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Alteration of functional loads after tongue volume reduction

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Structured Abstract

Objectives – An earlier study revealed that the patterns of biomechanical loads on bones around the tongue altered significantly right after tongue volume reduction surgery. The current study was to examine whether these alterations persist or vanish over time post-surgery.

Design – Five sibling pairs of 12-week-old Yucatan minipigs were used. For each pair, one had surgery reducing tongue volume by about 15% (reduction) while the other had same incisions without tissue removal (sham). All animals were raised for 4 weeks after surgery. Three rosette strain gauges were placed on the bone surfaces of pre-maxilla (PM), mandibular incisor (MI), and mandibular molar (MM); two single-element gauges were placed across the pre-maxilla-maxillar suture (PMS) and mandibular symphysis (MSP), and two pressure transducers were placed on the bone surfaces of hard palate (PAL) and mandibular body (MAN). These bone strains and pressures were recorded during natural mastication.

Results – Overall amount of all loads increased significantly as compared to those in previous study in all animals. Instead of decreased loads in reduction animals as seen in that study, shear strains at PM, MI, and MM, tensile strains at PMS, and pressure at MAN were significantly higher in reduction than sham animals. Compared to the sham, strain dominance shifted at PM, MI, and MM and orientation of tensile strain altered at MI in reduction animals.

Conclusion – A healed volume-reduced tongue may change loading regime significantly by elevating loading and altering strain-dominant pattern and orientation on its surrounding structures, and these changes are more remarkable in mandibular than maxillary sites.

Key words: bone pressure; bone strain; mastication; pig; tongue volume reduction

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Introduction

As an only muscular organ in craniofacial region, the tongue exerts weaker but more frequent forces on the surrounding bones during function. These characteristics may have more significant influences in its local mechanical environment than do the larger jaw muscles. Studies have further demonstrated that intrinsic tongue muscle activities are greater than those of the jaw elevators and extrinsic tongue muscles during chewing (1, 2). On the other hand, tongue volume and position are critical factors affecting craniofacial biomechanics, morphogenesis, and growth (3–5). Clinical evidence has demonstrated that the tongue volume influences not only the position of the dentition (6), but also mandibular arch size and posture (7). Our previous short-term studies revealed that biomechanical loads during mastication were significantly altered immediately after surgical tongue volume reduction, presented by decreased surface strains and pressures on its surrounding osseous tissues, along with the significant change of principal strain orientation (8). However, it is unknown whether or not this altered loading regime would persist or recover as a result of surgical wound healing, tongue reshaping and reposition, and functional compensation over time. This further investigation is more clinically important because the majority of surgical tongue volume reductions are performed in growing adolescent for treating congenital or acquired macroglossia, or as an adjunct procedure for surgical correction of craniofacial deformities, such as skeletal Class III and severe open-bite malocclusions.

Therefore, we launched the present study to investigate how a surgically volume-reduced tongue produces functional loads on its surrounding bones after surgical wound healing, tissue remodeling, functional compensation and adaptation, and the process of motor learning. We hypothesized that the loads in the anterior mouth would be persistent at the reduced level as a results of permanent loss of the anterior tongue mass, but the loads in the posterior mouth would be increasing as the results of functional compensatory effect in the posterior tongue. These working hypotheses are tested using the same approaches as previously published for examining the immediate effects on the tongue loads after its surgical volume reduction (8).

Materials and methods

Tongue surgery and wound healing

Five sibling pairs (10 in total, three males and two females in each group) of 12-week-old Yucatan minipigs were obtained from Sinclair Research Center, MO. Of each pair, one received the midline uniform glossectomy (reduction) as performed clinically (9) and the other had the same incisions without tissue removal (sham). The standard procedure for these surgeries was same as previously published (8). The tongue mass was reduced uniformly in 3 dimensions by about 15% of its original volume for reduction animals, and the same pattern of incisions as for the reduction animals was applied on sham animals (Fig. 1). Animals were raised for 4 weeks after the surgery. Full healing of the surgical injury was confirmed, and the final tongue volume and size measurements were performed as published elsewhere (10). All procedures were approved by the University of Washington Institutional Animal Care and Use Committee.

Device placement

Four weeks after the surgical tongue volume reduction, a procedure to place multiple load-recording sensors took place under anesthesia. These placements were the same as performed in the published acute study (8). In brief, three 45° stacked rosette strain gauges (Fig. 2, inset a) were glued onto right palatal surface of pre-maxilla (PM), lingual surfaces of anterior (between the 2nd and 3rd incisor, MI), and posterior (below the 3rd molar, MM) mandibular alveolar crests. Two single-element strain gauges (Fig. 2, inset b) were glued across the right pre-maxillo-maxillary suture (PMS) and mandibular symphysis (MSP). In addition, two miniature pressure

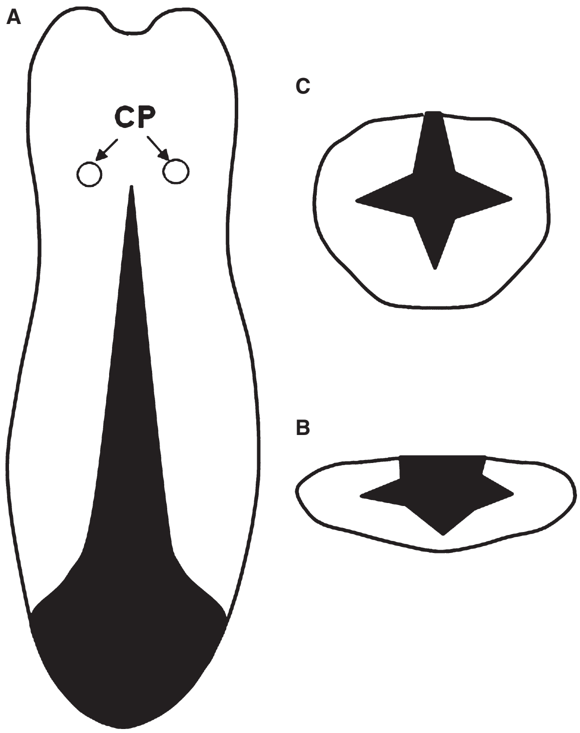

Fig. 1. Schema of the tongue surgery. Dark areas indicate the removed tongue mass. (A) dorsal view; (B,C) anterior and posterior coronal views. CP, circumvallate papillae.

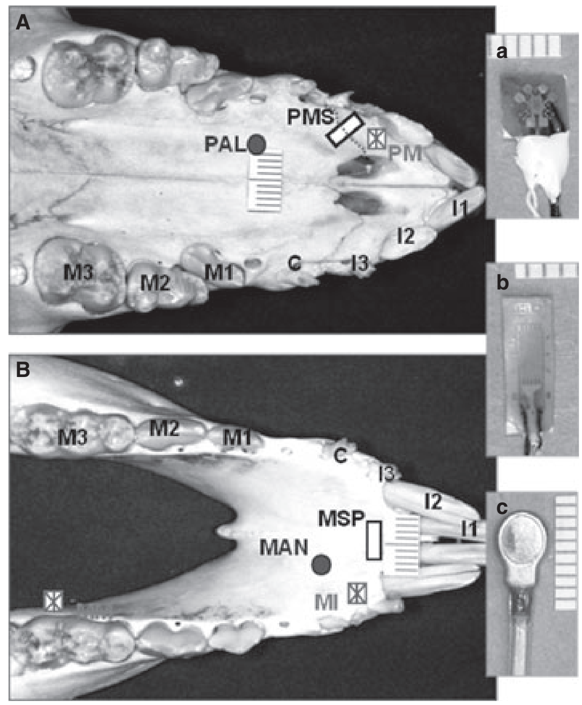

Fig. 2. Locations of strain gauges and pressure transducers. (A) palatal view of the maxilla and pre-maxilla. (B) lingual view of the mandible. Red: stacked rosette strain gauge (inset a); Black: single-element strain gauge (inset b); Blue: pressure transducer (inset c). I1–I3: the first, second, and third incisors; C: canine; M1–M3: the first, second, and third deciduous molars. The dotted line in A represents the pre-maxillary suture. PM: pre-maxillary palatal surface; MI: mandibular alveolar lingual surface at the location between the second and third incisors; MM: mandibular alveolar lingual surface below the third deciduous molar; PMS: pre-maxillo-maxillary suture of the palatal side; MSP: mandibular alveolar lingual surface at the symphysis; PAL: palatal process posterior to the canine; MAN: mandibular lingual surface between the right canine and first deciduous molar.

transducers (Fig. 2, inset c) were placed underneath the mucosa at the right hard palate (at the level distal to the canine, PAL) and the inner surface of mandibular body (between the canine and the 1st molar, MAN; Fig. 2). As a part of our standard procedures, wire electromyographic (EMG) electrodes were inserted into jaw and tongue muscles to examine muscle activities and to indentify chewing side, and fluorescent markers were glued on the upper and lower lips to videotape jaw movements (11). After these placements, the animal was allowed to wake up and a natural and unrestrained feeding was initiated for about 15–20 min by offering regular pig chow. While feeding, all signals from load-recording sensors (strain gauges and pressure transducers), EMG electrodes, and video camera were simultaneously sampled at 500 Hz using BioPac MP150 (BioPac, Santa Barbara, CA, USA) and Vicon Motus (Vicon Co., Los Angeles, CA, USA) systems. Detailed information about device calibration and data acquisition was published elsewhere (1, 8, 11, 12).

Data processing and statistics analysis

Signals from 10 to 15 consecutive chewing cycles from each pig were selected for analysis. A low pass of 16 Hz for both strain and pressure and a band pass of 60–250 Hz for EMG were used for digital filtering. AcqKnowledge III (version 3.9.0; Biopac Co.) in company with a custom-made Excel macro was used for digitizing 3-element rosette strain signals, and the principal tensile and compressive strains (the elongation or compression of one of the principal axes of strain relative to its original length), and the orientation of principal tensile and compressive strains were calculated using the standard formula provided by the manufacturer (13). Signals from single-element strains and pressures were calculated directly using AcqKnowledge III according to the calibration equations. *Post hoc* one-way ANOVA and non-paired *t*-tests were applied for detecting differences between groups, sites, and chewing sides. Paired *t*-tests were used to identify strain dominance (principal tensile vs. compressive) at each site and side within each group. The significant level was set as $p < 0.05$.

Results

Functional modification and morphological alteration

Although complete healing of surgical incisions was seen from the tongue surface (Fig. 3), significant modification in the feeding behavior still existed in the reduction animals 4 weeks after the reduction surgery. The typical presentations were to utilize the mandible, instead of the anterior tongue, to shovel food into the mouth for ingestion, and to move and shake the head intentionally during chewing and swallowing as a way to take an advantage of gravity (inertial pattern of food transport and swallowing), which led to a significantly longer feeding session with little change in chewing frequency. As described elsewhere (10), the surgical reduction resulted in remarkable morphological changes of the tongue. The tongue body becomes much shorter and narrower as compared to that of sham animals, resulting in the entire lower dental arch being visible (Fig. 3B). The tongue cast and post-mortem measurements further indicate that despite ongoing growth (comparison before and after the surgery in sham animals), the tongue reduction surgery significantly reduced the length and width of tongue body, but little change was found in its thickness and resulted in about 15% loss of both volume and weight of the tongue over a 4-week period post-operatively. The results of these measurements were published elsewhere (10).

Bone surface strains by rosette gauges

Figure 4 illustrates a typical recording from 3 rosette and 2 single-element gauges, and 2 pressure transducers while the pig was chewing. The chewing side was identified using the EMG signals from bilateral masseter muscles as previously described (14). Because pigs always chew in an alternate pattern and use both sides equally (15), chewing sides were roughly equally distributed in the samples. Typically, bone strains and pressures peaked following the activity burst of masseter muscles and showed slight difference between working and balancing sides.

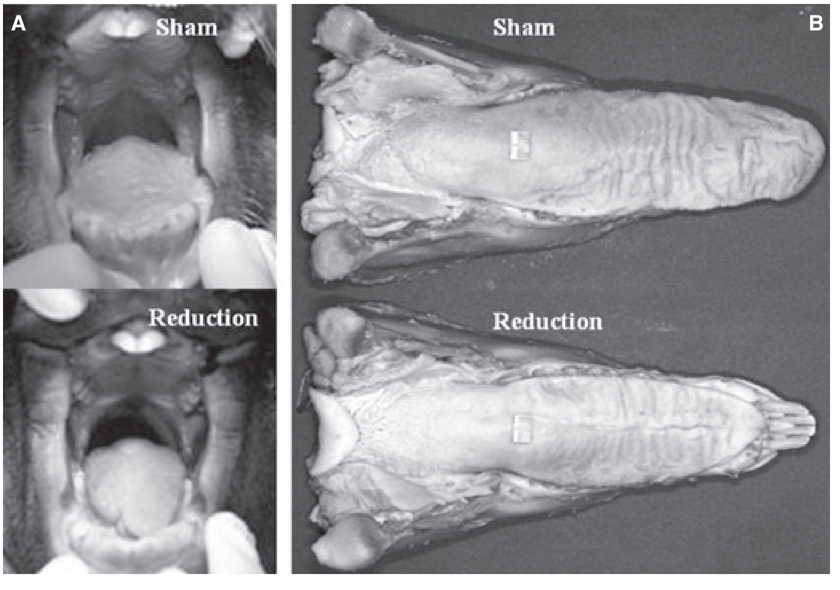

Fig. 3. Comparisons of the tongue morphological changes 4 weeks after surgery. (A) Intraoral view (B) Dorsal view.

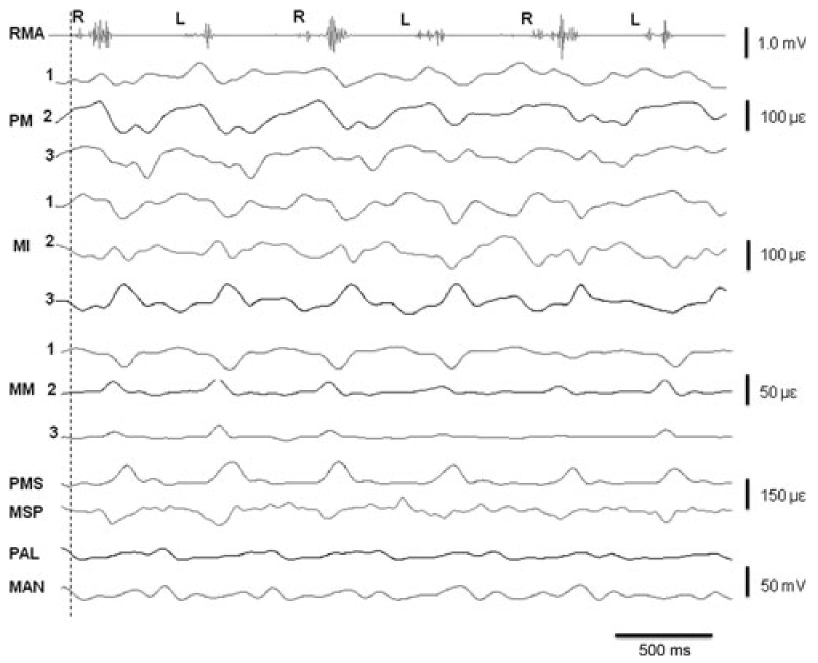

Fig. 4. Raw tracings of bone strains, pressures, and masseter electromyographic (EMG). The 3 elements of each rosette gauge correspond to 1, 2, and 3. R and L indicate the working side of mastication. A dotted line indicates the onset of right masseter activity during right-side chewing. RMA: right masseter muscle. Refer to Fig. 2 for all captions.

Bone surface strain from 3 rosette gauges at the PM, MI, and MM were summarized in Table 1 and Fig. 5. In most of the measurements, the principal tensile and compressive strains were more than 100 $\mu\varepsilon$ on both working and balancing sides. Surprisingly, reduction animals showed significantly higher shear strain (absolute sum of principal tensile and compressive strains, presenting the total strain) in all three sites for both sides. While the tensile and compressive dominant patterns of both working and balancing sides were seen in the PM (93.5 vs. 76.3, $p < 0.01$) and MI (51.2 vs. 122.6, $p < 0.01$), respectively, in the sham animals, no strain dominance (roughly equal values of principal tensile and compressive strains) was identified at these two sites ($p > 0.05$) in the reduction animals. On contrast, at the MM, while the sham showed no strain dominance (143.8 vs. 162.1, $p > 0.05$), the reduction had a clear tensile-dominant strain pattern (220.5 vs. 139.8, $p < 0.01$; Table 1, upper section, Fig. 5). With regard to the site differences, in the sham animals, except for principal strain orientations, all other strain values (principal compressive and tensile stain, and shear strain) of both chewing and balancing sides were significantly greater at the MM than those at the PM and MI. In the reduction animals, however, this site differences were only found in the tensile strain, that is, a greater tensile values at the MM than those at the PM and MI. In addition, an anterior-lateral shifting of the strain orientation was identified at the MI, resulting in a significantly larger angulation to the midline as compared to those at the PM and MM (Table 1, lower section, Fig. 5).

Bone surface strains by single-element gauges

Strain magnitudes, either tensile at the PMS or compressive at the MSP, were generally larger than those strain components measured by rosette gauges at the PM, MI, and MM. The largest one was tensile strain seen at the PMS (373 $\mu\varepsilon$, Fig. 6A). The MSP was located in the midline of the mandible; thus, strain values from both chewing and balancing were combined. The strain patterns were always tensile at the PMS and compressive at the MSP. Tensile strain at the PMS was greater on the working than balancing sides in the reduction, but no significant side differences in the sham animals (Fig. 6A). Similar to strain values obtained by the rosette gauges, significantly higher strains of both sides were seen at the PMS in the reduction animals as compared to those of the sham ones. Similar trend was also seen at the MSP, although no significance was detected.

Table 1. **Comparisons of principal bone strains (Mean ± SD, in $\mu\varepsilon$) between reduction and sham animals**

	Pre-maxilla (PM)		Mandible Incisor (MI)		Mandible Molar (MM)	
	Sham	Reduction	Sham	Reduction	Sham	Reduction
Working side						
Max	93.5 ± 60.9	119.5 ± 142.0*	51.2 ± 30.9	110.7 ± 94.4***	143.8 ± 105.6	220.5 ± 170.1**
Min	−76.3 ± 60.5	−128.4 ± 135.7*	−122.6 ± 94.7	−137.0 ± 127.3	−162.1 ± 86.7	−139.8 ± 137.8*
Shear	169.8 ± 114.2	247.9 ± 234.1***	173.8 ± 113.7	247.7 ± 200.5*	305.9 ± 139.8	360.3 ± 224.6**
Orient	31.9 ± 28.7	32.0 ± 24.6	39.8 ± 24.1	52.4 ± 39.7**	43.8 ± 41.1	28.1 ± 35.6
Balancing side						
Max	91.8 ± 60.5	102.1 ± 115.2**	48.6 ± 27.3	121.6 ± 96.4**	161.4 ± 118.6	212.5 ± 200.8**
Min	−72.2 ± 58.5	−120.4 ± 132.9*	−130.7 ± 93.9	−133.8 ± 117.0	−154.3 ± 76.8	−155.9 ± 148.5
Shear	164.0 ± 107.3	222.5 ± 212.8**	179.4 ± 113.2	255.4 ± 196.9**	315.6 ± 180.4	368.3 ± 273.7**
Orient	31.2 ± 30.2	24.7 ± 29.6	38.8 ± 25.0	57.2 ± 37.1**	39.1 ± 38.6	29.2 ± 30.9

	Working side				Balancing side			
Site comparison								
Sham	$F_{max} = 27.232^{\#\#\#}$ PM > MI$^{\#\#}$ MM > PM$^{\#\#\#}$ MM > MI$^{\#\#\#}$	$F_{min} = 18.091$ MI > PM$^{\#\#}$ MM > PM$^{\#\#\#}$ MM > MI$^{\#}$	$F_{shear} = 26.189^{\#\#}$ MM > PM$^{\#\#\#}$ MM > MI$^{\#\#\#}$	$F_{direc} = 2.342$	$F_{max} = 33.928^{\#\#\#}$ PM > MI$^{\#\#}$ MM > PM$^{\#\#\#}$ MM > MI$^{\#\#\#}$	$F_{min} = 18.634^{\#\#\#}$ MI > PM$^{\#\#}$ MM > PM$^{\#\#\#}$	$F_{shear} = 23.479^{\#\#\#}$ MM > PM$^{\#\#}$ MM > MI$^{\#\#\#}$	$F_{direc} = 1.259$
Reduction	$F_{max} = 8.141^{\#\#\#}$ MM > PM$^{\#\#}$ MM > MI$^{\#\#\#}$	$F_{min} = 0.086$	$F_{shear} = 3.715^{\#}$ MM > PM$^{\#}$	$F_{direc} = 6.274^{\#}$ MI > PM$^{\#}$ MI > MM$^{\#\#}$	$F_{max} = 6.915^{\#\#\#}$ MM > PM$^{\#\#}$ MM > MI$^{\#}$	$F_{min} = 0.751$	$F_{shear} = 4.583^{\#}$ MM > PM$^{\#}$	$F_{direc} = 12.173^{\#\#\#}$ PM > MI$^{\#\#}$ MI > MM$^{\#}$

Max: tension; Min: compression; Shear: Max + Min (absolute value); Orient (in degree): orientation of principal tensile strain relative to the midline line (PM and MI) or the occlusal plane (MM). *Paired and Non-paired *t* tests for tensile–compression comparison and sham-reduction comparisons, respectively. #ANOVA/Tukey for gauge site comparisons. *or #: $p < 0.05$; **or ##: $p < 0.01$; ***or ###: $p < 0.001$.

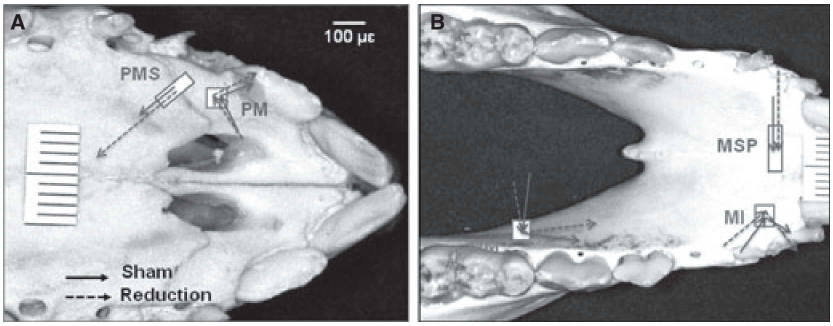

Fig. 5. Mean values and orientations of principal strains in the 3 rosette and 2 single-element gauge sites in the sham (solid arrows) and reduction (dotted arrows) animals (Only the working side is illustrated). (A) palatal surface of maxilla; (B) lingual surface of mandible. Arrows pointing toward the gauge site indicate compressive strain; arrows pointing away from the gauge site indicate tensile strain. Refer to Fig. 2 for captions.

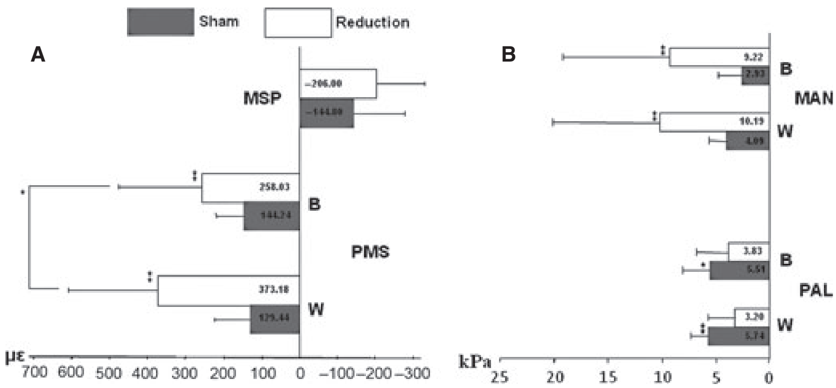

Fig. 6. Comparisons of single-element strain and bone surface pressure values. (A) Strain values at the PMS and the MSP between the reduction and sham animals. Positive and negative values represent tensile and compressive strains, respectively. (B) Bone surface pressures at the PAL and MAN between the reduction and sham animals. Numbers inside the bars indicate their mean values. W: working side; B: balancing side; $*p < 0.05$; $**p < 0.01$. Refer to Fig. 2 for captions.

Bone surface pressures

The magnitudes of bone surface pressure ranged from 2.93 to 10.19 kPa in the two groups. The pressures measured at the MAN were significantly higher than those at the PAL in the reduction ($p < 0.05$), but an opposite trend was found in the sham animals in both working and balancing sides. At the MAN, significantly higher pressure was shown in the reduction than the sham animals. However, an opposite trend was again seen at the PAL, where the pressures were significantly higher in the sham than the reduction animals in both working and balancing sides (Fig. 6B).

Discussion

Our previous study of *in vivo* functional loads (8) reported for the first time that both loading patterns and magnitudes on the osseous tissues directly surrounding the tongue are significantly affected right after the surgical volume reduction (short-term study). However, this study was unable to provide information about the effect of surgical tongue volume reduction in osseous loading over time following the healing of surgical intervention, the reshaping and reposition of the tongue, potential functional compensation, and adaptation through the process of motor learning. While our longitudinal tracking of tongue function after surgical volume reduction depicted the characteristics of altered functional deformation of the tongue over time after the surgery (16, 17), the consequences of these functional changes on the load production are unknown. The results from the present long-term study are to fill out this gap. However, the results of the present study are clearly beyond our expectations and contradict the proposed hypothesis. Some of them even showed an opposite trend to what we found in the previous acute study (8). The three questions were targeted to interpret these unexpected findings.

Why did the sham animals show remarkable changes in the magnitudes of bone surface strains and pressures as compared to those in the previous acute study?

The present study clearly revealed that, except for the PMS, all sites received as much as 2–3 times higher strains with changes in strain-dominant patterns and orientations as compared to those obtained from the previous acute study in the sham animals (8). It is reasonable to assume that this striking difference between these two studies is due to post-operative swelling and pain caused by the sham surgery, which prevents the tongue muscles from efficient contraction properly. This assumption is supported by our previously serial studies in tongue internal kinematics in which the internal tongue deformation during mastication was reduced ~8% in the anterior width, ~5% in the thickness, and ~3% in the length right after the sham surgery as compared to those measured in the intact animals (18, 19). However, the PMS strain was close to that seen in the short-term study (about 130–150 $\mu\varepsilon$). Given the fact that the PMS is located at an unfused fibrous intervening suture, it usually bears much higher tensile strain (more deformable) than the other osseous sites as demonstrated by our previous and other studies (8, 20). Therefore, the strengthened tongue muscle contraction as a result of surgical wound healing has less enhancing effect on this site. Because both the outer and inner surfaces of the PMS bear tensile strain during chewing (8, 20), this distortion is determined by not only the tongue pulling force, but also the occlusal contact–impact during chewing. Therefore, the similarity of the strain magnitudes between the acute and the current study in this site may imply that there is little change in occlusal contact–impact on the bone by a swelling and painful tongue during mastication.

Compared to those of the acute study, bone surface pressure at the PAL also increased about 150%, but the pressure at the MAN adversely decreased to 3–4 kPa (Fig. 6B) from 5 to 6 kPa seen in the acute study (8). This unexpected reduction in the MAN pressure may indicate that the healed tongue after the sham surgery might alter its moving and deforming modes to some extent which in turn produces less force and/or contact against the inner surface of mandible. This assumption need to be further verified by the data from the same source in the intact animals. Unfortunately, no such data are available from our serial studies in this topic.

Why did the reduction animals show higher bone strains than those of the sham animals?

The present study clearly demonstrated an opposite effects of the volume-reduced tongue on its surrounding bony surfaces to that found in the previous acute study (8), that is, significantly higher, rather than lower total bone strains in all of gauge sites as compared to those from the sham animals. In addition, the patterns of strain dominance were altered at all three sites (PM, MI, and MM) for rosette gages, along with the changes in the strain orientation at the MI (Table 1). Several reasons could be speculated for these dramatic changes. First, it has been proved that the tongue muscle repair after surgical injury is not the reconstitution of muscular structure but an adaption to a new morphology. The intricate three-dimensional architecture of the tongue musculature is not reconstructed, but is replaced by excessive fibrosis and formation of the scar tissue, which might hinder the process of myogenic regeneration, and limit the functional recovery of the tongue (21). Therefore, the more rigid scar tissue with fibrosis in the healed tongue could produce more loads in the bone surfaces during chewing. Second, due to the complex of tongue musculature and the lack of bony support, coactivation of multiple tongue intrinsic and/or extrinsic muscles is the basic requirement for tongue function, and the combination of concentric (shortening) and eccentric (lengthening) muscle contractions is the fundamental feature of the tongue kinematics (22–25). However, by reshaping its morphology and restructure of its tissue constituent after surgical healing and repair, these physiological features of the tongue might alter to some extent. This altered tongue kinematics might produce profound influences on its mechanical effects, including the changes of strain pattern and orientation, and the enhancement of strains magnitude. In other word, for the reduction animals, while the decreased bone strains found in our previous acute study might be due to the simple physical loss of tongue mass and post-surgical complications, the increased bone strain and altered strain pattern/orientation found in the present study are mainly derived from the tissue restructure of the tongue and the changes in its contraction modes in the healed volume-reduced tongue as demonstrated in the tongue kinematic and histological studies in these same animals (17, 21, 26).

Interestingly, the changes of two bone pressures in the reduction animals represented an opposite trend as compared to those of the sham animals, that is, significantly increased and decreased at the MAN and PAL, respectively (Fig. 6B). The same theory as described above could be used to explain the pressure increase at the MAN, but the decreased pressure at the PAL is unexpected. Because the direct press of the tongue dorsal surface against the middle hard palate during chewing is the only source of the pressure production at the PAL, it could be assumed that less or lighter pressing force was generated by a healed volume-reduced tongue during chewing. In the view of clinical prospective, this decreased force against the hard palate by the tongue could be helpful for vertical control of the surgical correction for skeletal open bite and reducing the relapse after orthopedic or orthodontic treatments (27, 28).

How do these changes in tongue functional loads affect craniofacial growth?

Even though the controversy of whether the tongue adapts to existing oral morphology, or actively molds its surrounding tissues is long-standing (29–31), numerous clinical studies have claimed that tongue size/volume/position may affect a number of elements of craniofacial growth and dental/occlusal development (6). Therefore, examining the cause–effect relationship between modification of tongue mass and alteration in craniofacial skeletal growth is imperative for understanding the underlying mechanism. Our previous longitudinal study on craniofacial skeletal components and dentition formation in the same animals used for the present study found that the reduction animals has a slower trend on the linear expansion of craniofacial skeletons, manifested by significantly decreased amounts in pre-maxilla and anterior mandibular lengths, mandibular ramus height, mid-face width, and anterior dental arch width as compared to those of the sham animal. A mass-reduced tongue also causes the decrease in bone mineral density in pre-maxilla/maxilla and anterior mandible examined as demonstrated by dual photon/energy X-ray absorptiometry (DEXA) (5). It is also worthwhile to indicate that despite the growth effects occurring in all three dimensions (width, height and length) of both facial and mandibular bones, the regions of anterior mouth and mandible are more affected than those of posterior mouth and naso-maxillary skeletons, respectively (5). Obviously, it is more legitimate to interpret these negative growth effects based on the current findings in functional tongue loads than those from the acute study (8).

The present study clearly demonstrates that except for the PAL, functional loads increased rather than decreased in the reduction animals, regardless of anterior or posterior regions, or mandible and naso-maxillary bones (Table 1, Figs 5 and 6). This fact leads to the dilemma that how the increased functional loads could have negative effect on the craniofacial growth, dental arch formation, and bone mineral density in growing animals. As we knew, the mechanical effect produced by the tongue during function is mainly derived from its modes of bodily motion and internal deformation. While bodily tongue movement before and after the surgery is not available from the current study, our longitudinal deformation data confirms that at week 1 after the surgery, masticatory deformations decreased in the anterior width and body length, but increased in the posterior widths and thickness significantly, as compared to the baselines (week 0) (17, 26). At week 2, the reduced deformational capacity in the anterior tongue (width and length) was slightly restored with better regularity of stereotypical chewing cycles than those seen at week 1 (17, 26). However, the increased deformation in the posterior tongue (widths and thickness) diminished as compared to those seen at week 1 (17, 26). At week 4, the restoration of anterior tongue deformation continued, but the deformational range in the posterior tongue further decreased and almost returned to those seen at the baseline (week 0) (17, 26). These time-course changes in tongue internal deformation clearly indicates that although there is a short-term loss of deformational capacity in the anterior tongue and a compensatory enhancing deformation in the posterior tongue, these distorted features diminished over time, presented by the restoration of reduced deformation in the anterior tongue and the vanishing of enhanced deformation in the posterior tongue over time. This type of functional modification in tongue internal deformation most likely stems from muscular plasticity and adaptation and also can be attributed to the motor learning process after the surgery. However, the increased masticatory loads along with ongoing functional recovery in the tongue internal deformation after the surgery might have less influences on negative growth effects. As seen in Fig. 2B, the anterior tongue shows a significant mass loss 4 weeks after the surgery, thus resting loads on the anterior mouth by the tongue could be significantly reduced. Given the traditional theory that resting load of the tongue plays more important role than functional load on growth due to long lasting (4, 32–34), it is reasonable to assume that reduced resting loads by the mass loss of the anterior tongue may be a major factor affecting craniofacial growth and bone mineral density negatively. In addition, the rosette strain data from the reduction animals shows clearly that the strain patterns were greatly different from those of the sham animals at the mandibular sites (Table 1, Fig. 5). Roughly equal compressive and tensile strains at the MI of reduction animals suggest that this site subjects to twisting rather than compression as seen in the sham during chewing. Also, a significantly higher tensile than compressive strains at the MM in the reduction animals suggest that this rigid site of the mandible no long undergoes both transverse bending and twisting as seen in the sham (8) and intact animals (14, 35, 36). These changes in the strain patterns with enhanced magnitudes may also attribute to the negative growth effect in the reduction animals.

Conclusions

This follow-up study on the tongue functional loads suggest that a healed volume-reduced tongue may change the loading regime significantly by elevating loading and altering the strain dominance on its surrounding osseous structures, and these changes are more remarkable in mandibular than maxillary sites. These conclusions contradict in part the proposed hypothesis that a healed volume-reduced tongue produces fewer loads on the anterior mouth during function.

Clinical relevance

Surgical tongue volume reduction is a valuable approach to treat symptomatic macroglossia, and an adjunct to surgical skeletal correction for dentofacial deformities, such as mandibular setback for Class III malocclusion, Le Fort osteotomy for severe open bite, and functional disorders, such as sleep-disordered breathing (SDB). However, the functional loading change after the surgery is unknown. The findings of this animal study provide this important information to the clinicians. Because the surgery is mainly performed in young population, the consequences of the altered loading regime on craniofacial growth, occlusal development, and bone quality should be carefully considered prior to the surgery.

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