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Quantifying Anatomic Deformations during Laryngoscopy

Xiaotian Wu¹, Joseph A. Paydarfar^{2,3}, and Ryan J. Halter^{1,2}

¹Thayer School of Engineering at Dartmouth College, 14 Engineering Dr., Hanover, NH 03755

²Geisel School of Medicine at Dartmouth College, 1 Rope Ferry Rd., Hanover, NH 03755

³Dartmouth-Hitchcock Medical Center, 1 Medical Center Dr., Lebanon, NH 03756

Abstract

For a variety of head and neck cancers, specifically those of the oropharynx, larynx, and hypopharynx, minimally invasive trans-oral approaches have been developed to reduce perioperative and long-term morbidity. However, in trans-oral surgical approaches anatomical deformation due to instrumentation, specifically placement of laryngoscopes and retractors, present a significant challenge for surgeons relying on preoperative imaging to resect tumors to negative margins. Quantifying the deformation due to instrumentation is needed in order to develop predictive models of operative deformation. In order to study this deformation, we used a CT/MR-compatible laryngoscopy system in concert with intraoperative CT imaging. 3D models of preoperative and intraoperative anatomy were generated. Mandible and hyoid displacements as well as tongue deformations were quantified for eight patients undergoing diagnostic laryngoscopy. Across patients, we found on average 1.3cm of displacement for these anatomic structures due to laryngoscope insertion. On average, the maximum displacement for certain tongue regions exceeded 4cm. The anatomical deformations quantified here can serve as a reference for describing how the upper aerodigestive tract anatomy changes during instrumentation and may be helpful in developing predictive models of intraoperative upper aerodigestive tract deformation.

Key terms

Computed tomography (CT); Trans-oral surgery (TOS); CT/MR-compatible laryngoscopy system

INTRODUCTION

Cancers of the head and neck (oral cavity, pharynx, and larynx) are the 5th most common cancers worldwide. The incidence of oropharyngeal cancer is rising, particularly in younger adults in economically developed countries, with incidence rates almost doubling from 0.79 to 1.39 (per 100,000) in the 36–44 years age group in the US^{4,11}. In 2017, there were an estimated 63,030 new cases of head and neck cancer with roughly 13,360 deaths in the US³².

One of the primary treatment modalities for these cancers involves surgical resection to negative margins. Surgical approaches to head and neck sub-sites such as the larynx and pharynx are challenging due to complex anatomy and confined spaces in which the surgeon has to operate. Traditional approaches to these sub-sites require extensive trans-mandibular or trans-cervical dissection, resulting in increased rates of complications and surgical morbidity. As a result, over the past decade there has been increased interest in using advances in robotics and laser technology to develop more minimally invasive trans-oral approaches such as trans-oral laser microsurgery (TLM) and trans-oral robotic surgery (TORS) – collectively referred to as trans-oral surgery (TOS) – to resect tumors of the pharynx and larynx. Although this shift towards minimally invasive approaches has decreased surgical morbidity^{15,18,19}, there are still two main limitations. 1) Since trans-oral surgery is a natural orifice “inside-out” approach, the ability to intraoperatively assess the extent of the tumor and locate critical anatomic structures (i.e. arteries) beneath the visible mucosal surface is limited. 2) Placing surgical retractors and laryngoscopes deforms the tumor and critical anatomy from their expected locations. Preoperative CT or MR imaging is obtained with the patient in a natural position, without a hyper-extended neck or a surgical scope/retractor in the mouth (Fig. 1), and therefore does not reflect the deformed anatomy present in the operative state.

The reported rates of positive margins after TORS and TLM is as high as 20%³⁶ and rates of major hemorrhage (requiring operative intervention or resulting in death) is as high as 7%²³. With the availability of intraoperative CT and MR imaging, scanning the patient during laryngoscopy in the ‘deformed’ state would enable surgeons to visualize the deformation that occurs during instrumentation for trans-oral surgery and may help to decrease these complication rates. While there could be obvious benefits to intraoperative scanning, these imaging facilities are expensive to operate, are not typically available, and the scanners are not compatible with the metal laryngoscopy systems currently used during TOS.

Image guided surgery through use of preoperative imaging and instrument tracking is an area of intense investigation²⁹. Surgical navigation of this type has proven effective in sinus⁸, skull base¹⁰, and neurosurgery¹², reducing complications and surgical morbidity. This technology has also been explored in thoracic³⁴, hepatic³³, and urological surgery^{16,17,26}, among others. It stands to reason that surgical navigation would also be beneficial in TOS. However, because of the soft tissue and airway deformation that occurs with placement of laryngoscopes and retractors during TOS, preoperative scans are rendered less useful for navigation and instead still require the surgeon to mentally predict how the tissue has deformed. We hypothesize that surgical navigation in TOS will lead to improved margin control and safety. In order to realize this, a critical first step is to understand and quantify the bony and soft tissue deformation that occurs during instrumentation. Soft-tissue deformation and bony displacement models based on data recorded intraoperatively could ultimately be used to augment preoperative images so that they better represent the intraoperative state, without requiring expensive intraoperative imaging facilities.

Intraoperative imaging with high resolution CT and MRI can be used to quantify soft tissue deformation and bony displacements that occur during instrumentation of the upper aerodigestive tract. However, since standard laryngoscopes are not CT/MRI compatible, we

designed a prototype CT/MR compatible laryngoscope²⁵ to enable us to quantify tissue deformation associated with patient instrumentation and to ultimately assess the efficacy of image guidance in trans-oral surgery. Here, we report on an optimized laryngoscope and the design and implementation of a complementary system to secure the scope to the patient. This paper presents this optimized CT/MR compatible laryngoscopy system and provides the first quantitative assessment of the anatomical deformations that occur during TOS instrumentation. Specifically, patients were imaged with CT both before and after instrumentation with our CT-compatible laryngoscopy system, the images were segmented and registered to each other, and both bony and soft tissue deformations were quantified. Since TOS primarily includes resection of tumors in the base of tongue, the pharynx, and the larynx, deformations of critical surrounding structures, including the mandible and hyoid bone as well as the tongue, were quantified here.

MATERIALS AND METHODS

Patient Protocol

Eight patients scheduled to undergo diagnostic laryngoscopy were recruited to participate in this Dartmouth-Hitchcock Medical Center (DHMC) Institutional Review Board approved study. Operations were performed at DHMC's Center for Surgical Innovation, which provides intraoperative CT capabilities. Patients with dental fillings, which could generate significant artifact on CT imaging, were excluded from this study. As such, all patients were either edentulous or had minimal dentition. Of the eight patients, six were male, two were female and their ages ranged from 44 to 74 (mean of 64 ± 10.6).

A plastic self-retaining lip retractor was positioned once the patient was placed under anesthesia. Twelve to sixteen small metallic fiducials (Ligacip (Ethicon US) for the first 4 patients, then ProTack (Covidien) for the next 4 patients) were secured to the surface of the patients' tongue and distributed evenly between the tip and circumvallate papillae at the start of each laryngoscopy. ProTack fiducials were eventually used because they were easier to secure to the tongue than the Ligacips. Both types of fiducials were CT opaque and small enough to not compromise visualization of the anatomy.

Following anesthesia and prior to any instrumentation, a CT scan with Omnipaque contrast (iohexol, 300mg/mL, 50mL) was acquired with the patient in repose. The custom laryngoscopy system was then positioned and an intraoperative CT scan was acquired after another 50mL injection of contrast. The tongue was always displaced to the patient's left during laryngoscopy; one head and neck surgeon (JAP) performed all laryngoscopies. A Siemens SOMATOM Definition AS 64 slice CT scanner was used for image acquisition with scan parameters set to acquire at 64×0.6 mm collimation with modulated kV and mAs. The contrast-enhanced CT scans were acquired at 5mm thickness following standard clinical protocols to minimize radiation dosage. Scans were then reconstructed to 1mm slices with B31s medium smooth+ kernel and larynx window in order to better segment the fiducials and bony structures.

Laryngoscopy System Design and Configuration

Our laryngoscope was 3D-printed on a Stratasys Objet Eden250 3D printer using MED610. MED610 is a biocompatible acrylic compound approved for use in devices with short-term mucosal-membrane contact of up to 24 hours. The scope was sterilized with high-level disinfectant (Revital-Ox; Steris Corporation, Mentor, Ohio) or low-temperature sterilization (STERRAD; Advanced Sterilization Products, Irvine, California). The laryngoscopy system consisted of a 3D-printed worm gear mechanism (Fig. 2A), PVC tubing, and a Plexiglas frame for CT/MR-compatibility. The worm gear of the system was printed on the same 3D printer but using RGD720, a transparent acrylic PolyJet material. The knob on the mechanism allowed the surgeon to adjust the angle (range of $+75^\circ$ to -64°) of the laryngoscope to maximize exposure; the range of motion and angular control is similar to the conventional metal positioning systems used during laryngoscopy. The system was designed to fit within the 27 in. bore of the scanner and positioned as shown in Fig. 2B.

Image Segmentation, Registration, and Analysis

Segmentation—3D reconstructions of key anatomical structures (skull, mandible, hyoid, tongue, and arteries) and the tongue fiducials were generated from image segmentation of both preoperative and intraoperative CT scans using Mimics (Materialise, Plymouth, MI). Bony structures and fiducials were segmented via thresholding, while the tongue and arteries were segmented using live-wire and region-growing algorithms within Mimics. The laryngoscope was also segmented in the intraoperative scan, but done manually. Each anatomic structure was defined as a 3D point cloud $\mathbf{P}_{structure}$ consisting of N points ($\mathbf{p}_x, \mathbf{p}_y, \mathbf{p}_z$)_{1:N} where N is unique for each segmented structure. Since the individual tongue fiducials could not be automatically segmented using thresholding (i.e. they all have approximately the same Hounsfield units), the segmented point cloud specifying the fiducials included clusters of points distributed across the tongue; we use a K-means clustering algorithm to specify the individual fiducials in a post-processing step as discussed below. All segmentations were exported as 3D models in .stl format. All subsequent processing and registration of the models was performed in MATLAB (MathWorks, Natick, MA).

Registration—Every patient's skull was manually registered to a fixed coordinate system defined by the Frankfurt plane⁵ (auriculo-orbital plane), the mid-sagittal plane, and the vertical porion plane (FMV, Fig. 3). The vertical porion plane was defined as the plane orthogonal to the Frankfurt plane while intersecting both porions. Since the FMV coordinate system was only dependent on the skull and the skull was assumed rigid, both pre- and intraoperative scans were aligned via the FMV. The deformations and shift of the tongue, mandible, and hyoid due to the insertion of the scope (and the resulting hyperextension of the neck) could be quantified through this registration. Instead of manually defining the FMV coordinate system again for the intraoperative scan, the intraoperative scan of the rigid skull was registered to the FMV frame of the preoperative scan using a modified iterative closest point (ICP) algorithm¹ (detailed below).

Bony Anatomy Deformation—The center of each bony structure was defined as the mean of the x,y,z-triplet specifying the position of each point in the corresponding 3D point-cloud (i.e. $\mathbf{c}_{hyoid} = (\bar{\mathbf{p}}_x, \bar{\mathbf{p}}_y, \bar{\mathbf{p}}_z)_{hyoid}$). While this point is not the true center of mass (centroid),

it was simple to compute and will be close to the true centroid because of the dense point-cloud models produced (1mm average closest point distance).

Center displacement and rotation in the mandible and hyoid bones were measured using a modified ICP algorithm to find the rigid transformation (${}^{intra}T_{pre}$) that aligns point-clouds defined in the preoperative state (P_{pre}) to those of the intraoperative state (P_{intra}) such that:

$$\begin{bmatrix} P_{intra} \\ 1 \end{bmatrix} = {}^{intra}T_{pre} * \begin{bmatrix} P_{pre} \\ 1 \end{bmatrix} \quad (1)$$

where P_{pre} and P_{intra} are 3D point clouds ($3 \times N$ points): $[p_x \ p_y \ p_z]'$ of the bony structures in the preoperative and intraoperative states, respectively. The row of 1s cast the equation into homogeneous coordinates. ${}^{intra}T_{pre}$ is a 4×4 transformation matrix in homogeneous form:

$\begin{bmatrix} R & t_{x,y,z} \\ 0 & 1 \end{bmatrix}$. R is the 3×3 rotation matrix from which the three rotation angles (a_x, a_y, a_z) defined about each axis can be extracted, and $t_{x,y,z}$ is the 3×1 translational vector composed of the three translations (t_x, t_y, t_z) in the direction of each axis.

Since the ICP algorithm performs point set registration, the density of the points impact the accuracy of the registration. Our 3D models contained approximately 130,000 points for the mandible and 15,000 points for the hyoid. To speed up computation while maintaining registration accuracy (mean closest point distance) to within 1mm, the mandible and hyoid models were uniformly downsampled to about 10,000 and 2,000 points, respectively. Rigid registration with these downsampled point sets resulted in submillimeter accuracy. Our implementation of the ICP algorithm involved 4 steps:

1. Compute the closest points from P_{pre} to P_{intra} based on Euclidean distance to establish point correspondences.
2. Compute the rigid registration of these corresponding points using the singular value decomposition (SVD) method. Only corresponding points with distances that are within 3 standard deviations from the mean are included.
3. Apply the registration to bring all P_{pre} points closer to P_{intra} including outliers determined in Step 2.
4. Repeat steps 1–3 with the updated P_{pre} until the average closest point distance is less than 0.01mm, the number of iterations exceeds 100, or if the change in average closest point distance is less than 1×10^{-5} mm.

We used the SVD implementation of the ICP algorithm detailed by Haralick et al¹³ with a modification to ensure a rigid transformation (specifically to prevent reflection in the rotation matrix) based on Myronenko and Song's lemma²⁴. Explicitly, let:

$$\begin{aligned}
 \mathbf{x}_n &= (\mathbf{P}_{pre})_n \\
 \mathbf{y}_n &= (\mathbf{P}_{intra})_n \\
 \mathbf{B} &= \sum_{n=1}^N (\mathbf{y}_n - \mathbf{c}_{intra})(\mathbf{x}_n - \mathbf{c}_{pre})'
 \end{aligned} \tag{2}$$

where $\mathbf{x}_n$ and $\mathbf{y}_n$ are the n^{th} column of $(\mathbf{P}_{pre})_n$ and $(\mathbf{P}_{intra})_n$ respectively, $\mathbf{c}_{pre}$ and $\mathbf{c}_{intra}$ are the aforementioned centers (3×1) of the point clouds $\mathbf{P}_{pre}$ and $\mathbf{P}_{intra}$, respectively, and $\mathbf{B}$ is the cross-covariance matrix of the corresponding point pairs in $\mathbf{P}_{pre}$ and $\mathbf{P}_{intra}$, scaled by N , the number of corresponding point pairs.

$\mathbf{UDV}'$ is defined to be the SVD of matrix $\mathbf{B}$, where $\mathbf{UU}' = \mathbf{I}$, $\mathbf{VV}' = \mathbf{I}$, and $\mathbf{D}$ is diagonal. In this case, $\mathbf{D}$ acts as a scaling matrix, and is not needed for our rigid rotation. The rigid rotational matrix $\mathbf{R}$ can then be written as:

$$\mathbf{R} = \mathbf{UCV}' \tag{3}$$

$$\text{where } \mathbf{C} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \det(\mathbf{UV}') \end{bmatrix}$$

The translation vector $\mathbf{t}_{x,y,z}$ is then:

$$\mathbf{t}_{x,y,z} = \mathbf{c}_{intra} - \mathbf{R} * \mathbf{c}_{pre} \tag{4}$$

The magnitude (Euclidean distance, t_{mag}) of the overall translation is then calculated from $\mathbf{t}_{x,y,z}$.

The ICP algorithm can be sensitive to the initial positions (especially rotation) of the point clouds¹. However, since the actual rotations of the bony anatomy due to instrumentation are not large (i.e. $<90^\circ$ in all three axes based on visual inspection), an initial rotation and translation transformation is not needed to guide the ICP algorithm.

To extract angles a_x , a_y , and a_z from the rotation matrix $\mathbf{R}$, we use a non-linear solver (Levenberg-Marquardt) with an initial state of [0,0,0] on the following equation:

$$\mathbf{R} - \mathbf{R}_z * \mathbf{R}_y * \mathbf{R}_x = 0 \tag{5}$$

where $\mathbf{R}_x$, $\mathbf{R}_y$, and $\mathbf{R}_z$ are the standard rotation matrices with unknowns a_x , a_y , and a_z ,

$$\begin{aligned}
 R_x &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(a_x) & -\sin(a_x) \\ 0 & \sin(a_x) & \cos(a_x) \end{bmatrix}, \\
 R_y &= \begin{bmatrix} \cos(a_y) & 0 & \sin(a_y) \\ 0 & 1 & 0 \\ -\sin(a_y) & 0 & \cos(a_y) \end{bmatrix}, \\
 R_z &= \begin{bmatrix} \cos(a_z) & -\sin(a_z) & 0 \\ \sin(a_z) & \cos(a_z) & 0 \\ 0 & 0 & 1 \end{bmatrix}.
 \end{aligned}$$

Since extracting three angles from a 3D rotation matrix is not unique, we define the rotational order to be X-Y-Z. This order was selected because we expected the dominant rotation associated with insertion of the laryngoscope to open the jaw to be about the x-axis.

Soft Tissue Deformation—To quantify soft tissue deformation (tongue), the clips on the preoperative tongue are assigned to one of seven regions: tip, center left, center middle, center right, posterior left, posterior middle, and posterior right (Fig. 4E). These regions are defined by a Voronoi tessellation⁹ of the tongue surface using seven anatomic-specific seed points (Fig. 4). A point on the tip of the tongue, p_{tip} , the middle of the tongue, p_{mid} , and on the circumvallate papillae, p_{cp} , are manually selected from the surface of the tongue to define the tongue's mid sagittal plane and a resulting coordinate system with the origin as the midpoint between p_{tip} and p_{cp} . The intersection of seven vectors, stemming from the origin of the new coordinate system, with the tongue surface defines the seed points for Voronoi tessellation (Fig. 4B). The only manual input required for this process is selecting the three points on the tongue used to determine the mid-plane (p_{tip} , p_{mid} , and p_{cp}).

The tongue fiducial centers were automatically determined using an iterative K-means algorithm. This approach clusters the entire fiducial point-cloud into subsets representing each fiducial. Each fiducial cluster has its own mean as defined by K-means, which we specify as the fiducial centers. Our implementation of the K-means algorithm consisted of three steps:

1. Perform regular K-means¹⁴ (MATLAB, Statistics and Machine Learning Toolbox) given the number of clusters (fiducials: 12–16) and 10 random initializations to identify the clusters and their centers with the lowest sums of point-to-center distances (d).
2. Calculate the mean ($\bar{d}$) of d for each cluster. If any cluster has a $\bar{d}$ that is two standard deviations more than the mean of $\bar{d}$ across all clusters, move the smallest cluster's center to the position of the largest cluster's center. Re-run K-means with the updated cluster centers.
3. Repeat step 2 until all $\bar{d}$ for each cluster are within two standard deviations of the overall mean.

Since each fiducial placed on a patient has the same size and shape, the average distance to cluster centers is expected to be consistent. Steps 2–3 ensure that clusters classify each

fiducial correctly especially when oblong-shaped fiducials are placed close together. The Euclidean distance between each corresponding tongue fiducial was then calculated and the mean distance within each of the seven tongue regions was computed.

RESULTS

There were no intra- or post-operative complications associated with this study. All patients tolerated the application of the fiducial markers without adverse effect or increase in post-operative pain.

CT scans acquired with the 3D printed polymer laryngoscope showed a clear improvement in image quality as compared to ones acquired with the traditional metal laryngoscope (Fig. 5). The metal-induced streak artifacts common in CT have been completely eliminated through use of the polymer laryngoscope.

Figure 5 highlights the soft tissue deformations that occur prior to and during laryngoscopy. There was slight opening of the jaw and hyperextension of the neck after placement of the fiducials but prior to laryngoscopy (Fig. 5C). Large soft tissue deformations were observed for the tongue and larynx after the laryngoscope was introduced (Fig. 5D).

Image Segmentation and Visualization

3D models of the anatomical structures of interest were generated through image segmentation of the patients' CT scans. Alignment of the patients' preoperative and intraoperative models via the FMV coordinate system provided a visual and qualitative assessment of the small inter-patient differences in anatomy and positioning (Fig. 6A–D). For the preoperative states, the general positions of anatomical structures for each patient were almost identical. For the intraoperative states, the laryngoscope was consistently placed in the right side of the patient's mouth, with the tongue displaced to the left. The tip of the laryngoscope was placed consistently in the vallecula (i.e. the intersection of the tongue base and epiglottis); the associated depth varied slightly between patients due to anatomical differences. A side-by-side comparison of the preoperative and intraoperative states of one patient shows the significant soft tissue deformation due to the presence of the scope (Fig. 6E–H).

Mandible and Hyoid Movement Quantification

Mandible and hyoid bone translations and rotations resulting from the insertion of the scope were computed (Table I). All translations and rotations were referenced to the defined center of each structure. On average, the mandible was predominantly shifted 10.6 ± 3.7 mm outward in the negative y-direction and 6.3 ± 2.3 mm to the right in the negative x-direction. The hyoid, shifted 9.7 ± 4.2 mm down in the negative z-direction, 5.1 ± 4.1 mm to the right in the negative x-direction, and 4.9 ± 3.3 mm in the negative y-direction. The direction of these translations matches expectations based on how the inserted laryngoscope manipulates the jaw and surrounding soft tissue.

The segmented mandible and hyoid model from one patient was used to visualize the displacements that occur in all 8 patients (Figs. 7). Average center displacements for the

mandible and hyoid were respectively 12.6 ± 3.6 mm and 13.3 ± 3.1 mm, with small rotations primarily about the central x-axis ($-5.8 \pm 2.9^\circ$ and $11.3 \pm 7.4^\circ$, respectively).

Tongue Fiducials Displacement Quantification

The tongue and fiducials of each patient were segmented (Fig. 8a) and individually evaluated. The ProTack fiducials were much easier to position and secure surgically than the Ligaclips and were therefore used in later patients. Regardless of the metallic fiducial used, both were easily delineated from the surrounding soft tissue during segmentation and fiducial type did not impact evaluation of tongue deformation. Clips were well-distributed across all regions of the eight patients' tongue with the exception of one case, in which they were concentrated more distally. This resulted in no clips being classified in the three posterior regions for this one patient.

Fiducial displacements ranged from an average minimum of 8 ± 3.8 mm up to an average maximum of 43.7 ± 3.6 mm across all eight patients, with most of the translation being on the right side of the tongue (Table II). Average displacement of the seven different regions of the tongue were: Tip – 22.9 ± 6.9 mm, Center Left – 14.1 ± 10.0 mm, Center Middle – 19.8 ± 11.8 mm, Center Right – 26.3 ± 12.3 mm, Posterior Left – 18.8 ± 8.5 mm, Posterior Middle – 28.6 ± 6.6 mm, and Posterior Right – 35.4 ± 6.6 mm (Fig. 8D). There were statistically significant differences (t-test, $p < 0.05$) in average displacement between a few of the regions (Table III). Fig. 8C visualizes the direction of the post-instrumentation, region-specific translations.

DISCUSSION

Tissue deformations during laryngoscopy were visualized using our MR/CT-compatible laryngoscopy system. CT images were artifact-free which enabled segmentation and 3D model development of several key anatomical structures (mandible, hyoid, tongue). Both translational and rotational deformations of these anatomical structures were quantified. On average, at least 1 cm of displacement was observed in all patients for these structures (Tables I and II). This displacement can be inferred from the difference between the preoperative and intraoperative patient scans, and illustrates that there is significant upper aerodigestive tract deformation as compared to the repose state seen in preoperative imaging.

The similar translational magnitudes observed between patients for the mandible and hyoid bones (12.6 ± 3.6 mm for mandible vs. 13.3 ± 3.1 mm for hyoid, Table I) presents an opportunity to predict translation of these rigid structures during laryngoscopy. For soft tissue, the relatively small standard deviation in the min (8 ± 3.8 mm), max (43.7 ± 3.6 mm), median (25.3 ± 4.8 mm), and mean (26.1 ± 3.3 mm) of tongue fiducial displacement magnitudes across all eight patients further supports consistent and predictable deformation. Furthermore, the significant differences in displacement between various regions demonstrate that these regions of the tongue have distinct and predictable deformation. We hypothesize that by knowing the position of the scope (i.e. through instrument tracking) and how tongue deformation varies as a function of anatomic location (as shown here), one

could provide more predictive power in terms of estimating displacement direction once the scope has been introduced.

Though only the mandible, hyoid, and tongue structures were analyzed for this paper, extending this deformation analysis to critical sub-surface soft-tissues including tumor and vasculature is possible. Tumor and vascular deformation could be quantified using a split-bolus contrast-enhanced CT protocol⁷ (initial dose for slower uptake in tumor, followed by second dose to provide vessel contrast) to segment the respective structures pre- and post-instrumentation. Determining corresponding points in the pre- and post-instrumented images for vessels may be easier than for the tumors since vascular structures have a number of identifiable 3D features (e.g. points of vascular bifurcation), while the tumor may not. Similar to how tongue fiducials were used here, sub-surface fiducials (e.g. radio-opaque biopsy clips or beads) placed using intraoperative image-guidance could be used to mark the boundaries of the tumor; however, this approach could significantly increase operative time. As an alternative, the displacements of the bony structures and tongue fiducials could be used as control points for performing a point-based non-rigid registration, such as 3D thin-plate-spline³, between the pre- and post-instrumented states of the tumor. This approach would provide a good approximation of point correspondences from which a deformation field can be determined.

Significance

MR/CT-compatible instruments allowed for intraoperative imaging to capture the real deformation that occurs during instrumentation. Study of upper aerodigestive tract anatomic deformation due to instrumentation has important applications in surgical guidance for tumor resection, in airway management, and in speech motor control. Biomechanical models have been in development for anesthetists to predict difficult cases of intubation in advance²⁸. Lloyd et al developed an interactive finite element biomechanical model of the orofacial anatomy based on a CT to study speech synthesis²². Airway modeling has also been performed using physical in vitro models⁶, and using in vivo CT reconstructions²⁰. Our quantification of real anatomical deformations due to instrumentation can further advance and validate these models for more accurate predictive models.

For facilities with intraoperative imaging and guidance capabilities, deformable registration can be used to register surgical planning to the intraoperative images and provide guidance to the surgeon through image overlay during trans-oral procedures such as TORS. Such deformable image registration and guidance techniques have been explored and developed by Reaungamornrat and Liu et al^{21,27} on porcine and cadaver models that show promising results. Their simulated intraoperative deformation entails an extended neck, opened mouth, and an anteriorly-pulled tongue with sutures, but it does not include actual instrumentation. The authors addressed the challenge of imaging conventional stainless steel instruments and suggested the use of radiolucent instruments or advanced reconstruction algorithms. Our study addresses their former suggestion. Verifying their algorithms on our patient dataset is a viable next step.

Other registration techniques can also be explored that make use of the endoscopic camera or tracked tools to provide the intraoperative information needed for registration without

resorting to expensive intraoperative scanners (CT/MR). Sharma, Volgger et al used long-range optical coherence tomography to map the stenotic airway during suspension microlaryngoscopy^{31,35}. Rucker et al developed a mechanics-based non-rigid registration algorithm for liver surgery that uses a laser range scanner to obtain their sparse intraoperative data³⁰. These alternatives to conventional intraoperative imaging could provide enough information to perform registration with preoperative scans using predictive models and deformation algorithms. Our in-vivo data can serve as ground truth validation for these soft tissue deformation algorithms and models to further their development.

Even with the luxury of intraoperative imaging capabilities, there is a need for predictive models and registration algorithms for many surgical procedures, especially ones that involve soft tissue deformations. Current intraoperative CT/MR scanners are expensive and time-consuming. Movements can occur throughout the procedure, which would require a new scan if solely reliant on intraoperative imaging. Surgeons would be reluctant to perform a new scan either to save time or to minimize radiation dosage to the patient, but at the cost of using outdated images to guide their procedures. An accurate deformable registration will minimize the need for repeated intraoperative scans if not eliminate them all together.

Ultimately, improved surgical outcomes in TOS and reduced patient morbidity while minimizing cost is the goal. In this paper, the general deformation patterns of various critical structures are quantified so surgeons can use the distance and angle measurements to predict deformation while looking at the preoperative images. This data will also be used in future work to create and validate deformation models in TOS to further relief surgeons of this difficult mental task.

Limitations of the study

The data of this study is valid for the technique employed by the sole surgeon who performed all the procedures. General consistency could potentially be compromised with the slight difference in technique used by other surgeons. Additionally, the variability in inter-patient anatomy, in laryngoscope size and design, and in exact laryngoscope placement makes it difficult to generalize the deformations that occur during laryngoscopy. Though we do see fairly consistent results in terms of general magnitude and direction of deformation, we need more information and data to progress to the accuracy and precision required of surgical image guidance. We speculate that tracking the scope or using intraoperative imaging alternatives would provide the additional information to alleviate this issue; ideally, we would want to include data from numerous surgeons and various instruments in the future to present a more comprehensive analysis of instrumentation induced tissue deformation.

Furthermore, tissue heterogeneity is not explored in this paper. The different mechanical properties of tumor and benign soft tissue in the head and neck² are likely to influence the deformation due to instrumentation. The mechanical properties of laryngeal and pharyngeal tumors are not well-documented and additional data collected from patients with tumors is needed to better explore the impact on tissue deformation. Finally, while the procedures were performed by a single surgeon using a fixed protocol, the loading conditions between patients may have slightly varied. These loading conditions along with the mechanical

properties of the tissue influence the overall deformation observed. Instrumenting a laryngoscope with force sensors and tracking its position within the oral cavity to define loading conditions during laryngoscopy would be a useful way of evaluating the relationship between loading conditions and deformation. The force and scope position coupled with pre- and post-instrumented images could be used to validate and refine deformation modeling parameters and build upon the database of tissue mechanical properties found in literature.

Conclusion

Our MR/CT-compatible laryngoscopy system allowed for intraoperative imaging to visualize and quantify anatomical deformations during laryngoscopy. Deformations were quantified and observed to be consistent across patients. The models and measurements obtained here can serve as a reference of how the upper aerodigestive tract anatomy changes during instrumentation and can assist surgeons operating without intraoperative guidance. As an example, soft-tissue deformation was greater than 2 cm in the posterior aspect of the tongue where many of the more challenging to access tumors are located. By knowing the general deformation magnitude and direction, surgeons might improve their localization of tumors during the difficult mental registration task required during TOS where these large deformations are observed. In addition, the tissue deformations quantified here can also serve as a validation dataset for biomechanical models and registration algorithms. Future development of these models and algorithms could help lay the foundation for developing predictive models of instrumentation-related deformation to be incorporated in surgical navigation systems for TOS.

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ABBREVIATIONS

CT	Computed Tomography
MR	Magnetic Resonance
MRI	Magnetic Resonance Imaging
TLM	Trans-oral laser microsurgery
TORS	Trans-oral robotic surgery
TOS	Trans-oral surgery
FMV	Anatomical coordinate system defined by the Frankfurt plane ⁵ (auriculo-orbital plane), the mid-sagittal plane, and the vertical porion plane
ICP	Iterative Closest Point algorithm
SVD	Singular Value Decomposition

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Fig. 1.

An example of preoperative imaging (A) misrepresenting the intraoperative state (B) where the highlighted tumor region is deformed due to the laryngoscope. Image in (B) augmented from Amicus Visual Solutions: http://www.medicalexhibits.com/obrasky/2010/10052_07Ap1.jpg

Fig. 2.

(A) CAD model of the angular adjustment mechanism. The worm gear allows the surgeon to adjust the position of the laryngoscope to better visualize the patient's larynx. (B) A model depicting the laryngoscopy system in suspension. The large outer ring represents the bore of the scanner. The laryngoscopy system includes the 3D printed laryngoscope, the angular adjustment mechanism, the Plexiglas mounting frame spanning the patient's chest, and a stabilizing PVC support arm linking the worm gear and frame. (C) An intraoperative photo of the laryngoscopy system in suspension.

Fig. 3. FMV coordinate system used to align all the patients' data, composed of the Frankfurt, mid-sagittal, and vertical porion planes.

Fig. 4.

(A) Three points (P_{tip} , P_{mid} , and P_{cp}) manually chosen to define the tongue's mid-plane. A coordinate system is subsequently defined. (B) Seven vectors emanate from the new origin to produce seven surface seed points as defined by the intersections of the vectors and the surface of the tongue. (C) Voronoi tessellation with the seed points to delineate the tongue into seven regions. (D) Three views of detailed angle definitions of the vectors. (E) Another view of the defined tongue regions and their labels.

Fig. 5.

Comparison of a CT scan with the traditional metal laryngoscope (**A**) vs one with our polymer laryngoscope (**B**). Note the lack of CT image artifacts. Skull-registered sagittal CT images of the same patient taken after intubation but prior to instrumentation (**C**) and after introduction and suspension of our polymer operating laryngoscope (**D**). Note the large soft tissue deformation occurring during manipulation.

Fig. 6.

Top row: Visual overlay of the reconstructed models of all eight patients via FMV in preop (A, C) and intraop states (B, D). **Bottom row:** Model of one of the eight patients in preop (E, G) and intraop (F, H) states.

Fig. 7. Mandible (**left**) and Hyoid (**right**) translations and rotations after instrumentation. **Top row:** displacements (blue) from the original preoperative position (gray); **Bottom row:** vectors representing center displacements for each patient. Note that the mandible shifted outward and to the right of the patient while the hyoid predominantly shifted down, to the right, and outwards.

Fig. 8. (A) Segmentation of patients' tongue and fiducials in skull-registered preoperative and intraoperative states. (B) One example of tongue fiducials segmented and classified into the seven regions. (C) Tongue fiducials average displacements for the seven different regions across all patients. (D) Quantification of tongue fiducials average displacement for the seven regions. For the averages in the posterior regions, N=7 because one patient did not have clips there.

Table 1

Mandible and hyoid translations and rotations after instrumentation

<i>Mandible</i>	t_x	t_y	t_z	t_{mag}	a_x	a_y	a_z
Avg	-6.3	-10.6	0.8	12.6	-5.8	1.7	-4.5
Std	2.3	3.7	0.9	3.6	2.9	1.0	2.4
<i>Hyoid</i>							
Avg	-5.1	-4.9	-9.7	13.3	11.3	-4.5	1.6
Std	4.1	3.3	4.2	3.1	7.4	2.3	5.8

(t_x, t_y, t_z, t_{mag}) (a_x, a_y, a_z) in degrees.

Tongue deformations characterized by displacements of fiducials on the tongue across all patients

Table II

	min.	max.	med.	mean	Tip	Cen. L	Cen. M	Cen. R	Pos. L	Pos. M	Pos. R
Avg	8.0	43.7	25.3	26.1	22.9	14.1	19.8	26.3	18.8	28.6	35.4
Std	3.8	3.6	4.8	3.3	6.9	10.0	11.8	12.3	8.5	6.6	6.6

Units in mm.

Table III

Tongue displacement differences between the seven regions (t-test)

	Tip	Cen. L	Cen. M	Cen. R	Pos. L	Pos. M	Pos. R
Tip	-	0.0590	0.5350	0.5026	0.3228	0.1280	**0.0035
Cent L		-	0.3129	*0.0464	0.3447	**0.0062	***0.0004
Cent M			-	0.2992	0.8560	0.1072	**0.0090
Cent R				-	0.1989	0.6754	0.1075
Back L					-	*0.0334	**0.0016
Back M						-	0.0776
Back R							-

p-values: <0.05*, <0.01**, <0.001***