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Motion of apical and laminal /s/ in normal and post-glossectomy speakers.

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Abstract: There are two ways to produce an /s/ in English: apical and laminal. They are almost identical perceptually and the reason for choosing one type is not well understood. This study questions whether one type is preferred in certain conditions, such as high vs low palate height or in post-surgical tongue adaptation. This study examines palate height, and motion of critical and non-critical tongue regions in 8 normal speakers and 8 post-glossectomy patients who have had surgical resection of squamous cell carcinomas of the tongue. Speech was recorded with tagged-MRI and processed to track displacement and velocity of 2-D midsagittal tongue tissue points in the tongue tip and body during the utterance of the word "a souk". Results indicate that subject category had a greater effect on /s/ motion than palate height. Both critical and non-critical articulators in subjects with apical /s/ used higher velocity and displacement on average than subjects with laminal /s/. Compared to patients with larger resections, patients with smaller resections had larger velocities and displacements in both tongue areas suggesting less debility. The single patient with flap reconstruction showed the highest velocity and greatest displacement, suggesting a different type of articulatory compensation.
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1. Introduction

The function of the tongue involves a highly complex coordination of its different muscles to produce the precise movements necessary for proper speech, mastication, and deglutition. The tongue is a muscular hydrostat[5], with no bones or joints, which means it requires an architecture of 3D orthogonal muscles to move and deform it when producing speech. Furthermore, muscles maintain a constant volume when they deform. Therefore, loss of tongue mass and motor control, which occur during glossectomy surgery, creates challenges in reaching the palate and elevating the tongue tip during speech.

Oral cancers have the 7th highest incidence in the United States and squamous cell carcinoma of the tongue is the most common intraoral malignancy, accounting for 25-40% of oral carcinomas. Tongue cancer has recently increased 5-6-fold in younger adults aged 20-44 years and 2-fold in older adults[10]. Glossectomy is resection or amputation of the tongue, and is the most common treatment of tongue cancer in the US. The tongue may either be closed primarily or reconstructed, oftentimes with a free flap[15]. Patient adaptation to removal of tongue tissue and the type of closure procedure that best allows patients to retain function after surgery are not well understood.

This study considers patient adaptation in the sounds /s/ and /k/. One of the more difficult sounds for glossectomy speakers is the /s/. This sound requires precise placement of the tongue and jaw to produce a narrow constriction in the alveolar region of the palate and direct the airstream toward the incisors; slight errors are acoustically salient. Interestingly, the normally spoken /s/ can be produced using at least two different gestures. The apical /s/ uses the tongue tip to contact the alveolar ridge, the laminal /s/ uses the tongue blade[3]. These gestures are both quite prevalent among normal speakers and there is no known determinant for a speaker's use of one versus the other. For the glossectomy patient, however, tongue tip control may be impaired, so that laminal /s/ may be easier to produce. The /k/ sound requires tongue body elevation, which may be impaired by the loss of tissue and resulting difficulty elevating the tongue since its mass cannot be increased. It was previously shown that post-operative tongue function is positively correlated with the volume of tongue tissue remaining[8]. The present study examined patients whose resection is in the lateral margin, on one side of the tongue only, and midway between the anterior and posterior tongue. In all cases the tip has been preserved. However, tongue tip innervation is damaged, because the resection cuts many of the nerves that flow into it. It is the goal of this study to determine if glossectomy patients who produce a normal sounding /s/ differ from controls in the /s/ type produced, and whether closure procedure plays a role.

Measuring tongue motion during speech is difficult because the tongue is deep within the vocal tract, has a high number of degrees of freedom, and its functional motion is rapid. Cine-MRI has been previously used to study tongue surface motion in the sagittal plane[13]. Cine-MRI data provides information on tongue surface motion, but tells nothing of the internal deformation of the tongue, which is important in a muscular hydrostat. Tagged MRI (tMRI) was developed as a means to visualize the internal muscle of the myocardium[1]. tMRI places temporary tags within the muscular tissue, which move with the tissue. The tags are tracked using the Harmonic Phase (HARP) method, which tracks every pixel in the MR image so that data in between the tags of t-MRI is not lost[9]. The tracked tags provide detailed information about soft-tissue deformation, which makes it possible to compute many other regional function measurements, such as, displacement and velocity.

The purpose of this study is to quantitatively compare the changes in tongue motion due to the glossectomy surgery relative to normal controls. The study will evaluate the effects of subject group, resection size, closure procedure and s-type on the velocity and displacement of the tongue during speech.

2. Materials and Methods

2.1 Subjects and Speech Tasks

Two subject groups consisted of eight glossectomy patients and nine normal controls respectively. Five patients had T1 (< 2cm in longest dimension), and three had T2 (2-4cm) squamous cell carcinomas with no nodal involvement or metastasis. Tumor location was limited to the freely movable tongue from the circumvallate papilla anteriorly to the junction of the tongue with the floor of the mouth. All patients were at least 8 months post surgery and had a partial, unilateral, glossectomy with tip preservation. Seven of the glossectomy patients had primary closure of the surgical site and one or the T1's had a radial forearm free flap (RFFF) reconstruction. All subjects had a hearing test to confirm normal hearing and speech reception threshold since deficits in these areas can affect speech production quality.

The speech task was the word "a souk." This task was within the MRI repeat time of 2 sec per utterance, which includes a breath. This task initially requires tongue-tip elevation into the /s/ followed by tip lowering and retraction of the tongue body into /u/, and then elevation of the body into /k/. It begins with a neutral vowel and maximizes tongue deformation by engaging the jaw very little

2.2 Instruments: MRI Recordings

MRI Procedures: Cine-MRI and tagged-MRI were collected on a 3.0 T Siemens Tim Treo, with 8-channel Head and Neck coil. A 1-second speech recording was made with 26 time-frames/sec. In-plane resolution was 1.875 mm/pixel and slice thickness was 6 mm. FOV was 24 cm. Multiple repetitions were summed to create each slice: 5 for Cine, and 3 for tagged. However, 4 tagged collections were needed to acquire a cosine and sine triggered data set for both the vertical and horizontal tags[7]. The number of slices collected varied based on the size of the subject's tongue. Tagged-MRI and cine-MRI images were collected in identical sagittal planes, only the midsagittal data are presented here.

The patients were recorded repeating "a souk" using cine-MRI and tagged-MRI. In the MRI machine subjects wore earphones to reduce noise, and to hear the acoustic metronome cue. A trigger system, based on the work of Masaki et al. ([6]) and Shimada et al. ([11]), was used to provide metronome cues to the subject and to synchronize speech onset with acquisition of MRI data.

2.3 Data Reduction and Analyses

Two tissue points were chosen just inferior to the tongue tip (TT) and the tongue body (TB) in the locations that contacted the palate during /s/ and /k/, respectively. These points were tracked over all time frames (TFs). Displacement and velocity of each point were calculated for each subject relative to resting position (TF-1). Further calculations were made including:

- Ds_{TT} , displacement of the tip during /s/, is the largest displacement up to 4 TFs before tongue-palate contact for /s/. Displacement of the tongue body (Ds_{TB}) was noted during that same TF.
- Vs_{TT} and Vs_{TB} - average velocity between TF-1 and /s/-contact for the tip and body.
- Dk_{TB}, displacement of the tongue body during /k/, is the largest displacement of the tongue body within 2 TFs before /k/ contact. Displacement of Dk_{TT} was noted during that same TF.

Statistical Analysis: A power analysis was not performed in this study because glossectomy, being a rare condition, there was not enough prior information available in the literature. One-way Analysis of Variance (ANOVA) was used to compare the separate effects of resection size, closure procedure, and glossectomy vs. control on mean velocity and displacement of the two points on the tongue tip and body during speech. Two-way ANOVA was used to evaluate the effects of s-type and surgical status on the Mean V and MaxD during speech. A $P \leq 0.05$ was considered significant. Because the N was small, any result from P=0.051 to P=0.12 was reported as a trend.

3. Results

The effect of subject group was considered on tongue displacement and velocity. A trend was seen in tongue tip displacement during production of /k/. Dk_{TT} was larger in patients (2.93±1.7mm) than controls (1.78±0.96mm), (F=3.136, P=0.10)). There were no significant differences between groups for tongue body displacement (P=0.66). Subject group also did not significantly affect the amount of displacement occurring during the /s/ (Ds_{TT}: P=.34, Ds_{TB}: P=.92). The effect of subject group on mean velocity into the /s/ was also non-significant (Vs_{TT} , P=0.25, Vs_{TB} , P=0.97).

The effect of /s/-type was also examined. There were no significant effects of /s/-type on displacement of the critical articulator (Ds_{TT}, P=.46; Dk_{TB}, P=.82). There was a trend for the tongue tip to move faster during apical /s/ (11.50±3.1mm/s) than laminal /s/ (8.38±4.1mm/s) (Vs_{TT}, P=.14), but no effect was seen in the body (Vs_{TB}, P=.74). There was no significant interaction between subject group and /s/ type, either during the /s/ ($Ds_{TT,}$, P=.75; Ds_{TB} , P=.99) or the /k/ (Dk_{TB} , P=.25; Dk_{TT} , P=.96). There were no significant interactions between subject group and /s/ type for velocity (Vs_{TT}, P=.36; Vs_{TB}, P=.99)

Interpatient comparisons showed that tumor sizes had a significant effect on critical articulators. Ds_{TT} was significantly faster for T1 (11.66±3.5 mm/s) than for T2 patients (4.76±3.2 mm/s) (F=7.85, P<0.03). A trend showed greater Dk_{TB} for T1 (5.06±1.0mm) than T2 patients (3.46±1.6) (F=3.31, P<0.12). There was no significant difference in Vs_{TB} (P=0.94) or Ds_{TT} (P=0.276). One patient, who had a flap reconstruction, had faster tongue tip and body motions, and greater displacements (See Table 1).

Table 1. Mean Velocity and Maximum Displacements in patients with primary closure vs RFFF.

Closure Procedure	N	Vs_{TT} (mm/s)	Vs_{TB} (mm/s)	Ds_{TT} (mm)	Dk_{TB} (mm)
Primary	7	8.48±4.8	8.17±4.0	3.45±1.6	4.21±1.3
Flap	1	13.18	11.59	7.73	6.25

4. Discussion

4.1 Surgical Status

Glossectomy patients had a trend toward a larger tongue tip displacement during the /k/ than the controls. In most of the subjects the tongue body reached its maximum displacement during the /k/. As the tongue transitioned from the /s/, through the /u/ and /k/, the tongue body was elevated toward the palate as the tongue tip was retracted. One explanation for the larger tip displacement during /k/ is the reduced tongue volume in glossectomy patients. As a muscular hydrostat, the volume of the tongue remains constant as the tongue is deformed during speech. As the tongue body is elevated to form the /k/, the width and length of the tongue must decrease to accommodate this upward expansion. Reduced tongue volume requires a greater decrease in the length and width to achieve palatal contact.

No differences were found in mean velocity of the tongue tip or body into the /s/. For the tongue body, normal velocity can be attributed to the musculature and motor innervation being unaltered by the glossectomy surgery, leading to no post-surgical difference in the functionality. For the tip, it might be that compensation was provided by the fully innervated, unaffected side of the tongue. However, normal tongue velocity may not correspond to acceptable speech. Bressman and colleagues [2]found decreased speech acceptability in patients with partial lateral glossectomies due to decreased control of midline grooving and overall tongue symmetry, which are important in forming the /s/.

No significant differences were found in the maximum displacement of the tongue tip or body, or in the displacements of the tip and blade into /s/ and /k/. These findings can be explained by compensation from the unaffected side. In addition, the palate assists in making consonant sounds by providing a boundary and a structure to brace the tongue against. Previous research by Stone et al. (2009) found that compared to controls, glossectomy patients showed altered motion of the tongue in the transition from /u/ to /k/ attributed to rigidity of scar tissue, larger forces required to move the weight of a flap reconstruction, or adaptation to scar tissue and/or flap reconstruction. In spite of this evidence, this study found there to be unaltered displacement into the /k/ in glossectomy patients. This suggests that although the internal tongue motion may be altered in glossectomy patients, the tongue is able to compensate to elevate the tongue body to produce palatal contact.

The tongue tip displaced similarly across subject groups when it was a critical and non-critical articulator. The tongue body, however, was displaced more by patients during critical articulation than non-critical articulation, but not by controls. This may indicate that the patients used the body to assist the tip during /s/ rather than elevate in preparation for the upcoming /u/ and /k/.

4.2 Resection size

Patients with larger resections had a statistically slower tongue tip velocity into the /s/ than patients with smaller resections. As the size of the resection increases, damage to the musculature and innervations will increase. Slowing the tip would allow improved precision of the /s/. The tongue body velocity was similar across resection sizes. The effects of the resection would be greater on the tip because of its location. The musculature and innervation of the tongue body were relatively unaltered by the surgical procedures used here, therefore the body should retain its function better than the tongue tip.

This may be explored further by comparison with the controls. Tongue tip displacement was not different between patients and controls. Moreover, there were no significant differences noted in Ds_{TT} and Dk_{TB} in glossectomy patients with smaller and larger resection sizes. Since the V_{TT} was slower, but the displacement was the same, it would be expected that the production of the /s/ along with other sounds requiring the use of the tongue tip may take the patients longer to form. In order to properly form the /s/ the tongue tip must be brought forward in the mouth to contact the palate. Likewise, proper formation of the /k/ requires the body of the tongue to be elevated until palatal contact is made. It is reasonable, therefore, to find a lack of difference in displacement due to resection size, because the tongue is required to displace a given amount, regardless of the rate at which it is moved. Therefore, the slower tongue tip motion for T2 than T1 patients, may represent slower speech for tongue-tip sounds, not greater precision. The slower tongue tip velocity in patients with larger resections may be an indication of greater speech impairment, which is consistent with previous research that found the post-operative assessment of speech to be positively correlated with the amount of tongue tissue remaining[8] . Additional examination of overall phoneme timing is needed.

4.3 Closure Procedure

There was only one subject with flap reconstruction so no statistical tests were carried out. Compared to patients with primary closure, the flap patient had the fastest tip and body velocity and the greatest maximum displacements of any patient. This finding may indicate better compensation for the missing tongue tissue due to the flap. The flap increases overall tongue volume, but adds bulk and weight to the tongue. This could slow the tongue, but does not appear to. The flap may stabilize the tongue by contacting the palate and allowing better control. More data is needed to assess if this finding occurs with other flap reconstructions.

There is conflicting evidence in the literature on the effects of the closure procedure on the post-operative speech. Some found post-operative speech to be more lucid with primary closure[4]), others found this to be true with flap reconstruction[14], and a third source found no significant difference in post-operative speech between the closure methods[8]. The results here indicate possible quantitative differences in tongue motion in flap patients that may be consistent with altered post-operative speech.

The increased MaxD of the flap patient appears to be consistent with the findings of Stone and others[12] who found a difference in the mechanics of the inferior longitudinal muscle in flap-reconstructed glossectomy patients. Production of /s/ required increased elongation of the inferior longitudinal muscle. In the transition from the /s/ to /u/ normal speakers compressed the two ends of the tongue and elevated the middle of the tongue while rotating the inferior longitudinal muscle. The flap reconstructed patient appeared to rotate the tongue backward around a central core located within the flap with no rotation within the inferior longitudinal muscle. This could be an explanation for the increased displacement noted in the flap patient here as well.

4.4 /s/-type

There was a slight trend for the tongue tip to move slower during laminal /s/ than apical /s/. It has been observed in other datasets, though not this one, that glossectomy patients tend to prefer laminal s-type over apical s-type. A slower tongue tip could explain this preference. More data needs to be examined to support this claim, however.

4.5 Study Limitations

The major limitation in this study is the small number of subjects, which did not lend for many significant findings. Therefore, many of the observations that were made cannot be conclusive, but still help to clarify some of the changes in tongue motion that are occurring due to glossectomy. In addition, all of the measurements made in this study were done in the 2D mid-sagittal plane of the tongue and 2D and 3D differences in the sides of the tongue were not accounted for. Changes in the right and left halves of the tongue are particularly important in these patients since only one half of the tongue was primarily affected by the tumor and resection. This study is on-going and new subjects are currently being recruited. As more data becomes available, further analysis will enable us to refute or accept the findings here. This study serves as a guide for future research as it highlights areas worthy of further exploration and sets a baseline level of knowledge about kinetic changes the post-glossectomy tongue.

5. Conclusions

Although this line of research was limited by the number of subjects available for study, several interesting findings were made that warrant further investigation. The lack of differences in tongue motion between normal controls and glossectomy patients, suggests retention of tongue mobility post-glossectomy. Patients with larger resections had more difficulty in tongue tip control during speech and the one flap reconstruction patient also showed highly altered tongue motion. S-type was not found to have an effect on tongue motion. The findings suggests that post-glossectomy debility in speech found in previous studies is more likely attributed to qualitative, rather that quantitative changes in tongue motion. Removal of tongue tissue with/or without reconstruction appears to alter deformability of the muscular tongue hydrostat in a manner not sufficiently described in quantitative terms of velocity and displacement. A more complex method for evaluating 3D deformation must be developed to clarify the complex deformation of the tongue and how it is affected in the post-glossectomy patient.

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