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Research Article

The Effects of Palate Features and Glossectomy Surgery on /s/ Production

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Purpose: The aims of this article were to determine the effects of hard palate morphology and glossectomy surgery on tongue position and shape during /s/ for patients with small tumors. The first expectation was that laminal /s/ would be more prevalent in patients, than apical, due to reduced tongue tip control after surgery. The second was that patients would hold the tongue more anteriorly than controls to compensate for reduced tongue mass.
Method: Three-dimensional tongue volumes were calculated from magnetic resonance imaging for the whole tongue and the portion anterior to the first molar during the /s/ in /əsuk/ for 21 controls and 14 patients. These volumes were used to calculate tongue anteriority and cross-sectional shape. Dental casts were used to measure palate perimeter, height, and width of the hard palate.
Results: Palate height correlated with tongue height in controls ($p < .05$), but not patients. In patients, tongue anteriority correlated negatively with canine width and cross-sectional tongue shape ($p < .05$). Controls with a high palate favored laminal /s/. Patients preferred laminal /s/ regardless of palate height ($p < .01$).
Conclusions: For controls, hard palate height affected tongue height; a higher palate yielded a higher tongue. For patients, hard palate width affected tongue width; a narrower palate yielded a more anterior tongue. Tongue shape was unaffected by any palate features. Preference for /s/ showed an interaction effect between subject and palate height. Controls with high palates preferred a laminal /s/. All patients preferred a laminal /s/; glossectomy surgery may reduce tongue tip control.

The present study uses magnetic resonance imaging (MRI) to examine three-dimensional (3D) tongue behavior during the consonant /s/ spoken by controls and patients that have undergone glossectomy surgery. Glossectomy patients have had part of their tongue removed surgically due to cancer. The tongue normally produces the sound /s/ by elevating the tongue tip or blade, grooved at the midline, against the alveolar ridge. Elevation and grooving of the tongue tip can be challenging for glossectomy patients, however, as tongue size is reduced and innervation of the tip is diminished (Borggreven et al., 2005; Mády et al., 2002; Nicoletti, Soutar, Jackson, Wrench, & Robertson, 2004). The present study examined how glossectomy speakers adapt their tongue behavior to produce /s/ despite the loss of lingual tissue and the reduced innervation. In order to correctly ascertain the effect of the missing tissue on tongue shape and position, however, it is valuable to identify whether normal variation in hard palate morphology affects tongue position during the production of /s/ and whether any palatal variations are more or less advantageous to glossectomy speakers.

Impact of Palatal Features on Tongue Placement

The hard palate (hereafter, palate) and teeth create peripheral limits within which the tongue can travel. They are also crucial to the formation of /s/ as lateral tongue pressure against the palate and teeth produces the midline groove and directs the airstream anteriorly into the incisors. Examinations of normal variation in palate height have shown palate effects on several English speech sounds, particularly those made near the palate. During high vowels (ɪ, i, e, u), tongue height varied directly with palate height (Hasegawa Johnson, Pizza, Alwan, Cha, & Haker, 2003). Likewise, high front vowels and /j/ showed more articulatory variability for speakers with high palates than those with low palates (Brunner, Fuchs, & Perrier, 2009). Palate height also appears to affect how subjects contrast the articulation of /s/ versus /ʃ/; speakers with high palates used a higher tongue body during /ʃ/ as well as tongue retraction

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to make the contrast (Weirich & Fuchs, 2013). The present study will examine the effects of palate height on tongue behavior during /s/ and will include other measures that have not been previously studied, namely, palate width and palate perimeter, which are defined by the teeth.

In American English, the teeth are the lateral contact point for the tongue in /s/ (cf. Stone & Lundberg, 1996). Many dental procedures change the position or shape of the teeth and, thus, the perimeter shape of the hard palate. Because the /s/ is dependent on dental anatomy, the success of dental procedures is often assessed by determining the quality of /s/ (cf. Fujiso, Nozaki, & Van Hirtum, 2015; Mehringer, 1963; Runte et al., 2001). Fujiso et al. (2015) indicated that a speech screening tool to qualitatively assess dental procedures is best when using the fricative /s/, due to its reproducibility, consistent air flow, and intraoral pressure. In addition to the alteration of /s/ by dental treatment, natural malocclusions and dental variability can also have an effect on speech. The following dental features have been associated with /s/ errors: canine width, high palate, open bite, degree of protrusion, spaces, rotation of anterior teeth, and the thickness of the alveolar ridge in the upper anterior region (Rathbone & Snidecor, 1959). Despite the evidence that the perceptual quality of /s/ is affected by palate features, such as height and dentition, it is not understood how *tongue behavior* is affected by palate feature differences. Thus, the present study examined the effects that ordinary variations in palate features have on tongue position and tongue shape during /s/ in English.

Glossectomy

The morphology of the tongue is changed by glossectomy surgery. Although tongue anatomy is fairly consistent across healthy speakers (Stone et al., 2016), speakers who have undergone glossectomy surgery, to remove lingual cancer, have notable changes in muscle anatomy and motor control due to loss of tissue. Squamous cell carcinoma accounts for approximately 90% of all oral cancers (Quintero, 2010) and is responsible for approximately 95% of tumors within the tongue (Moore, Johnson, Pierce, & Wilson, 2000), specifically the lateral border. The extent of the tumor is classified via the tumor–node–metastasis system (Greene et al., 2015), which can be used to aid in prognosis. Glossectomy surgery includes resection (removal) of the entire tumor, along with a 1–1.5-cm margin of clean tissue around the entire perimeter of the tumor. The size of the tumor and the treatment method have the largest impact on the functional recovery (Nicoletti et al., 2004). In small tumors, the majority of the tongue musculature remains intact and is able to compensate for the missing tissue.

Insight from these adaptations could provide insight into therapeutic modifications to aid patients with larger resections. Thus, the present study examined glossectomy speakers with small tumors, and controls, to determine whether glossectomy /s/ formation is affected more by tongue parameters or by palate parameters.

To produce an /s/, the anterior tongue is carefully positioned behind the incisors with full lateral palatal contact to prevent any air from escaping laterally. The cross-sectional shape of the tongue near the constriction contains a groove that funnels and directs the air stream to the lingual surface of the maxillary incisors. Even tongues with small resections, however, may produce /s/ in different manners from intact tongues. Glossectomy patients must overcome excised muscles and nerves to produce a midline tongue groove and to position the constriction at the alveolar ridge for /s/. Bressman, Jacobs, Quintero, and Irish (2009), for example, studied 21 English consonants in glossectomy patients and found /s/ to be one of the four most distorted consonants. With less tongue mass than controls, patients may use greater forward positioning of the tongue or a thinner shape, which might distort the /s/.

Apical Versus Laminal /s/-Type

In actuality, there is an additional feature of /s/ that may prove challenging for glossectomy speakers, which has been overlooked in the study of glossectomy speech. In English, there are two types of /s/ production (cf. Dart, 1991). The first type, apical /s/, elevates the tongue tip to create the constriction that generates the /s/ turbulence. The second, laminal /s/, elevates the tongue blade to create the constriction with the alveolar ridge, and the tip is lower. These two types are virtually identical acoustically and are often considered to vary idiosyncratically. There is previous evidence, however, that both glossectomy surgery and palate height affect /s/-type. Stone et al. (2013) found that controls with low palates tended to use apical /s/ and controls with high palates tended to use laminal /s/. Patients, however, were more likely to use laminal /s/ irrespective of palate height. The present study extends this work by measuring the effect of additional palate features and objectively measuring tongue position and shape.

This study focuses on two questions: (a) Does a speaker's palatal anatomy influence their preferences for apical versus laminal /s/ production, tongue shape, or tongue position? (b) Does tongue surgery have an impact on these relationships? To answer these questions, this study measures two tongue and four palate features: the percentage of the tongue that is in the anterior oral cavity (anteriority), the shape of the tongue near the vocal tract constriction, as well as palate height, palate width at two locations, and palate perimeter.

Method

Subjects

Thirty-five subjects consisting of 21 controls (8 white males [WM], 3 African American males [AAM], 6 white females [WF], 4 African American females [AAF]; mean age = 36.6; age range = 22–59) and 14 patients (10 WM and 4 WF; mean age = 47.3; age range = 29–61) were used in this study. All subjects were native American English speakers from the Maryland–Pennsylvania region and in good health, except that the patients had glossectomy surgery. All subjects had dental casts of their teeth available for measurement and had no interdental spacing due to missing teeth. We did include five subjects (three controls, two patients) who had previous bilateral extraction of the premolars. The extraction spaces were closed orthodontically so there was no interdental spacing. Premolar extraction alters the palatal proportions by disproportionately decreasing the subject's ratio of palate length to canine width due to a shortened palate perimeter but a maintained canine width. All subjects had good-quality MRI data.

Patients were studied between 9 months and 8 years following the surgical removal of squamous cell carcinoma at Johns Hopkins Hospital or the University of Maryland Hospital. Tumors were in the lateral margin of the tongue and small in size. In the opinion of the surgeons, a delay of 8 months post-surgery was sufficient for good recovery of speech for patients with no radiation. Seven patients had T1 tumors (< 2 cm longest dimension), the other seven patients had T2 tumors (2–4 cm longest dimension), and all were N_0 (no lymph node involvement) and M_0 (no presence of metastasis). Partial glossectomy surgery removed the unilateral lingual tumors, without crossing the midline and, in all cases, preserving the tongue tip. One T2 patient (#28) had a radial forearm free flap closure procedure. All other patients received primary closures in which the resection was sutured.

Two types of perceptual tests were run. First, intelligibility scores from the Sentence Intelligibility Test (Yorkston, Beukelman, & Tice, 1996) were determined for the patients. Two judges (one dentist and one dental student) listened to audio tapes and wrote down the sentences. Their scores, though almost identical, were averaged. The T1 patients were all 99%–100% intelligible. The T2 patient intelligibility percentages were 94, 95, 98, 99, 100 × 3. The second perceptual test was a comparison of patient productions of /s/ and /ʃ/. These two consonants were repeated by the patients in vowel–consonant–vowel sequences (VCVs), five times each, with /V = i, a, u/, yielding 15 tokens of each consonant. Three judges (one speech-language pathologist and two dentists) listened to a recording of these VCVs for all patient data in randomized order and identified each consonant as /s/ or /ʃ/. The results showed that for three patients, /s/ was perceived occasionally as /ʃ/ by at least one judge. Patients 22 and 24, both T1s, had two of 15 /s/ tokens misheard as /ʃ/ by one judge. Patient 34, a T2 and the only patient who underwent post-surgical radiation, had five of 15 tokens misheard by all three judges.

Speech Task

The phrase /əsuk/ (pronounced "a souk") was chosen as the speech task for multiple reasons. The duration of /əsuk/ is less than 1 s, which is within the tagged MRI data collection time limit (tagged data not used in this study). The first phoneme, /ə/, provided a neutral tongue position and a vocal tract shaped like a uniform tube. It served as a reference position against which to measure the other sounds. The second syllable, /suk/, used primarily backward tongue motion providing fairly simple tongue deformations. It also used the high vowel, /u/, which minimizes jaw motion, thus requiring vocal tract shaping to be done primarily by the tongue. The /s/ time frame was identified previously by three independent judges and categorized independently as apical or laminal by visual inspection using criteria consistent with Dart (1991). Disagreement by one was addressed by consultation among the three judges.

MRI Instrumentation and Recording

In order to perform this study, various instruments were used to collect the necessary data: high-resolution MRI (hi-res MRI), cine-MRI, and digitized dental casts. The tooth roots of the first molar (M1) and the second premolar (PM2) were identified in the hi-res MRI data and served as landmarks for measures of tongue anteriority (Ant%) and cross-sectional tongue shape ($Tng_{H/W}$). Hi-res MRI provides excellent anatomical information, but it can take as long as 1 min to acquire enough images to reconstruct a 3D volume. Therefore, tongue motion was studied using cine-MRI data. Cine-MRI uses shorter time frames to create a movie, although it has poorer spatial resolution and, therefore, less "crisp" anatomic detail. Cine-MRI was used to choose time frames corresponding to phonemes of interest such as /s/ and /ə/ and to measure the volume of the whole and anterior tongue.

A 3.0 Tim Trio MRI machine was used with a 12-channel head coil and a 4-channel neck coil using a segmented gradient echo sequence (Siemens Healthcare GmbH, 2017). In addition, a T2-weighted Turbo Spin Echo sequence with an echo train length of 12 and echo time/repetition time (TE/TR) of 62 ms/2500 ms was used. The field of view is 240 mm × 240 mm with a resolution of 256 × 256. Each data set contains a sagittal, coronal, and axial stack of images encompassing the tongue and surrounding structures. Cine-MRI creates a single movie by an ensemble summation of multiple repetitions of the speech task. Each repetition of the task is broken down into 26 time frames of 0.038 ms each and recorded separately. Each time frame (1–26) is averaged with the same time frame from all repetitions to boost signal strength because the signal emitted by the hydrogen protons in the short time frame is quite weak. The cine-MRI recordings were made during a 1-s recording period within a 2-s repeat cycle. There were 5–9 sagittal, 8–10 coronal, and 8–12 axial tissue slices. The speech task was repeated five times per tissue slice and summed up to yield one cine-MRI movie per slice, with 26 time frames and a 1-s duration. The recording time was 20 min per word, including the collection of tagged data not used in this study. In-plane resolution was 1.875 mm × 1.875 mm, and slice thickness was 6 mm. Subjects spoke the words to a 4-beat metronome to increase the precision of repetitions (Masaki et al., 1999). The subjects were trained for 10–15 min to repeat /əsuk/ to this 4-beat metronome, where each beat signaled a task: 1—/ə/, 2—/suk/, 3—inhale, 4—exhale. The same speech task and metronome were used inside the scanner. Experimenters listened to the speaker to assure they followed the beat; subjects that did not have measurable data were excluded as described under Subjects. Speech was recorded in the MRI scanner using a noise-cancelation fiber-optic microphone (OptoAcoustics Ltd.). The MRI audio recordings contained the beats, the MRI noise, and speech. Although noisy, the audio files could be used to synchronize phonemes manually to the MRI frames of interest.

For both hi-res and cine-MRI, tissue slices were collected separately for each orientation (sagittal, coronal, axial) with a rest between. The hi-res MRI was collected with T2 weighting, and subjects held their tongue still for approximately 1 min for each of the three orientations. The hi-res MRI in-plane resolution was 0.9 mm, and slice thickness was 3 mm. Two hi-res slices fit within one cine slice and, thus, were spatially aligned.

MRI Post Processing

Three-dimensional super-resolution volumes (hereafter, supervolumes) were created from the two-dimensional MRI images as follows. The raw MRI images contained anisotropic voxels (Cine: 1.87 × 1.87 × 6 mm; Hi-res: 0.97 × 0.97 × 3 mm). The supervolume construction interpolated the slices to create isotropic voxels with the in-plane resolution in all three dimensions: 2 × 2 × 2 mm and 1 × 1 × 1 mm (Woo, Stone, & Prince, 2015). Supervolumes were created for a hi-res set and each of the 26 time frames of the cine speech task. An enhanced supervolume was created for the /ə/ and /s/ time frames by overlaying the high-resolution maxilla onto the cine supervolume (Hwang, 2015).

Change in Anteriority

Anteriority was defined as the percent of the tongue volume anterior to M1. To calculate anteriority, the whole tongue was segmented manually from all 26 tongue supervolumes for each subject, using custom software (Lee et al., 2014; Figure 1). Segmentation was done by labeling the voxels inside the tongue border as "tongue." The tongue volume (V_{Tot}) was calculated by summing up the number of voxels labeled as tongue using ITK-SNAP (Yushkevich et al., 2006). To calculate the anterior volume (V_{Ant}), a cutoff plane was created, based on the position and angle of the M1 roots in the enhanced supervolume for /ə/ and /s/. This location was chosen because it maintained the entire tip and much of the blade in the anterior region. The cut was done by selecting three points—one at each M1 alveolus and a point mid palate that was perpendicular to the occlusal plane. These three points were used to slice the segmented tongue at M1 (Hwang, 2015). This plane determined how much of the tongue was anterior to M1 (see Figure 1b). Anteriority was defined as V_{Ant} divided by V_{Tot}. Change in anteriority from /ə/ and /s/ (ΔAnt%) was used for the statistical analyses using Equation (1).

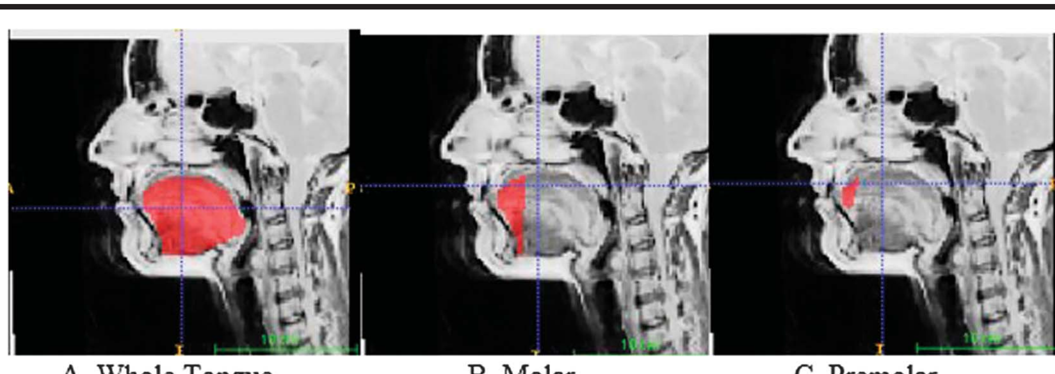
$$\Delta\text{Ant\%} = \left[(V_{\text{Ant}}/V_{\text{Tot}})_{ə} - (V_{\text{Ant}}/V_{\text{Tot}})_{s}\right] \times 100 \quad (1)$$

The variables in Equation (1) are defined as follows: ΔAnt% = change in percent of anteriority from /ə/ to /s/; V_{Ant} = volume of tongue anterior to M1; V_{Tot} = total tongue volume. ΔAnt% is a standardized value that measures the percent change between /ə/ and /s/, thus normalizing the data to accommodate differences in tongue size between subjects.

Tongue Shape: Height, Width ($\text{Tng}_{\text{H/W}}$)

The cross-sectional shape of the anterior tongue ($\text{Tng}_{\text{H/W}}$) at the constriction was measured at the second premolar (see Figure 1c). The second premolar (PM2) was determined to be the best location at which to calculate tongue height (H) and width (W) as it was anterior enough to reflect /s/ shaping and still contain sufficient tissue to measure cross-sectional tongue shape reliably during the /ə/ and /s/ for all subjects. The height and width measures were not affected by tongue size as they were used in a ratio.

Figure 1. Segmented tongue volumes, in red, superimposed over the high-resolution magnetic resonance imaging in ITK-SNAP representing (a) whole tongue volume, (b) anterior tongue volume segmented at mid-mesial and distal of the first molar, and (c) anterior tongue volume segmented at the second premolar.



The points for calculating $Tng_{H/W}$ at PM2 were picked in ITK-SNAP using the enhanced cine supervolumes for /ə/ and /s/ and the tongue volume cuts made at PM2. A custom MATLAB (Mathworks, Inc.) script was used to extract the *x, y,* and *z* coordinates associated with each point. The mid-sagittal slice was used to pick the superior and inferior points used to calculate the height (H) of the tongue. The axial slice that included the tongue tip was used to pick points on the lateral tongue borders used to calculate width (W).

Dental Casts

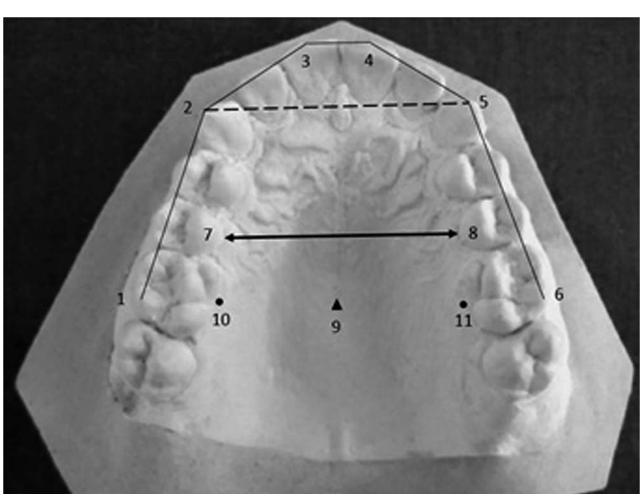
Dental impressions and stone casts were previously digitally scanned using an optical scanner (Ortho Insight 3D Scanner; Motion View Software, LLC). Eleven landmark points were selected on each dental cast and saved as *x, y,* and *z* coordinate points using MeshLab (Cignoni et al., 2008; see Figure 2 and Table 1).

Four variables, namely, palate perimeter, palate height, and palate width at the canine and second premolar, were calculated from the landmarks in Figure 2 using Equation (2).

$$DIST\ P_m\ to\ P_n = \sqrt{\left[(x_1-x_2)^2 + (y_1-y_2)^2 + (z_1-z_2)^2\right]} \quad (2)$$

Equation (2) is a 3D version of Pythagoras' theorem used to calculate the 3D distance between any two points in Figure 2: P_m and P_n. PalP was determined by summing up the distances between points 1–6 along the dental arch (solid line). $PalW_C$ and $PalW_{PM}$ were calculated as the distance between points 2 and 5 (dotted line) and points 7 and 8 (arrow line), respectively. Point 9 was the highest point of the palate between the right and left first molars at the lingual gingival margins (points 10 and 11). PalH was measured using only the *y* coordinate. The *y*-distance was calculated by averaging the *y* values between points 9 and 10 and between points 9 and 11, in case subjects had gingival height differences between the right and left sides. Palates below 14 mm were considered "low palates," and 14 mm and above were considered "high palates," based on our work and the literature (Shapiro, Redman, & Gorlin, 1963).

Figure 2. Maxillary cast indicating the location of picked points; the palate perimeter (PalP) is defined by points 1 to 6 (solid line), palate width at the canine ($PalW_C$) is the distance from points 2 to 5 (dashed line), and palate width at the second premolar ($PalW_{PM}$) is the distance from points 7 to 8 (arrowhead line). Pts 1&6 = distal buccal cusp tip of M1; pts 2&5 = cusp tip of canines; pts 3&4 = mid incisal edge of central incisors; pts 7&8 = gingival margin of PM2; pt 9 = deepest mid palate. Note that points 7 and 8 are the first premolars in the case of PM2 extractions.



Calculations and Statistical Analyses

Three tongue parameters, namely, ΔAnt%, $Tng_{H/W}$, and /s/-type, were studied with respect to four palate parameters, PalP, $PalW_C$, $PalW_{PM}$, and PalH, for controls and patients separately. Spearman *rho* correlations were performed in MYSTAT (Systat Software, Inc.) to compare the continuous tongue measurements $Tng_{H/W}$ to ΔAnt% to each other and to the continuous palatal measurements, PalP, $PalW_C$, $PalW_{PM}$, and PalH (see Table 2 for data). Spearman *rho* correlations were also used to compare TngW to $PalW_C$ and TngH to PalH. TngH and TngW were not normalized for scale; however, the correlations compare each person's tongue anatomy to their own palatal anatomy. The effects of /s/-type on ΔAnt% and on $Tng_{H/W}$ ratio were tested using separate Mann–Whitney *U* tests for controls and patients. As a final note, a complex chi-square test was performed on /s/-type, palate height, and subject group.

Results

Aims 1 and 2 examined the effects of palate features and glossectomy surgery on the anteriority and cross-sectional shape of the tongue.

Palatal Effects on the Tongue

In controls, Spearman *rho* correlations compared ΔAnt% with the four palate features: PalP, $PalW_C$, $PalW_{PM}$, and PalH. Spearman *rho* correlations were also used to compare $Tng_{H/W}$ with the same four palate features and to ΔAnt%. None of the correlations were significant. However, when the $Tng_{H/W}$ was broken into its height and width components, TngH was significantly correlated to PalH ($\rho = .57$, $t = 2.79$, $p < .05$). A higher tongue accompanied a higher palate.

These same analyses were also performed on the patients, with different results. A significant correlation was found between ΔAnt% and $PalW_C$ ($\rho = -.62$, $t = -2.89$, $p < .05$). A larger $PalW_C$ was accompanied by less ΔAnt%. A significant correlation was also found between ΔAnt% and $Tng_{H/W}$ ($\rho = -.571$, $t = -2.51$, $p < .05$). Tongue cross-sectional shape was flatter when the tongue was more anterior.

Table 1. Abbreviations and definitions of variables used in the study.

Abbreviation	Meaning	Brief description of calculation
PalP	Palate perimeter	Distance *along* the maxillary dental arch from left to right mesial buccal cusp of the first molar
$PalW_C$	Canine width	Canine cusp tip to contralateral canine cusp tip
$PalW_{PM}$	Second premolar	Lingual gingival margin to contralateral lingual gingival margin
PalH	Palate height	Vertical height difference from lingual gingival margin of the first molar to mid palate (left and right sides averaged)
TngH	Tongue height	Tongue height at the second premolar
TngW	Tongue width	Tongue width at the second premolar
$Tng_{H/W}$	Height:Width	Ratio of TngH to TngW
V_{ANT}	Anterior volume	Volume of tongue anterior to the first molar
V_{TOT}	Total volume	Volume of the entire tongue
Ant%	Percent anteriority	The volume of V_{ANT} divided by V_{TOT}
ΔAnt%	Change in % of anteriority	The difference in Ant% between /s/ and schwa

Premolar Extractions

The five subjects with premolar extractions were examined further. The interesting palate feature for this group was PalP, because the removal of the premolars shortens the PalP but does not affect the other dental features measured here. A shorter PalP might result in a larger ΔAnt%, because the extracted teeth were anterior to the first molar. Because there were only five subjects with bilateral premolar extractions, statistical calculations could not be done. Instead, Figure 3 shows that although the subjects with extracted premolars (solid markers) were among the smallest PalPs, they did not have greater ΔAnt% of the tongue than other subjects; in fact, they were at the low end of ΔAnt%. Thus, bicuspid extraction did not have an observed effect on ΔAnt%.

Relationship Between PalH and /s/-Type in Controls Versus Patients

Aim 2 sought a relationship between glossectomy surgery and /s/-type using a complex chi-square test. Table 3 shows the apical and laminal /s/ usage for controls and patients with high and low palates. Controls with a high PalH were more likely to use laminal /s/ (9/12 subjects), and controls with a low PalH were less likely to use laminal /s/ (1/9 subjects). Patients, on the other hand, were more likely to use laminal /s/ irrespective of PalH (11/14 patients). These results were statistically significant ($\chi^2 = 13.2$, $p < .01$, $df = 3$).

Discussion

This study investigated several factors that might affect the movement of the tongue, the tongue dimensions, and the placement of the tongue tip during /s/. The first aim was to determine the relationships between several palate and tongue features in controls. The second aim was to explore the relationship between palate parameters and tongue features in patients. In addition, the study documented the relationship between glossectomy surgery, palate height, and the use of apical versus laminal /s/. Knowledge of these relationships may assist in further understanding the effects of palate features on tongue behavior during speech, glossectomy, and other patient groups' speech strategies, and the effects of orthodontic treatment on tongue behavior.

Palatal Effects on Tongue Behavior

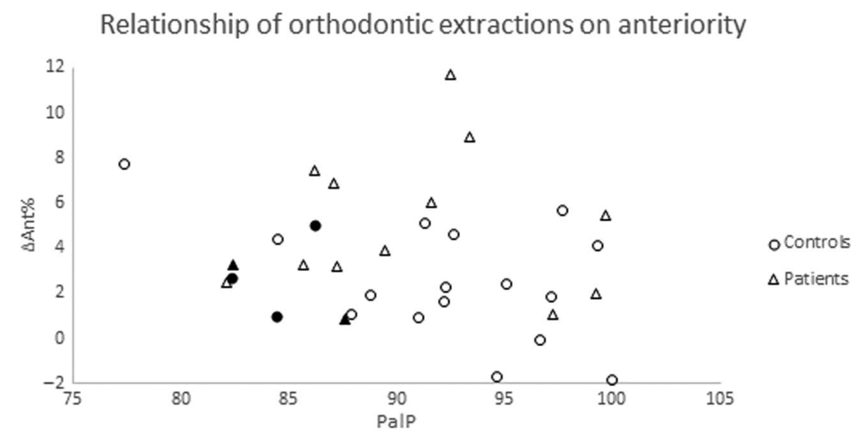
For controls, the only significant palatal effect was a correlation between PalH and TngH. This is consistent

Table 2. Subject data for palate and tongue features.

Subject data		Palate features[a]				Tongue features[b]			
		PalP (mm)	$PalW_C$ (mm)	$PalW_{PM}$ (mm)	PalH (mm)	TngH (mm)	TngW (mm)	$Tng_{H/W}$	ΔAnt%
Controls	*M*	91.5	34.5	32.2	13.9	18.8	28.1	0.7	2.8
	SD	6.1	2.6	3.2	1.8	2.3	8	0.2	2.7
	N	20	20	17	20	20	20	20	21
Patients	*M*	90.2	33.3	30.6	13.5	18.8	31.7	0.6	4.5
	SD	5.9	3.9	3.1	2.4	2.5	12.5	0.2	3.6
	N	14	14	13	13	14	14	14	14

[a]Palate features are palate perimeter (PalP), palate width at the canine ($PalW_C$), palate width at the second premolar ($PalW_{PM}$), and palate height at the first molar (PalH). [b]Tongue features are tongue height at the second premolar (TngH), tongue width at the second premolar (TngW), the ratio of tongue height and width ($Tng_{H/W}$), and the change in percent of anteriority between the schwa and the /s/ (ΔAnt%).

Figure 3. Graphical representation of the effect of orthodontic bicuspid extractions on ΔAnt% when compared with the other nonextraction subjects. Orthodontic subjects, indicated by solid markers, show small palate perimeters (PalP) and average changes in anteriority (ΔAnt%).



with previous research showing that when the speech sound requires a high tongue body, its elevation is sensitive to palate height (Brunner et al., 2009; Hasegawa Johnson et al., 2003; Weirich & Fuchs, 2013). This effect was not seen in patients, suggesting that they could not elevate the tongue to accommodate the higher palate. In most cases, this did not result in a misperception of /s/ as /ʃ/. However, three patients occasionally had their /s/ perceived as /ʃ/, as described in Subjects. Patient 34 had the largest $PalW_C$ of all subjects (39.0 mm; average = 33.98) and one of the largest ΔAnt% (5.5; avg = 3.5, avg patients = 4.5, avg controls = 2.8). This was the opposite of most other subjects, reflected in the significant negative correlation between $PalW_C$ and ΔAnt%. This patient might benefit from widening and retracting his tongue tip during /s/. Due to the glossectomy surgery, however, he may not be able to widen his tongue despite the ample width available in the canine region.

It is well known that the anterior–posterior position of the tongue tip/blade is critical for the creation of the /s/ sound; too anterior a position may result in a /θ/ sound and too posterior may sound like /ʃ/ (cf. Edwards, 1997). For controls, the usual differences in PalH and PalW had no significant effect on ΔAnt%. For patients, however, ΔAnt% correlated negatively with both $Tng_{H/W}$ and with $PalW_C$. The first correlation, between ΔAnt% and $Tng_{H/W}$, showed that if the tongue tip protruded more forward during the /s/, the tongue was flatter or more deeply grooved at the premolar. Typically tongue protrusion includes narrowing in both the horizontal and vertical dimension, by activating the transversus and verticalis muscles together. In this case, primarily the vertical dimension was reduced, probably to retain the midline groove shape of the tongue and direct the air forward toward the incisors. In the introduction, we considered that patients might compensate for reduced tongue tissue by positioning the tongue more anteriorly or narrowing the tip in one dimension. Results indicate that patients used a more anterior position and also a flatter tongue.

The second significant correlation showed that patients with a wider $PalW_C$ used less anteriority. The production of /s/ includes contact between the tongue and the lingual surface of the teeth as well as the lateral palate (Stone & Lundberg, 1996). It is possible that the wide $PalW_C$ required more lateral tongue expansion, leaving less tongue tissue available to move anteriorly. The controls did not make this accommodation, because they did not lose tissue or neurological control. Thus, anteriority, a feature that glossectomy patients can control using the unaffected posterior tongue, is sensitive during /s/, to palate width *at* the constriction but not palate height *posterior* to the constriction. Patients with other types of disorders may similarly modify tongue features that they are able to control locally.

Of interest, $PalW_C$, $PalW_{PM}$, and PalP had no effect on $Tng_{H/W}$ for either the controls or the patients. One explanation is that accuracy of cross-sectional tongue shape

Table 3. Observed /s/-type among patients and controls with high and low palate heights (PalH).

/s/-Type	Controls with high PalH	Controls with low PalH	Patients with high PalH	Patients with low PalH	Grand total
Apical	3	8	2	1	14
Laminal	9	1	3	8	21
Grand total	12	9	5	9	35

($Tng_{H/W}$) is so crucial to creating the constriction that shapes the air stream for /s/ that it is impervious to palate features. The shape may be determined entirely by phonetic requirements, and thus, speakers produce a precise shape irrespective of hard structure features. The small standard deviation in the $Tng_{H/W}$ is consistent with the idea that $Tng_{H/W}$ is due to phonological constraints and is therefore resistant to palate differences.

/s/-Type

The second significant relationship was found between subject group and /s/-type. Several interesting observations emerged between patients and controls. First, patients were more likely to use a laminal /s/ than controls, consistent with the difficulty in elevating the tongue tip after surgery (see Table 3). In the general population, the two /s/-types are considered to be idiosyncratic. However, the patients studied here all had tumors in the lateral margins of the tongue posterior to the tip/blade region. Surgical resection of the tumor cuts the nerves to the tip on the affected side. The preponderance of laminal /s/ in patients is consistent with difficulty in elevating the tongue tip for an apical /s/ post-surgery and compensation by using a laminal /s/. These results are consistent with the results of Stone et al. (2013).

The Effects of Premolar Extraction

The third interesting result was the lack of effect in tongue behavior due to premolar extraction. The extraction subjects were not at the extremes of any measures made. More subjects are necessary to allow a statistical analysis. Other orthodontic procedures, especially those that alter the $PalW_C$, such as rapid palatal expansion (RPE) or surgically assisted rapid palatal expansion (SARPE), may alter /s/ production; however, it is unclear if such changes in $PalW_C$ will affect the acoustics or only the anatomical placement of the tongue tip. Current dental studies show that speech acoustics are only affected during the time of appliance placement (individuals undergoing RPE) and return to baseline after appliance removal (Stevens, Bressmann, Gong, & Tompson, 2011). Therefore, the transverse change may alter tongue ΔAnt%, but not acoustics. No studies have been found that compare tongue or speech features before and after SARPE. It would be interesting to see if RPE affects tongue ΔAnt%.

Limitations

In generalizing the results of this study, there are several constraints due to the patient population. First, a few subjects had premolar extractions. Because this was not a controlled variable, they are few in number, and their results need confirmation with a larger sample. Second, the patients in this study are not representative of all glossectomy patients. Often, cancer resection removes a larger portion of the tongue and may require partial or full resection of the jaw and associated teeth. The patients within this study had only small tumors (T1–T2) and no loss of teeth or jaw. Additional findings may result from a more inclusive study.

Conclusion

This study examined the effects of palate features and tongue modifications due to glossectomy surgery on tongue behavior during /s/. Results showed that for controls, small differences in dentition and oral morphology did not affect tongue behavior during /s/. The exception was a positive correlation between palate height and tongue height. In patients, tongue anteriority and anterior tongue shape were significantly correlated, showing an inability to control these independently. Anteriority was related to palate width at the canines, but tongue shape was not, possibly due to the requirements of /s/. Neither was tongue feature affected by palate height, perimeter, glossectomy surgery, or the /s/-type. Glossectomy surgery, however, did affect the /s/-type. Controls with a low palate tended to use apical /s/; those with a high palate preferred laminal /s/. Patients mostly used laminal /s/ regardless of palate height, perhaps because it does not require tongue tip elevation.

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