THE ANATOMICAL RECORD 299:132–140 (2016)

# Internal Kinematics of the Volume-Reduced Tongue: A Longitudinal Microsonometric Study

**JIE CHEN,[1,2] VOLODYMYR SHCHERBATYY,[3] AND ZI-JUN LIU[1]***
[1]Department of Orthodontics, University of Washington, Seattle, Washington
[2]Department of Stomatology, Xin Hua Hospital Affiliated to Shanghai Jiao Tong University School of Medicine, Shanghai, China
[3]Department of Genes and Behavior, Max Planck Institute for Biophysical Chemistry, Gottingen, Germany

---

ABSTRACT

This study examined tongue internal kinematics during feeding over time after its volume reduction. Six ultrasonic crystals were implanted into the tongue to record distance changes in anterior width (AW), bilateral lengths (LENG), posterior thicknesses (THICK), and posterior dorsal (PDW) and ventral (PVW) widths in five sibling pairs of Yucatan minipigs (N = 10). In each pair, one received tongue volume reduction surgery (reduction), and the other had the identical incisions without tissue removal (sham). Functional deformation of the tongue from preimplanted ultrasonic crystals was recorded during natural feeding 1 day before, 7–8, 13–15, and 28–30 days after the surgery. The results revealed that feeding behavior and tongue functional deformation were unchanged over time in the sham pigs. However, at Days 7–8, more frequent and longer ingestion episodes were seen in the reduction as compared with the sham. Moreover, deformational changes in AW and LENG decreased, whereas those in THICK, PDW, and PVW increased significantly ($P < 0.001$). At Days 13–15, the reduced deformational changes in LENG ($P < 0.01$) slightly restored, and the increased deformation in THICK ($P > 0.05$), PDW ($P < 0.01$), and PVW ($P < 0.05$) diminished. At Days 28–30, the restoration of AW and LENG continued ($P < 0.01$-$0.05$), but previously enhanced deformations in THICK, PDW, and PVW were no longer significantly different from the baseline ($P > 0.05$). These results suggest that the tongue volume reduction has significant and persistent impacts on feeding behaviors and tongue internal kinematics, and the restoring capacity of internal kinematics in the anterior tongue is limited and incomplete over time. Anat Rec, 299:132–140, 2016. © 2015 Wiley Periodicals, Inc.

**Key words: tongue kinematics; tongue volume reduction; ultrasound; mastication; pig**

---

By contracting the extrinsic and intrinsic muscles of the tongue, the tongue performs motor functions that exert force through various complex shape changes (Mu and Sanders, 1999; Kayalioglu et al., 2007). These changes include simultaneous lengthening and shortening of different regions and a variety of nonlinear movements without altering tissue volume (Kier et al., 1989; Nishikawa et al., 1999; Sokoloff, 2004), which produce kinematic and biomechanical effects (displacement, deformation, and load production). Tongue body volume reduction surgery is a valuable approach for

---

Grant sponsor: NIDCR; Grant number: R01DE15659 (to Z.-J.L.); Grant sponsor: Overseas Talents Training Program of Xin Hua Hospital Affiliated to Shanghai Jiao Tong University School of Medicine (to J.C.).

*Correspondence to: Zi-Jun Liu, Department of Orthodontics, University of Washington, Box 357446, Seattle, WA 98105. Fax: (206) 685-8163. E-mail: zjliu@uw.edu

Received 28 May 2015; Revised 18 August 2015; Accepted 25 August 2015.

DOI 10.1002/ar.23278

treating congenital or acquired macroglossia in growing adolescent, or as an adjunct procedure for surgical correction of craniofacial deformities, such as severe skeletal open-bite and Class III malocclusions (Frohlich et al., 1993; Wolford and Cottrell, 1996; Miyawaki et al., 2000; Hotokezaka et al., 2001; Chau et al., 2011; Chung et al., 2012). Several techniques have been described to reduce the tongue volume, varying from removing an anterior or central wedge of the tongue to excision of the complete anterior and lateral margins of the tongue (Wang et al., 2003).

Given the fact that the tongue is a volume-dependent muscular organ because of its hydrostat nature, significant changes in tongue movement and internal deformation of various dimensions during function are anticipated when the volume is reduced surgically. Our previous short-term study (Shcherbatyy et al., 2008) has demonstrated that tongue volume reduction alters the tongue internal kinematics, and the dimensional losses in the anterior tongue caused by the volume reduction can be compensated by increased deformation in the posterior tongue during mastication. However, those data were collected immediately after the tongue surgery (acute experiment); thus, the surgical injury and pain might affect the normal kinematics of the tongue. A number of longitudinal studies (Tomlinson et al., 2007; Chau et al., 2011; Shipster et al., 2012; Heggie et al., 2013) have shown that surgical tongue reduction may not achieve complete normality in tongue function and appearance. However, few studies have been identified regarding whether or not such an altered internal kinematics would be persistent or be recovered over time as a result of surgical wound healing, tongue reshaping or reposition, and functional compensation. Our long-term study revealed that a healed volume-reduced tongue transformed loading regime significantly on its surrounding osseous structures by elevating loading amplitude and altering strain-dominant pattern and orientation (Ye et al., 2013), while the neurovascular bundles of the tongue remained intact (Perkins et al., 2008). However, it is unknown how the load source, that is, tongue kinematics, alters over time after the tongue volume reduction. For addressing this question, we took a further step to carry out this study, which longitudinally examined the deformational changes of various tongue dimensions during natural mastication following a uniform tongue volume reduction over the period of 4 weeks in the same pig model. We hypothesized that internal kinematics of a volume-reduced tongue would decrease significantly at the region of the anterior tongue, and a compensatory enhancement in the posterior tongue would be persistent over time.

## MATERIALS AND METHODS

### Animals

Three male and two female sibling pairs ($N = 10$) of 12-week-old Yucatan miniature pigs (body weight: $13 \pm 2$ kg) were obtained from Sinclair Research Center (Columbia, MO). Daily training and handling for 3–5 days were performed before the experiments for acclimation of the pigs to the laboratory and experimental environment. Body weight was monitored once a week during the entire experimental period of 6 weeks. All experimental procedures were approved by the University of Washington Institutional Animal Care and Use Committee.

### Electromyography and Jaw Movement Videotaping

After 3–5 days training, electromyography (EMG) was acquired using the Biopac system (BioPac Co., Goleta, CA) during natural feeding. Nickel-chromium wire electrodes (0.05 mm in diameter) were inserted into tongue extrinsic and intrinsic tongue muscles and jaw muscles under isoflurane anesthesia, along with the placement of fluorescent jaw markers. The procedures for these EMG recording and synchronized jaw movement videotaping were the same as those previously published (Kayalioglu et al., 2007; Liu et al., 2009).

### Ultrasound Crystal Implantation Surgery

Under isoflurane anesthesia through intubation, all pigs received an aseptic surgery to implant ultrasonic crystals with a skin button set (Sonometrics Co., London, ON, Canada). An incision along the midline of the submandibular region was made, and a long-beak hemostat was used to create a tunnel to reach the designed crystal locations, which were confirmed by manual intraoral palpations. By using another long-beak straight hemostat, six ultrasonic crystals with B-barb (2 mm in diameter) were implanted into the target locations through these tunnels. These six crystals were located in the tongue body (anterior 2/3) to circumscribe a wedge-shaped configuration as illustrated in Fig. 1A: No. 1 and No. 2 were 15 mm posterior to the tongue tip; No. 3 and No. 4 were 5 mm anterior to each circumvallate papilla; No. 5 and No. 6 were 10–12 mm ventrally deeper to No. 3 and No. 4, respectively. Similar to the acute studies published previously (Shcherbatyy and Liu, 2007; Shcherbatyy et al., 2008), the following seven crystal pairs were selected from this configuration to represent dimensional changes of the tongue: anterior width (AW, Nos. 1–2), right and left lengths (RL and LL, Nos. 1–3 and Nos. 2–4, respectively), right and left posterior thicknesses (RT and LT, Nos. 3–5 and Nos. 4–6, respectively), and posterior dorsal and ventral widths (PDW and PVW, Nos. 3–4 and Nos. 5–6, respectively). These crystals functioned as tiny transducers that transmit and receive ultrasound signals and report the real-time distance between two crystals, with a claimed resolution of 0.018 mm (Fig. 1B). The crystals were stabilized in the place through their barbs and by suturing the proximal end of their leading wire onto the adjacent submandibular tissue using an absorbable suture (Gut 4-0). No intra-oral incision or exposure was made for the crystal implantation. Next, a subcutaneous tunnel was created from the submandibular region to the right back. The leading wires of the implanted crystals were led through this tunnel and were positioned 10 cm posterior to the occipital protuberance where a female interface of skin button set (Fig. 2, inset a) was secured to the skin using 2-0 silk sutures and its connecting pins were protected by a screwed cover (Fig. 2, inset b).

Immediately after all six crystals were implanted and incisions were closed, the tongue was placed in a resting position, and the linear distances of each dimension (distance between each designated crystal pairs) were measured using a digital caliper and a needle compass. These measurements were defined as the "implantation lengths." Antibiotic (Clavamox) was administered with

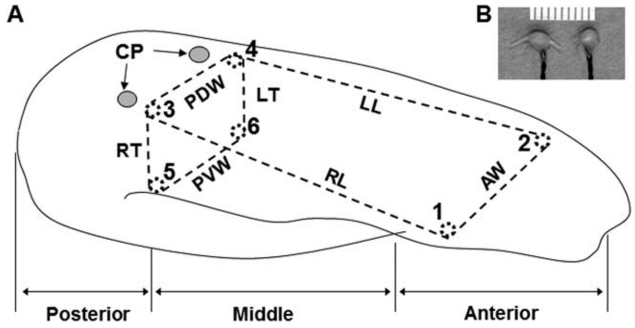

Fig. 1. Implantation of six ultrasonic crystals in the tongue body. **A**: Wedge-shaped configuration of implanted crystals array. Numbers indicate the location of each crystal, and a given dimension of the tongue is represented by a pair of crystals. 1–2: anterior width (AW); 3–4: posterior dorsal width (PDW); 5–6: posterior ventral width (PVW); 1–3 and 2–4: right and left lengths (RL and LL), respectively; 3–5 and 4–6: right and left thicknesses (RT and LT), respectively. Arrows indicate two circumvallate papillae (CP). Please note that the crystals No. 5 and No. 6 (dotted circles) were implanted 10–12 mm ventrally deeper to the crystals No. 3 and No. 4, respectively. **B**: A pair of 2-mm B-barb ultrasonic crystals. (Modified from Shcherbatyy V, Liu ZJ, Anat Rec, 2007, 290, 1288–1299, © Wiley, with permission.)

food one day before the surgery and for 5 days after the surgery. Buprenorphine (0.01–0.05 mg/kg, intramuscular) was given every 8–12 hrs for 5 days for postsurgical pain relief. The daily training and handling resumed the next day.

## Baseline Recording

One week after implantation surgery, the baseline recording of tongue internal kinematics was carried out. To accomplish this, after 24-hrs fasting, the pigs were first anesthetized for EMG wire electrode insertions and the placement of the jaw movement markers, which were the same as did for the preimplantation session. Then, the implanted skin button was connected to the microsonometric system through the plug-in cables (Fig. 2, inset c). After waking up from anesthesia, the regular pig pellets were offered, and the ultrasound signals from implanted crystals during natural feeding were collected at the sampling rate of 250 Hz by using SonoLab program (Ver.3.4.26-RC3, Sonometrics Co.), along with the simultaneous recordings of EMG and videotaping of jaw movement. The recorded crystal signals served as the baseline of internal kinematics of the tongue, whereas the repeated recordings of EMG and jaw movement were used to verify possible functional interference caused by the crystal implantation.

## Volume Reduction Surgery

One day after the baseline recording, aseptic tongue surgeries took place in each of sibling pairs. One underwent volume reduction (reduction group, N = 5), which was performed within the region circumscribed by the six preimplanted crystals using the uniform midsagittal tongue volume reduction (Davalbhakta and Lamberty, 2000). This procedure allows the tissue resections occurring in the anterior two-thirds of the tongue, and reducing not only length and width, but also thickness. The details of this surgery were published previously (Shcherbatyy et al., 2008) (Fig. 3). The other one received the identical incisions and sutures as the reduction pigs, but no tongue tissue was removed (sham group, N = 5).

After surgery, the tongue was placed in the rest position, and the distances between each crystal pairs were recorded again. By comparing with the "implantation length," the dimensional losses by the reduction or sham surgeries were calculated as published elsewhere (Perkins et al., 2008). Then anesthesia was ceased, and the pigs were set back to their pen upon regaining consciousness. The administrations of antibiotics and analgesics were the same as performed after surgical implantation described above.

## Longitudinal Recordings and Off-Line Data Analysis

The daily training and handling resumed 2 days after the tongue surgery. Ultrasound signals from implanted crystals during natural feeding were collected longitudinally at the following three time points after the tongue surgery: Days 7–8, 13–15, and 28–30. The procedures of these longitudinal recordings were the same as the baseline recording (Fig. 2).

Off-line data analyses were performed by selecting stable and consecutive 15–20 chewing cycles from a 3-min masticatory sequence of each session using SonoView program (Sonometrics Co.). Selection standards included signal rhythmicity, regularity, and consecutiveness. Outputs of wave data from each designated crystal pairs acquired during rhythmic and stereotyped chewing cycles were exported to an Excel spreadsheet where a custom-made macro program processed the following values from each chewing cycle at a given crystal pair through the visual-basic edited algorithm: (*i*) minimal value (valley), the amplitude measured at the starting of distance increase; and (*ii*) maximal value (peak), the amplitude measured at the starting of distance decrease. To avoid the confounding effects by the potential variation of distance between each crystal pairs at the implantation and between tracking time points, all measurements of distance changes in various dimensions were converted to the percentages of their corresponding initial distances, which were measured by placing the tongue at the rest position when the pig was under anesthesia for the insertion of wire-EMG electrodes in each session. Because of the fragility of ultrasonic crystals and uncooperativeness of some pigs, not all crystal pairs were operational throughout the entire tracking period, which lasted from 1 day before the tongue surgery (D1) to the terminal day (28–30 days after the tongue surgery, D28–30). The actual sample sizes of successful recordings over four time points are summarized in Table 1.

## Statistical Analysis

SPSS (Version 11.0.1; SPSS, Chicago, IL) for Windows was used for the statistical analysis. Descriptive statistic was performed for all means, standard deviations, and ranges of distance changes. Further exploration was done to examine their normal distribution through skewness calculations. One-way analysis of variance was used, followed by Tukey's *post hoc* tests. Nonpaired $t$ test was performed to compare distance changes of each crystal pair between the two groups at each time point. Probability of 0.05 or

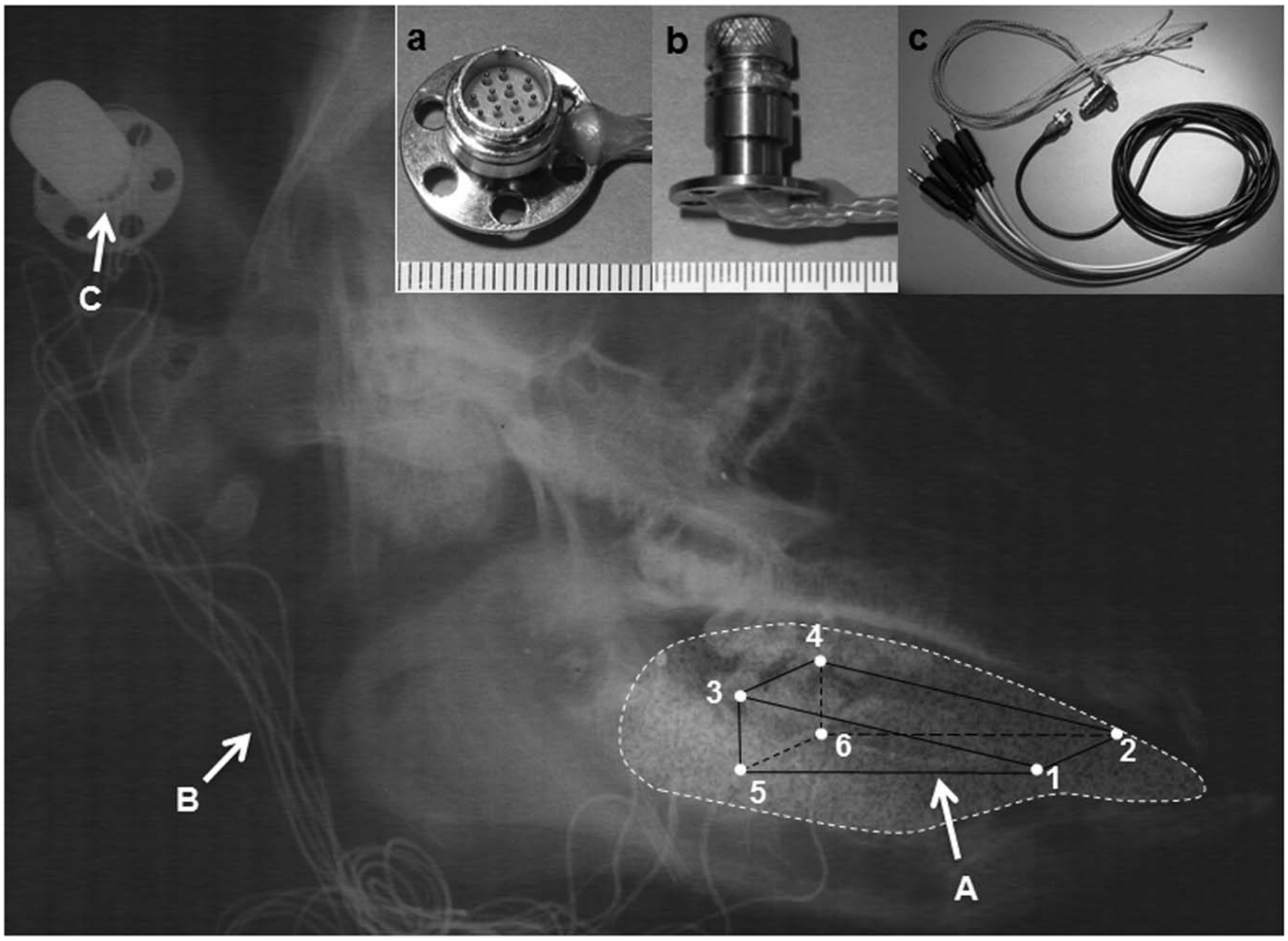

Fig. 2. A cephalometric radiograph showing the implanted crystals array and a skin button set. The white dashed line outlines the tongue shape and the black solid lines depict the wedge-shaped configuration of six implanted crystals (white dots). Numbers indicate the location of crystals. **A**: The tongue and ultrasonic crystal array; **B**: Leading wires of implanted crystals; **C**: Skin button. Insets: A skin button set. **a**: Female connector; **b**: Screwed cover; **c**: Male connector and plug-in cables. Refer to the captions of Fig. 1 for numbers and dimensions in the crystal array.

less was considered to indicate statistical significance. For Tukey's pair-wise comparisons over time in each group, the significance levels were adjusted by Bonferroni correction.

## RESULTS

No noticeable functional impairment was identified by comparing EMG and jaw movement data acquired before and after crystal implantation. However, as compared with the sham pigs, significant modifications in feeding behavior were observed in the reduction pigs throughout this longitudinal investigation. Typically, a reduction pig utilized the mandible, instead of the anterior tongue, to shovel food into the mouth for ingestion, then moved and shook the head intentionally for chewing and swallowing as a way to take an advantage of gravity (inertial pattern). The feeding session lasted significantly longer than that of the sham pigs. The food leaking from the mouth corners during feeding was often seen at the initial 1–2 weeks after the surgery in the reduction pigs. However, the amount of daily food consumption of the reduction pigs was similar to that of the sham pigs, and both groups showed significant body weight gain over time ($P < 0.01$), but no significant difference of body weight between the two groups at any time points was identified (Fig. 4).

Because statistical analyses did not show any significant differences of dimensional changes between right and left lengths (RL and LL) and thicknesses (RT and LT), values of the lengths and thicknesses from the two sides were combined. Therefore, the total of five parameters, that is, AW, bilateral length (LENG), posterior thickness (THICK), posterior dorsal (PDW), and ventral (PVW) widths, were used to examine the characteristics of tongue internal kinematics during natural feeding between the reduction and sham groups.

Longitudinal recordings indicated that tongue functional deformation was unchanged over time in the sham pigs as compared with the normal unoperated control pigs previously reported (Shcherbatyy and Liu, 2007). However, significant distortions were observed over time in the reduction pigs. At Days 7–8 after the surgery (D7–8), more frequent and longer ingestion episodes interposed in masticatory sequence as compared with the baseline (D1). The difference of tongue deformational pattern between chewing and ingestion episodes seen at D1 became less distinct, particularly in the body length changes (Fig. 5). Furthermore, dimensional changes in AW and LENG significantly decreased (20%–35%), whereas those in THICK, PDW, and PVW increased significantly (10%–20%) for both chewing and ingestion as compared with D1 (Figs. 5 and 6). At Days 13–15 after the surgery (D13–15), the reduced deformational capacities in AW and LENG were slightly restored, with better regularity of stereotypical chewing cycles than those seen at D7–8. However, the increased deformation in THICK, PDW, and PVW diminished as compared with those seen at D7–8 (Fig. 6). At D28–30, although the feature of ingestion episode in the reduction pigs existed and the restoration of AW and LENG deformation continued, the deformational ranges in THICK, PDW, and PVW further decreased (Fig. 6).

As summarized in Fig. 7, in both reduction and sham groups, the largest deformational change relative to the initial distances was seen in AW (30.5% ± 2.3%), and the smallest in PVW (14.8% ± 1.5%) and LENG (16.4% ± 1.4%) at D1. As compared with the sham pigs, deformational changes during chewing in the reduction pigs significantly decreased in AW (16.7% ± 1.3%, $P < 0.001$) and LENG (12.24% ± 0.7%, $P < 0.001$), but changes in the posterior tongue body (THICK: 24.2% ± 1.7%, PDW: 22.3% ± 2.1%, and PVW: 20.2% ± 1.9%) enhanced significantly ($P < 0.001$) at D7–8. At D13–15, the reduced deformational capacity in AW (18.2% ± 1.8%; $P < 0.001$) and LENG (12.53% ± 1.5%; $P < 0.01$) slightly restored, with the better regularity of stereotypical chewing cycles than those seen at D7–8. However, the increased deformation in THICK (22.4% ± 1.7%; $P > 0.05$), PDW (21.2% ± 1.2%; $P < 0.01$),

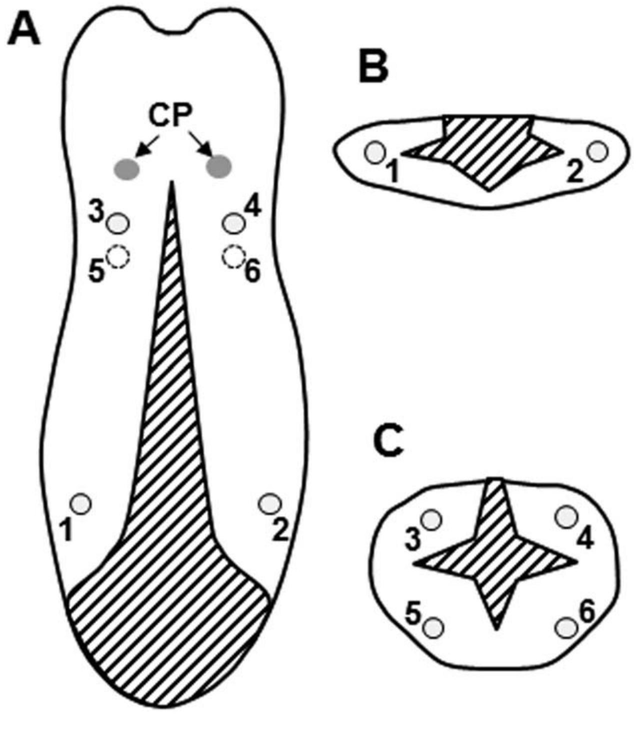

Fig. 3. Diagram of the uniform tongue volume reduction surgery. Shaded areas represent surgical incisions and removed tongue tissue for the volume reduction. Arrows indicate two circumvallate papillae (CP). **A**: Dorsal view of the entire tongue. Circles and numbers indicate implanted crystal sites. **B**: Cross-sectional view at the junction of anterior 1/3 and 2/3 of the tongue. **C**: Cross-sectional view at the location 5 mm anterior to the two CPs of the tongue. Refer to the captions of Fig. 1 for numbers and dimensions in the crystal array. (Modified from Shcherbatyy V, Perkins JA, Liu ZJ, Anat Rec, 2008, 291, 886–893, © Wiley, with permission.)

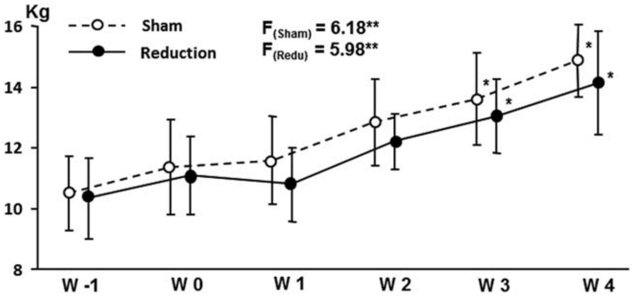

Fig. 4. Comparison of body weight gains over 6-week experimental period. W-1: 1 week before the tongue volume reduction or sham surgeries; W0: day of the tongue surgery; W1, W2, W3, and W4: 1, 2, 3, and 4 weeks after the tongue surgery, respectively. *F*-values and superscripted asterisks indicate overall significance over four time points in each group by analysis of variance. $^{**}P < 0.01$. The asterisks above the data points indicate significant difference as compared with the baseline (W-1) in each group by Tukey's *post hoc* tests with Bonferroni correction. $^{*}P < 0.01$. There is no significant difference between the two groups at each time point. (Modified from Perkins JA, Shcherbatyy V, Liu ZJ, Otolaryngol Head Neck Surg, 2008, 139, 291–297, © American Academy of Otolaryngology-Head and Neck Surgery Foundation, with permission.)

**TABLE 1. Sample sizes of successful microsonometric recordings**

| Time | Group | AW | RL | LL | RT | LT | PDW | PVW |
|---|---|---|---|---|---|---|---|---|
| D1 | Sham | 4 (89) | 4 (89) | 4 (92) | 4 (89) | 4 (90) | 4 (89) | 5 (113) |
| | Reduction | 4 (94) | 4 (94) | 4 (94) | 4 (95) | 5 (119) | 4 (95) | 5 (119) |
| D7–8 | Sham | 4 (92) | 3 (70) | 4 (92) | 4 (92) | 4 (92) | 3 (70) | 4 (92) |
| | Reduction | 4 (91) | 4 (91) | 4 (91) | 4 (91) | 4 (91) | 4 (91) | 4 (91) |
| D13–15 | Sham | 4 (87) | 3 (65) | 4 (87) | 4 (87) | 4 (87) | 3 (65) | 4 (87) |
| | Reduction | 3 (68) | 4 (89) | 4 (89) | 4 (89) | 4 (89) | 4 (89) | 4 (89) |
| D28–30 | Sham | 4 (90) | 3 (68) | 4 (90) | 4 (90) | 4 (90) | 3 (68) | 4 (90) |
| | Reduction | 3 (64) | 3 (65) | 4 (87) | 4 (87) | 4 (87) | 3 (65) | 4 (87) |

Numbers in parentheses represent sampled chewing cycles; D1, D7–8, D13–15, and D28–30 represent the time point 1 day before and 7–8, 13–15, and 28–30 days after the tongue volume reduction or sham surgeries, respectively.
AW: anterior width; PDW and PVW: posterior dorsal and ventral widths; RL and LL: right and left lengths, respectively; RT and LT: right and left thicknesses, respectively.

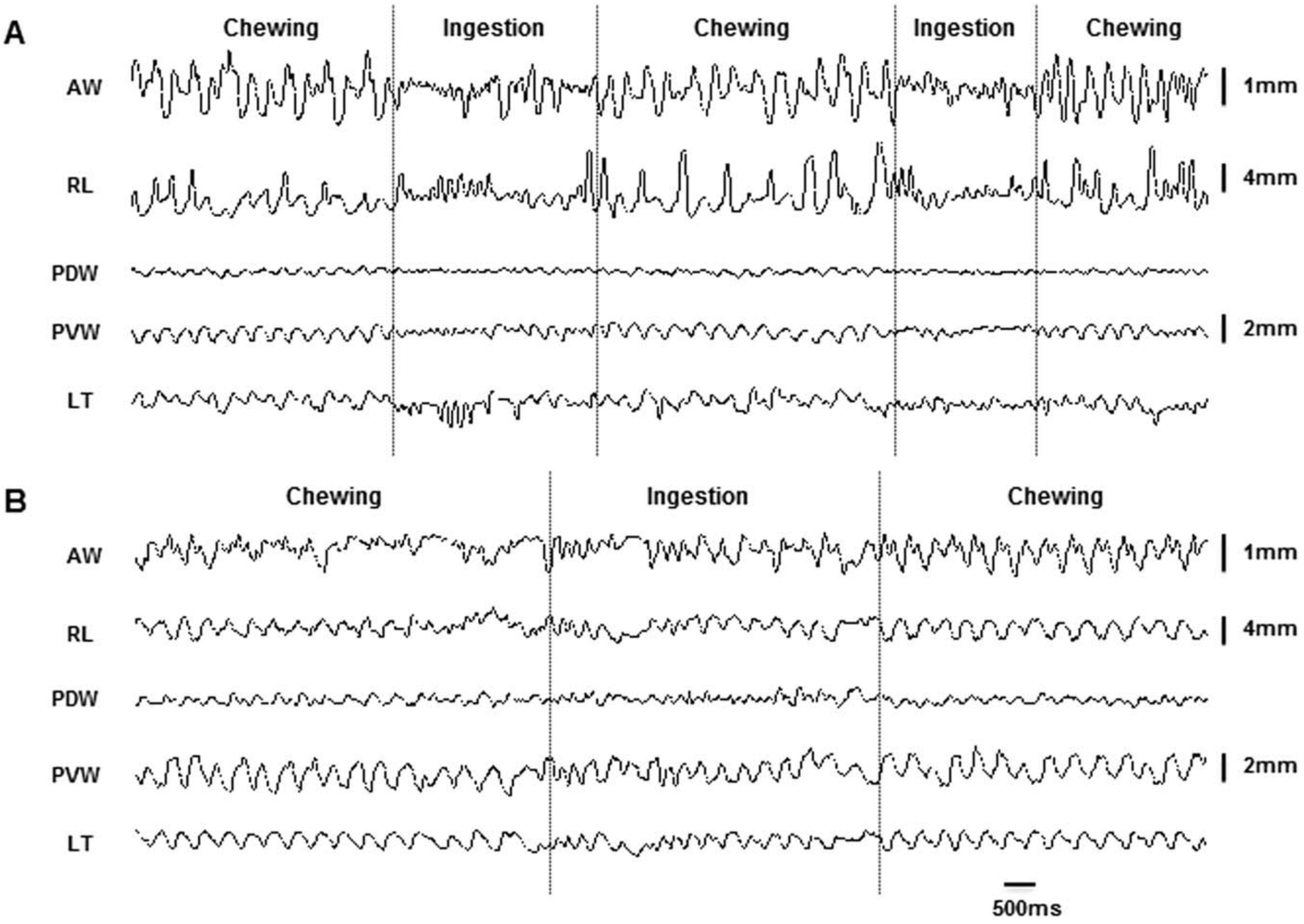

Fig. 5. Raw microsonometric tracings of the deformational changes during natural feeding from Pig #25. **A**: Before the reduction surgery; **B**: One week after the reduction surgery. Dotted vertical lines separate chewing and ingestion episodes of a masticatory sequence. Refer to Fig. 1 for dimensional captions.

and PVW (19.1% ± 1.5%; $P < 0.05$) diminished as compared with those seen at D7–8. At D28–30, the restoration of anterior tongue body deformation continued despite still significantly lower than those of the sham pigs ($P < 0.01$–$0.05$), but the deformational ranges in the posterior tongue body further decreased and were not significantly different from those of the sham pigs and the baseline level at D1.

## DISCUSSION

Several surgical procedures for anterior resection of the tongue have been described (Wang et al., 2003; Balaji, 2013). All the techniques aim to reduce the bulk of the tongue, such as length, width, thickness, or all of them and to preserve the neurovascular bundles. Clinically, tongue volume reduction surgery is performed as part of the total treatment in acquired macroglossia, or orthodontic and orthopedic treatment for skeletal Class III malocclusion or anterior open bite. This is because the relatively enlarged tongue after mandibular set-back or Lefort osteotomy is not only potential source of relapse but also results in various functional disorders (Miyawaki et al., 2000; Hotokezaka et al., 2001). A number of long-term studies have shown the impacts of tongue reduction surgery on speech, sensation, taste, psychology, feeding, and drooling (Van Lierde et al., 2010; Shipster et al., 2012; Matsumoto et al., 2014). However, few studies have been identified with regard to the effect of a volume-reduced tongue on its motor function over time. Our previous study reported for the first time that tongue volume reduction alters the tongue internal kinematics significantly (Shcherbatyy et al., 2008). Unfortunately, that study was unable to address the question about whether these negative effects on the tongue internal kinematics are transient or relatively permanent consequences following the tongue volume reduction.

This study demonstrated that both feeding behavior and deformational pattern of the tongue are not significantly affected by the sham surgery as compared with the results from normal unoperated pigs previously reported (Shcherbatyy and Liu, 2007), and the period of 6-week rapid growth has no apparent influences on the tongue internal kinematics. However, significant modifications in feeding behavior was clearly observed over time in the reduction pigs, indicating the persistent impact on the ability of food ingestion, transportation, chewing, and possibly swallowing due to the loss of anterior tongue mass. Of course, these kinematic alterations in the reduction pigs might also partially result from the postsurgical pain, in particularly during the initial 1–2 weeks after the

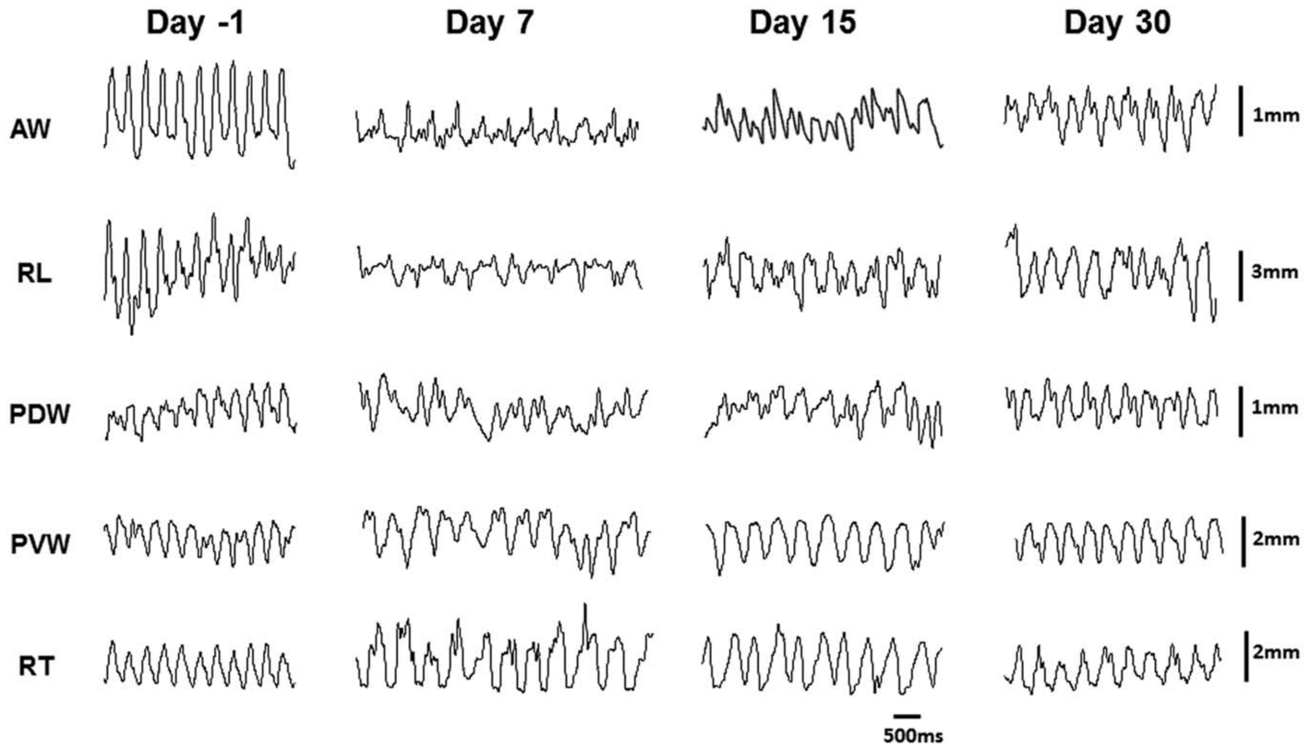

Fig. 6. Zoomed microsonometric tracings of chewing in a reduction pig over time. D1, D7, D15, and D30 indicate the time point 1 day before and 7, 15, and 30 days after the tongue volume reduction surgery, respectively. Refer to Fig. 1 for dimensional captions.

surgery. However, because the sham pigs received the same surgical incisions as the reduction pigs but showed similar features of feeding behavior and tongue internal kinematics to those seen on normal unoperated animals in this study, the influences of postsurgical pain on tongue internal kinematics should be considered moderate or minor (Shcherbatyy and Liu, 2007).

The longitudinal tracking further revealed that both rhythm and amplitude of tongue dimensional changes during feeding modified over time in the reduction pigs. At D7–8, the basic features of functional deformation during chewing still remained, but more frequent and longer ingestion episodes interposed in masticatory sequence with the decrease in the regularity and amplitudes of AW and LENG and increased amplitudes in THICK, PDW, and PVW. These results suggested that changes in the posterior tongue (both widths and thickness) were significantly enhanced to compensate for the loss in the AW and body length. In addition, from D13–15 to D28–30, the amplitude of AW and LENG increased but THICK, PDW, and PVW decreased. Although the recovery of deformational capacity in the anterior tongue body did not reach the level of baseline or the sham pigs, the compensatory enhancement of deformational capacity in the posterior tongue body gradually vanished and almost returned to the level of the baseline at D28–30. These time-course changes in tongue body functional deformation clearly indicate that although the tongue deformational capacity subjects to a short-term loss in the anterior part and a compensatory enhancement in the posterior part, these distorted features are diminishing over time. It is worthy to note that although there was some recovery, the restoration of the deformational capacity in the anterior part at the end of this experiment (D28–30) was still significantly smaller than that of baseline (D1). This relatively long-term negative impact might stem from the fact that the healing after the tongue volume reduction surgery is not a process of myogenic regeneration, but fibrosis and formation of the scar tissue, as evidenced by our histological studies (Perkins et al., 2008; Ye et al., 2010). Because the performed tongue volume reduction surgery was only involved in the anterior and middle parts of the tongue (tongue blade and body), with little invasion close to the region of the two circumvallate papillae, the observed changes in tongue internal kinematics are most likely derived from the loss of the tongue mass. It is also worthy to note that because the midline area of the tongue is made of fibrous septum, bundles of the bilateral muscle group of tongue are often approximated when the tip is reconstructed. This newly formed structure may fail to provide synchronous function as does an intact tongue (Ye et al., 2010). Based on all of these morphological and histological alterations, maladaptation of tongue internal kinematics may be initiated due to the natures of muscular plasticity and the consequence of motor learning, as seen in the present longitudinal observations. Apparently, this type of maladaptive internal kinematics in a volume-reduced tongue does not result in a functional performance as good as an intact tongue, evidenced by behavior alterations and reduced deformational capacity in the anterior tongue during feeding and potential

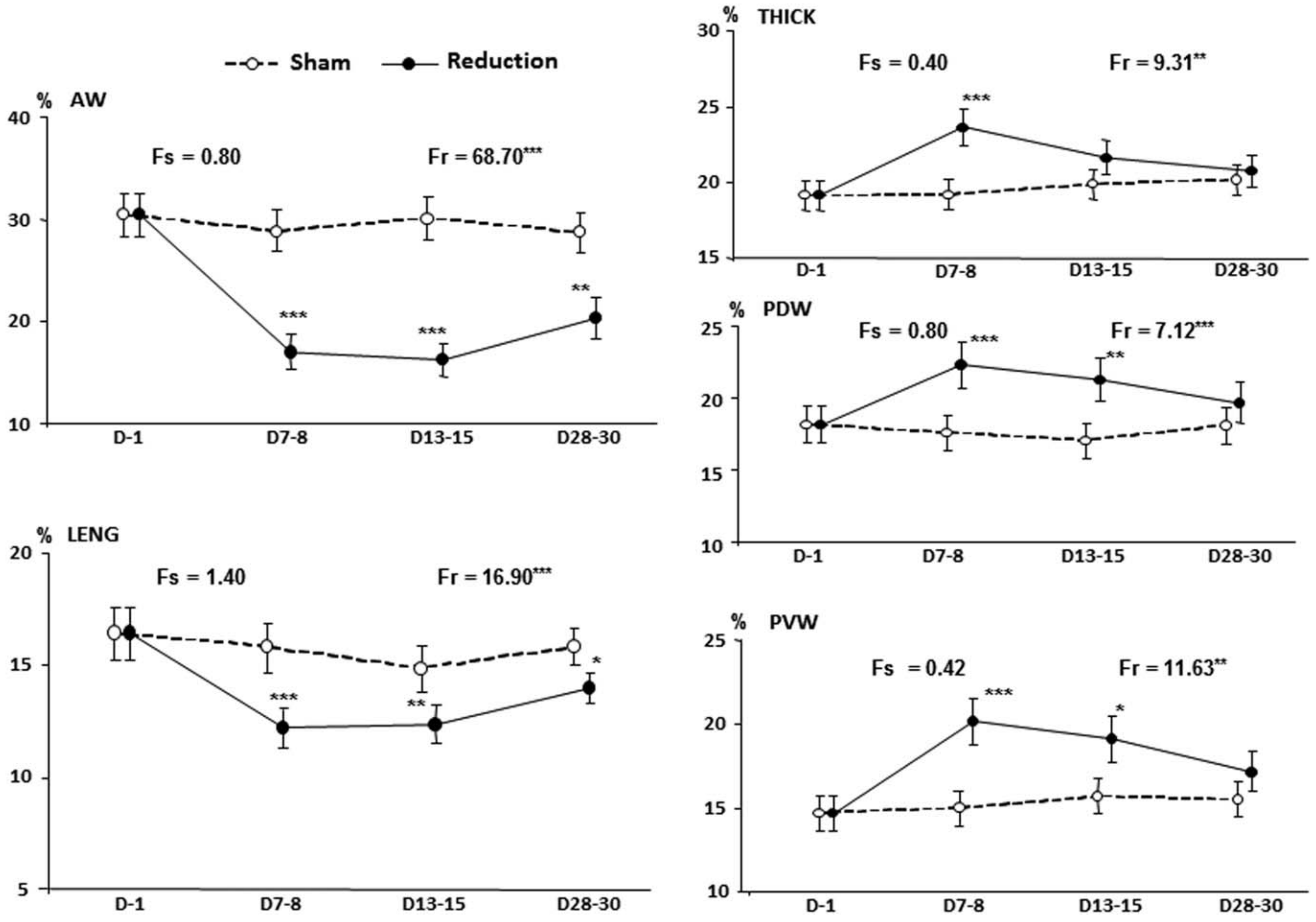

Fig. 7. Comparisons of deformational ranges of each dimension over time during chewing between the reduction and sham groups. The left two panels indicate the anterior width (AW) and lengths (LENG), and right three panels indicate the posterior widths (PDW and PVW) and thickness (THICK). $F_s$ and $F_r$ represent *F*-values of analysis of variance tests in the sham and reduction group, respectively. Asterisks superscripted at *F*-values indicate overall significance across four time points. $^{**}P < 0.01$; $^{***}P < 0.001$. Asterisks superscripted at the data points indicate significant difference of deformational changes at each time point between the two groups by nonpaired *t* tests. $^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$. All values were converted to the percentages of rest-position distance of each dimension. D1, D7–8, D13–15, and D28–30 represent the time point 1 day before and 7–8, 13–15, and 28–30 days after the tongue volume reduction or sham surgeries, respectively.

negative consequences on craniofacial growth and occlusal development (Liu et al., 2008).

Although successful, the implantable microsonometric technique for the longitudinal and dynamic tracking of tongue internal kinematics should be considered as a challengeable and demanding approach because of the frangible nature of implanted ultrasonic crystals and the difficulty of infection control around the skin button implanted area. These disadvantages limited that this study was only able to do the longitudinal tracking for about 4 weeks after the tongue surgery. Therefore, it is premature to state that this type of maladaptation of the internal kinematics of a volume-reduced tongue would persist over months or years. The other limitation of the current study is that only one surgical method of tongue volume reduction was applied with the identical reduction rate of 18%–20% (Perkins et al., 2008). Therefore, it is unknown that whether other surgical approaches with different volume reduction rates would result in different changes in internal kinematics of the tongue.

In conclusion, the present results suggest that in the pig: (*i*) the tongue internal kinematics is not subject to significant changes over time during the rapid growth period; (*ii*) the tongue body volume reduction has significant and persistent impacts on both feeding behavior and tongue internal kinematics over time; (*iii*) the restoring capacity of internal kinematics in the anterior tongue after the reduction surgery is limited and incomplete over time; and (*iv*) the tongue internal kinematics should be considered volume-dependent, and may subject to maladaptation.

## ACKNOWLEDGEMENTS

The authors thank Dr. Jonathan Perkin for his help on tongue surgeries and Dr. Xian-Qin Bai for her help on animal experiments and general laboratory assistance. Thanks go to Dr. Sue Herring for her invaluable inputs during the whole course of this study.

## LITERATURE CITED

Balaji SM. 2013. Reduction glossectomy for large tongues. Ann Maxillofac Surg 3:167–172.

Chau H, Soma M, Massey S, Hewitt R, Hartley B. 2011. Anterior tongue reduction surgery for paediatric macroglossia. J Laryngol Otol 125:1247–1250.

Chung CJ, Hwang S, Choi YJ, Kim KH. 2012. Treatment of skeletal open-bite malocclusion with lymphangioma of the tongue. Am J Orthod Dentofacial Orthop 141:627–640.

Davalbhakta A, Lamberty BG. 2000. Technique for uniform reduction of macroglossia. Br J Plast Surg 53:294–297.

Frohlich K, Ingervall B, Schmoker R. 1993. Influence of surgical tongue reduction on pressure from the tongue on the teeth. Angle Orthod 63:191–198.

Heggie AA, Vujcich NJ, Portnof JE, Morgan AT. 2013. Tongue reduction for macroglossia in Beckwith Wiedemann syndrome: review and application of new technique. Int J Oral Maxillofac Surg 42:185–191.

Hotokezaka H, Matsuo T, Nakagawa M, Mizuno A, Kobayashi K. 2001. Severe dental open bite malocclusion with tongue reduction after orthodontic treatment. Angle Orthod 71:228–236.

Kayalioglu M, Shcherbatyy V, Seifi A, Liu ZJ. 2007. Roles of intrinsic and extrinsic tongue muscles in feeding: electromyographic study in pigs. Arch Oral Biol 52:786–796.

Kier WM, Smith KK, Miyan JA. 1989. Electromyography of the fin musculature of the cuttlefish *Sepia officinalis*. J Exp Biol 143:17–31.

Liu ZJ, Shcherbatyy V, Gu G, Perkins JA. 2008. Effects of tongue volume reduction on craniofacial growth: a longitudinal study on orofacial skeletons and dental arches. Arch Oral Biol 53:991–1001.

Liu ZJ, Shcherbatyy V, Kayalioglu M, Seifi A. 2009. Internal kinematics of the tongue in relation to muscle activity and jaw movement in the pig. J Oral Rehabil 36:660–674.

Matsumoto K, Morita K, Jinno S, Omura K. 2014. Sensory changes after tongue reduction for macroglossia. Oral Surg Oral Med Oral Pathol Oral Radiol 117:e1–e2.

Miyawaki S, Oya S, Noguchi H, Takano-Yamamoto T. 2000. Long-term changes in dentoskeletal pattern in a case with Beckwith-Wiedemann syndrome following tongue reduction and orthodontic treatment. Angle Orthod 70:326–331.

Mu L, Sanders I. 1999. Neuromuscular organization of the canine tongue. Anat Rec 256:412–424.

Nishikawa KC, Kier WM, Smith KK. 1999. Morphology and mechanics of tongue movement in the African pig-nosed frog *Hemisus marmoratum*: a muscular hydrostatic model. J Exp Biol 202:771–780.

Perkins JA, Shcherbatyy V, Liu ZJ. 2008. Morphologic and histologic outcomes of tongue reduction surgery in an animal model. Otolaryngol Head Neck Surg 139:291–297.

Shcherbatyy V, Liu ZJ. 2007. Internal kinematics of the tongue during feeding in pigs. Anat Rec 290:1288–1299.

Shcherbatyy V, Perkins JA, Liu ZJ. 2008. Internal kinematics of the tongue following volume reduction. Anat Rec 291:886–893.

Shipster C, Morgan A, Dunaway D. 2012. Psychosocial, feeding, and drooling outcomes in children with Beckwith Wiedemann syndrome following tongue reduction surgery. Cleft Palate Craniofac J 49:e25–e34.

Sokoloff AJ. 2004. Activity of tongue muscles during respiration: it takes a village? J Appl Physiol (1985) 96:438–439.

Tomlinson JK, Morse SA, Bernard SP, Greensmith AL, Meara JG. 2007. Long-term outcomes of surgical tongue reduction in Beckwith-Wiedemann syndrome. Plast Reconstr Surg 119:992–1002.

Van Lierde KM, Mortier G, Huysman E, Vermeersch H. 2010. Long-term impact of tongue reduction on speech intelligibility, articulation and oromyofunctional behaviour in a child with Beckwith-Wiedemann syndrome. Int J Pediatr Otorhinolaryngol 74:309–318.

Wang J, Goodger NM, Pogrel MA. 2003. The role of tongue reduction. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 95:269–273.

Wolford LM, Cottrell DA. 1996. Diagnosis of macroglossia and indications for reduction glossectomy. Am J Orthod Dentofacial Orthop 110:170–177.

Ye W, Abu AF, Liu ZJ. 2010. Assessment of cell proliferation and muscular structure following surgical tongue volume reduction in pigs. Cell Prolif 43:562–572.

Ye W, Duan YZ, Liu ZJ. 2013. Alteration of functional loads after tongue volume reduction. Orthod Craniofac Res 16:234–245.