissue deformation in the region of interest was not a limiting factor. However, the majority of trans-oral resections would result in deformation of the soft tissue and translation of the bony structures to the point of rendering preoperative imaging unusable due to unacceptable target registration error^{26,4}. The current study utilizes a CT/MRI-compatible laryngoscopy suspension system⁵ and the availability of intraoperative CT capabilities to explore the feasibility of image-guided surgical navigation during suspension laryngoscopy.

The goal of this proof of concept study was to establish the registration workflow, determine registration accuracy, and identify limitations and areas for further research in surgical navigation for TOS. Placement of surface fiducials on the anterior and lateral neck as well as anterior and lateral face provided an initial registration accuracy of 1 mm or less in the region of the larynx and pharynx. Target registration accuracy was confirmed using surface landmarks such as the thyroid notch as well as internal landmarks such as the anterior commissure. Setup time for these four patients was long (average 76 minutes) but not unexpected given the uniqueness of this approach. With each consecutive case starting with the second patient, setup time decreased. Although not the major objective of the study, we did note subjective benefit, in all four patients, to the use of surgical navigation in planning the trans-oral resections, specifically the additional reassurance regarding the extent of tumor and location of anatomic structures.

Several limitations of the current technology and approach were identified. A major limitation is the need to obtain an intraoperative scan in order to achieve accurate registration. Although only few institutions have high resolution intraoperative CT capabilities, cone beam CT is more readily available. Cone beam CT with a flat-panel detector has been examined for obtaining intraoperative imaging during head and neck procedures²⁷; however, this technology is hampered by limited visualization of soft tissues and tumor due to noise and artifact. Even with high resolution contrast enhanced CT, difficulties in accurate tumor delineation, especially with smaller tumors is well recognized²⁸. To circumvent this problem, Reaungamornrat et al. have developed a deformation registration method which uses intraoperative cone beam CT to align preoperative CT or MRI to the intraoperative state²⁹. Using this deformation method, these authors have demonstrated significant target localization improvement when utilizing video overlay with augmentation of critical structures in the surgeon console during TORS^{30–32}.

Additional tumor visualization benefit could potentially be achieved if the same deformation method were applied to preoperative PET imaging or possibly with the use of intra-operative fluorescent imaging.

Re-registration because of changes that occur during surgery also poses a significant challenge. With repositioning of the laryngoscope or soft tissue changes that occur during resection, previously registered images will no longer be valid. Real-time updating of the CT imaging is possible; however, this would result in additional radiation exposure and operative delay due to scan acquisition and re-registration. Narrowing the scan window to just the region of interest would not be feasible as it will reduce the registration accuracy due to limited fiducial points. Given these concerns, for this study we did not readjust the CT compatible laryngoscope after placement; once the navigation portion of the procedure was concluded, the scope was switched over to a conventional laser compatible laryngoscope. Ultimately, to enable image guided surgical navigation for TOS in a manner that is both efficient and reduces radiation exposure, computational methods for registering the preoperative imaging to the intraoperative state would most likely be required. This computational modeling could be further fine-tuned using alternative forms of intraoperative visualization that do not emit radiation such as ultrasound³³, laser range scanning^{23,34}, or endoscopic view point selection³⁵.

Another limitation identified in the current study is the method of display of the images during navigation. Most Otolaryngologists are accustomed to viewing sinus CTs in the coronal, axial, and sagittal planes during image-guided sinus surgery. However, this form of tri-planar image presentation was more difficult to follow given the additional soft tissue deformation of the upper aerodigestive tract as well as the presence of the laryngoscope. The use of augmented or virtual reality, in which imaging information is incorporated within the real-time surgical view, is an area of active research in multiple surgical disciplines^{21,36,37} including otolaryngology^{30,38,39}. Segmentation of the areas of interest – such as the tumor, anatomic landmarks, and vascular structures – and presenting this imaging information as an overlay on the endoscopic or microscopic view would be more intuitive and allow the surgeon to maintain focus on the surgical field without diverting attention to the navigation imaging.

The navigation probes currently commercially available for either electromagnetic or optical navigation are not specific to trans-oral surgery and as outlined in the results section have individual limitations. The ideal probe would provide sufficient length, malleability, and rigidity for use through the laryngoscope both in a straight-line fashion as well as probing around corners. Table 3 provides a summary of the limitations of the current technology and possible solutions. Future investigation would also require an analysis of the value proposition presented by introducing this type of technology. This would include studies examining decreases in operative time, improvement in surgical margin control, and reductions in peri-operative morbidity.

In conclusion, we present a proof of concept study examining image-guided surgical navigation in trans-oral surgery utilizing a CT-compatible laryngoscopy system and intraoperative CT imaging. In this study, we find that it is possible to achieve acceptable

registration accuracy using surface fiducials placed on the neck and face. In this cohort, intraoperative navigation did provide insights regarding extent of tumor and ability to approach resection in a trans-oral fashion. Finally, several limitations of the current technology were outlined with the goal of laying the groundwork for future investigation into this field.

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References

1. Williams CE, Kinshuck aJ, Derbyshire SG, et al. Transoral laser resection versus lip-split mandibulotomy in the management of oropharyngeal squamous cell carcinoma (OPSCC): a case match study. *Eur Arch Otorhinolaryngol*. May.2013 doi: 10.1007/s00405-013-2501-5
2. Lee SY, Park YM, Byeon HK, Choi EC, Kim S-H. Comparison of oncologic and functional outcomes after transoral robotic lateral oropharyngectomy versus conventional surgery for T1 to T3 tonsillar cancer. *Head Neck*. Jul.2013 doi: 10.1002/hed.23424
3. Wu X, Paydarfar JA, Halter RJ. Quantifying Anatomic Deformations During Laryngoscopy. *Annals of Biomedical Engineering*. Mar 14.2018 :1–14. [PubMed: 29019076]
4. Ma AK, Daly M, Qiu J, et al. Intraoperative image guidance in transoral robotic surgery: A pilot study. *Head Neck*. 2017; 39(10):1976–1983. DOI: 10.1002/hed.24805 [PubMed: 28755399]
5. Paydarfar JA, Wu X, Halter RJ. MRI- and CT-Compatible Polymer Laryngoscope: A Step toward Image-Guided Transoral Surgery. *Otolaryngol -- Head Neck Surg*. 2016; 610:1–3. DOI: 10.1177/0194599816650176
6. Medtronic Synergy Craniel AXIEM Pocket Guide, Revision 7. 2011. 82–85.
7. Weinstein GS, O'Malley BW, Magnuson JS, et al. Transoral robotic surgery: a multicenter study to assess feasibility, safety, and surgical margins. *Laryngoscope*. 2012; 122(8):1701–1707. DOI: 10.1002/lary.23294 [PubMed: 22752997]
8. Hinni ML, Salassa JR, Grant DG, et al. Transoral laser microsurgery for advanced laryngeal cancer. *Arch Otolaryngol Head Neck Surg*. 2007; 133(12):1198–1204. DOI: 10.1001/archoto.133.12.1198 [PubMed: 18086960]
9. Moore EJ, Olsen SM, Laborde RR, et al. Long-term functional and oncologic results of transoral robotic surgery for oropharyngeal squamous cell carcinoma. *Mayo Clin Proc*. 2012; 87(3):219–225. DOI: 10.1016/j.mayocp.2011.10.007 [PubMed: 22386176]
10. Holsinger FC, Sweeney AD, Jantharapattana K, et al. The emergence of endoscopic head and neck surgery. *Curr Oncol Rep*. 2010; 12(3):216–222. DOI: 10.1007/s11912-010-0097-0 [PubMed: 20425082]
11. Grant DG, Hinni ML, Salassa JR, Perry WC, Hayden RE, Casler JD. Oropharyngeal cancer: a case for single modality treatment with transoral laser microsurgery. *Arch Otolaryngol Head Neck Surg*. 2009; 135(12):1225–1230. DOI: 10.1001/archoto.2009.185 [PubMed: 20026820]
12. Monnier Y, Simon C. Surgery Versus Radiotherapy for Early Oropharyngeal Tumors: a Never-Ending Debate. *Curr Treat Options Oncol*. 2015; 16(9):42.doi: 10.1007/s11864-015-0362-4 [PubMed: 26187797]
13. Haughey BH, Hinni ML, Salassa JR, et al. Transoral laser microsurgery as primary treatment for advanced-stage oropharyngeal cancer: A united states multicenter study. *Head Neck*. Jan.2011 :1–12. DOI: 10.1002/hed.21669

14. Rosenthal EL, Warram JM, Bland KI, Zinn KR. The status of contemporary image-guided modalities in oncologic surgery. *Ann Surg*. 2015; 261(1):46–55. DOI: 10.1097/SLA.0000000000000622 [PubMed: 25599326]
15. Citardi MJ, Batra PS. Intraoperative surgical navigation for endoscopic sinus surgery: rationale and indications. *Curr Opin Otolaryngol Head Neck Surg*. 2007; 15(1):23–27. DOI: 10.1097/MOO.0b013e3280123130 [PubMed: 17211179]
16. Dalgorf DM, Sacks R, Wormald P-J, et al. Image-guided surgery influences perioperative morbidity from endoscopic sinus surgery: a systematic review and meta-analysis. *Otolaryngol Head Neck Surg*. 2013; 149(1):17–29. DOI: 10.1177/0194599813488519 [PubMed: 23678278]
17. Farag A, Rosen M, Evans J. Surgical Techniques for Sinonasal Malignancies. *Neurosurg Clin N Am*. 2015; 26(3):403–412. DOI: 10.1016/j.nec.2015.03.011 [PubMed: 26141359]
18. Haberland N, Ebmeier K, Hliscs R, et al. Neuronavigation in surgery of intracranial and spinal tumors. *J Cancer Res Clin Oncol*. 2000; 126(9):529–541. DOI: 10.1007/s004320000122 [PubMed: 11003565]
19. Stella F, Dolci G, Dell'Amore A, et al. Three-dimensional surgical simulation-guided navigation in thoracic surgery: A new approach to improve-RESULTS:-in chest wall resection and reconstruction for malignant diseases. *Interact Cardiovasc Thorac Surg*. 2014; 18(1):7–12. DOI: 10.1093/icvts/ivt440 [PubMed: 24144806]
20. Simpson AL, Kingham TP. Current Evidence in Image-Guided Liver Surgery. *J Gastrointest Surg*. 2016; 20(6):1265–1269. DOI: 10.1007/s11605-016-3101-7 [PubMed: 26956008]
21. Pervez A, Ahmed K, Thompson S, Elhage O, Khan MS, Dasgupta P. Image guided robotic surgery: current evidence for effectiveness in urology. *Arch Ital Urol Androl*. 2014; 86(4):245–248. DOI: 10.4081/aiua.2014.4.245 [PubMed: 25641443]
22. Herrell SD, Kwartowitz DM, Milhoua PM, Galloway RL. Toward Image Guided Robotic Surgery: System Validation. *J Urol*. 2009; 181(2):783–790. DOI: 10.1016/j.juro.2008.10.022 [PubMed: 19091336]
23. Herrell SD, Galloway RL, Su L-M. Image-guided robotic surgery. *Curr Opin Urol*. 2012; 22(1):47–54. DOI: 10.1097/MOU.0b013e32834d4ce5 [PubMed: 22080871]
24. Feichtinger M, Pau M, Zemmann W, Aigner RM, Kärcher H. Intraoperative control of resection margins in advanced head and neck cancer using a 3D-navigation system based on PET/CT image fusion. *J Cranio-Maxillofacial Surg*. 2010; 38(8):589–594. DOI: 10.1016/j.jcms.2010.02.004
25. Desai SC, Sung C-K, Genden EM. Transoral robotic surgery using an image guidance system. *Laryngoscope*. 2008; 118(11):2003–2005. DOI: 10.1097/MLG.0b013e3181818784 [PubMed: 18849862]
26. Paydarfar, J; Wu, X; Halter, R. Quantified Tissue Deformation During Laryngoscopy. American Head and Neck Society 9th International Conference on Head and Neck Cancer; Seattle, WA. July 16–20, 2016; <http://ahns.jnabstracts.com/2016/Detail?ID=76028>. Published 2016
27. Daly MJ, Siewerdsen JH, Moseley DJ, Jaffray Da, Irish JC. Intraoperative cone-beam CT for guidance of head and neck surgery: Assessment of dose and image quality using a C-arm prototype. *Med Phys*. 2006; 33(10):3767–3780. DOI: 10.1118/1.2349687 [PubMed: 17089842]
28. Daisne J-F, Duprez T, Weynand B, et al. Tumor Volume in Pharyngolaryngeal Squamous Cell Carcinoma: Comparison at CT, MR Imaging, and FDG PET and Validation with Surgical Specimen. *Radiology*. 2004; 233(1):93–100. DOI: 10.1148/radiol.2331030660 [PubMed: 15317953]
29. Reaungamornrat S, Liu WP, Wang AS, et al. Deformable image registration for cone-beam CT guided transoral robotic base-of-tongue surgery. *Phys Med Biol*. 2013; 58:4951–4979. DOI: 10.1088/0031-9155/58/14/4951 [PubMed: 23807549]
30. Liu WP, Richmon JD, Sorger JM, Azizian M, Taylor RH. Augmented reality and cone beam CT guidance for transoral robotic surgery. *J Robot Surg*. 2015; 9(3):223–233. DOI: 10.1007/s11701-015-0520-5 [PubMed: 26531203]
31. Liu WP, Reaungamornrat S, Deguet A, et al. Toward intraoperative image-guided transoral robotic surgery. *J Robot Surg*. 2013; 7(3):217–225. DOI: 10.1007/s11701-013-0420-5 [PubMed: 25525474]

32. Liu WP, Reaugamornrat S, Sorger JM, Siewerdsen JH, Taylor RH, Richmon JD. Intraoperative image-guided transoral robotic surgery: pre-clinical studies. *Int J Med Robot.* 2015; 11(2):256–267. DOI: 10.1002/rcs.1602 [PubMed: 25069602]
33. Lee MW. Fusion imaging of real-time ultrasonography with CT or MRI for hepatic intervention. *Ultrasonography.* 2014; 33(4):227–239. DOI: 10.14366/usg.14021 [PubMed: 25036756]
34. Rucker DC, Wu Y, Clements LW, et al. A Mechanics-Based Nonrigid Registration Method for Liver Surgery Using Sparse Intraoperative Data. *IEEE Trans Med Imaging.* 2014; 33(1):147–158. DOI: 10.1109/TMI.2013.2283016 [PubMed: 24107926]
35. Robu MR, Edwards P, Ramalhinho J, et al. Intelligent viewpoint selection for efficient CT to video registration in laparoscopic liver surgery. *Int J Comput Assist Radiol Surg.* 2017; 12(7):1079–1088. DOI: 10.1007/s11548-017-1584-7 [PubMed: 28401399]
36. Vávra P, Roman J, Zon a P, et al. Recent Development of Augmented Reality in Surgery: A Review. *J Healthc Eng.* 2017; 2017doi: 10.1155/2017/4574172
37. Volonté F, Pugin F, Bucher P, Sugimoto M, Ratib O, Morel P. Augmented reality and image overlay navigation with OsiriX in laparoscopic and robotic surgery: Not only a matter of fashion. *J Hepatobiliary Pancreat Sci.* 2011; 18(4):506–509. DOI: 10.1007/s00534-011-0385-6 [PubMed: 21487758]
38. Winne C, Khan M, Stopp F, Jank E, Keeve E. Overlay visualization in endoscopic ENT surgery. *Int J Comput Assist Radiol Surg.* 2011; 6(3):401–406. DOI: 10.1007/s11548-010-0507-7 [PubMed: 20577827]
39. Citardi MJ, Agbetoba A, Bigcas J-L, Luong A. Augmented reality for endoscopic sinus surgery with surgical navigation: a cadaver study. *Int Forum Allergy Rhinol.* 2016; 6(5):523–528. DOI: 10.1002/alar.21702 [PubMed: 26718626]

Figure 1.
A – CT/MRI compatible polymer laryngoscope in suspension with surface fiducial markers placed. B – Endoscopic and navigation views during the procedure.

Figure 2.
Electromagnetic trackers used. A - Medtronic Malleable Suction; B - Medtronic StealthStation EM Flexible Stylet.

Figure 3. The “Sphere of Predicted Registration Accuracy” during the registration process in Patient #4. Note that the sphere encompasses the larynx and pharynx, indicating that the registration error in this region is no more than 1.0 mm. In this case, the registration error metric is also 1.0 mm.

Figure 4. Tracker placed at anterior commissure in Patient #1 (A – Axial view & B – Endoscopic view) and Patient #2 (C – Axial view & D – Endoscopic view). Note accuracy of target registration between the endoscopic and navigation images.

Figure 5.

Patient #1. A – The sagittal view demonstrates that the laryngocele extends beyond what is visualized endoscopically along the anterior aspect – note the position of the lip of the scope along the hyoid bone, compressing the laryngocele (white arrow). B – Coronal view. C – Axial view. D – Endoscopic view with tracking probe along the superior surface of the laryngocele.

Figure 6. Patient #2. Malleable tracking suction was used to correlate endoscopic assessment of tumor extent inferiorly with cross-sectional imaging. A – Coronal view. B – Sagittal view. C – Axial view. D –Endoscopic view.

Figure 7.

Patient #3. A – Coronal view. B – Sagittal view. Tracking probe is placed along the medial edge of the tumor. Note the location of the tracker with respect to the lip of laryngoscope and the anterior edge of the tumor (white arrow). C - Axial view provides reassurance that tumor does not appear to spread submucosally beyond the visualized medial mucosal edge (arrow). D – Endoscopic view with probe placed along medial edge of tumor.

Figure 8.

Table 1

Indications, procedures, tumor characteristics, margin status, and complications for each patient in this series.

Patient	Pathology	Site	Stage	Procedure	Final Margins	Complications
1	Laryngocele	Internal/External Larynx	N/A	Trans-oral CO2 laser excision	N/A	None
2	SCCa	Supraglottic larynx	T1N0	TLM excision	Negative	Readmit for dehydration, G-tube placement
3	SCCa	Base of tongue	T2N0	TLM and open resection, right neck dissection	Negative	None
4	SCCa	Aryepiglottic fold	T3N2c	TLM excision and bilateral neck dissection	Negative	Initial positive margin requiring take back for re-excision

SCCa – squamous cell carcinoma

TLM – trans-oral laser microsurgery

Table 2

Tracking method with the type of tracker used for each patient. The registration error metric is defined as the registration accuracy within a 10 cm radius sphere centered on a point corresponding to the center of the individual fiducials. If this metric is greater than 5 mm, the system will not proceed to navigation and registration must be repeated.

Patient	Tracking Method	Registration Setup Time (min)	Registration Error Metric (mm)	Tracker used	Subjective Benefits
1	Optical	83	0.5	Passive planar registration probe SureTrak 2 passive tracker attached to Jako laryngeal suction	Provided assurance that trans-oral resection of laryngocele was feasible
2	EM	99	1.5	Malleable tracking suction	Appreciation of inferior extent of tumor and relation to hyoid and pre-epiglottic fat
3	EM	63	0.7	EM Flexible Stylet	Appreciation of relation between lip of scope and anterior edge of tumor Reassurance that surface edge of tumor corresponded with submucosal extent
4	EM	60	1.0	EM Flexible Stylet	Appreciation of relationship between lip of scope and anterior extent of tumor, location of hyoid, and pre-epiglottic fat

EM - electromagnetic

Table 3

Limitations of current technology and areas of potential investigation.

Limitations of current technology and approach		Possible solutions/areas of investigation
Imaging:	Intra-operative imaging is required in order to achieve accurate image registration. CT imaging may not provide the best visualization of smaller tumors.	Deformation modeling of pre-operative images to provide accurate register to intra-operative state. Combination of several imaging modalities (e.g. MRI, PET, CT, fluorescence) to improve tumor visualization.
Instrumentation:	Current tracking instrumentation is not designed for use through the laryngoscope. CT/MRI compatible laryngoscope is not currently approved for use with laser and cannot be used during the resection portion of the procedure.	Develop tracking instruments specific to laryngoscopy. Ideally, these instruments would allow tracking at the tip to enable tracking around corners. This would be best suited for EM tracking. Polymer scope will require testing and approval for laser use.
Display:	The tri-planar view is not as anatomically easy to follow in the upper aerodigestive tract as in endoscopic sinus surgery, especially with the tissue deformation created by the laryngoscope.	Video overlay of the tumor and relevant anatomy on the real-time endoscopic or microscopic images. Consider 3D endoscopy.
Registration:	Real-time updating of the imaging during resection or with necessary re-positioning of the scope would require re-scanning and registering the patient.	Alternative intra-operative imaging modality during resection (e.g. ultrasound).