A novel ultrasound technique to measure genioglossus movement in vivo

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Kwan BC, Butler JE, Hudson AL, McKenzie DK, Bilston LE, Gandevia SC. A novel ultrasound technique to measure genioglossus movement in vivo. J Appl Physiol 117: 556–562, 2014. First published June 26, 2014; doi:10.1152/japplphysiol.01257.2013.—Upper airway muscles are important in maintaining airway patency. Understanding of their roles in healthy subjects and those with upper airway disorders is limited. To address this, we tested a novel ultrasound (US) method to measure genioglossus (GG) movement in real time. GG is the largest upper airway dilator. Inspiratory movement was minimal. Other studies have also noted abnormal GG electromechanical responses in OSA patients both awake and asleep (e.g., Refs. 18, 20, 22, 33, 44). While treatment of upper airway disorders requires better understanding of the biomechanics of the upper airway, diagnostic imaging of the oral cavity is not used routinely due to several factors. Endoscopic modalities, such as fiber-optic nasopharyngoscopy, are unable to demonstrate how each tongue muscle contributes to overall movement of the tongue in quiet breathing (5, 42, 53). Fluoroscopy involves exposure to radiation and is unable to characterize the internal deformation of soft tissues of the tongue (38, 41). MRI and computed tomographic imaging have also been used to evaluate the upper airway muscles and lumen diameters in normal subjects and subjects with sleep-disordered breathing (8, 10, 14, 48). However, these techniques are expensive, time-consuming, and less likely to gain widespread clinical use. Computed tomographic imaging also involves exposure to radiation. Ultrasound (US) imaging offers potential advantages for clinical imaging of the upper airway (40) and has previously been used to demonstrate dynamic upper airway movements during swallowing and sleep assessment (50, 51). It is noninvasive, does not emit radiation, can resolve soft tissue structures, and can display cross-sectional anatomy and tissue motion in real time (52). A recent review also demonstrated good reliability of two-dimensional US measurements of human limb muscle fascicle lengths and pennation across a range of experimental conditions, including muscle contraction and relaxation (26). The need for enhanced upper airway imaging was highlighted by recent tagged MRI reports of subjects with OSA studied during quiet breathing (7) and mandibular advancement (3, 8). In subjects with a low apnea-hypopnea index, there was simple forward movement of the posterior GG with inspiration, while in severe OSA (apnea-hypopnea index > 50/h) inspiratory movement was minimal. Other studies have also noted abnormal GG electromechanical responses in OSA patients both awake and asleep (e.g., Refs. 18, 20, 22, 33, 44).

Therefore, the present study was designed to assess ultrasoundography as a method to image the human GG. We hypothesized that 1) US can be used to quantify movement of the GG during quiet breathing in awake healthy subjects; 2) the maximal displacement occurs in the inferoposterior part of the GG; 3) the major displacement is in an anterior direction during inspiration; and 4) US imaging provides reproducible measurements of GG movement across different imaging sessions. Preliminary data were presented as an abstract (21).

MATERIALS AND METHODS

Twenty normal subjects (10 men and 10 women) volunteered for this study. None had a history of major respiratory or sleep disorder. Subject characteristics are given in Table 1. All participants completed the Epworth Sleepiness Scale (24) and Berlin Sleep Questionnaire.
that consistent breathing could be achieved during ultrasonography. Bands (Inductotrace, Ambulatory Monitoring, Ardsley, NY) to ensure of each subject was monitored using calibrated respiratory inductance

position, usually with its tip on the incisors. In this position, it is likely Subjects were asked to position the tongue in its usual “resting”

remain awake, and to breathe through their nose throughout the study. Padding for the head, neck, and shoulders maintained

photograph of the head position of each subject was also taken for

were made with the aid of two goniometers: one aligned along the

spinous process of C7 vertebrae to 37–42°. Angle measurements

in addition, the anteroposterior position of the head relative to the lower
cervical spine was standardized. The angle between horizontal plane and a line from lateral angle of eye to tragus was constrained to 77–82°, and the angle between horizontal plane and a line from tragus to spinous process of C7 vertebrae to 37–42°. Angle measurements were made with the aid of two goniometers: one aligned along the horizontal plane and the other along the measurement plane. A digital photograph of the head position of each subject was also taken for further analysis. Padding for the head, neck, and shoulders maintained the desired head and neck posture. Subjects were asked to relax, remain awake, and to breathe through their nose throughout the study. Subjects were asked to position the tongue in its usual “resting” position, usually with its tip on the incisors. In this position, it is likely that the force-generating capacity of the tongue was high and has been described as the GG optimum length (45, 49). The resting ventilation of each subject was monitored using calibrated respiratory inductance bands (Inductotrace, Ambulatory Monitoring, Ardsley, NY) to ensure that consistent breathing could be achieved during ultrasonography.

Signals were digitized at 1 kHz using a CED1401 data acquisition system and Spike2 software (Cambridge Electronic Design, Cambridge, UK). Respiratory data were analyzed offline to determine the inspiratory time, tidal volume, and respiratory rate. The onset of inspiration was taken from the signal of the abdominal inductance band (12, 13).

US scanning and analysis. US images were collected using a Philips iU22 system (Andover) with a curved array C8–5 transducer, which has a probe frequency of 5–8 MHz. To visualize the tongue, the handheld transducer was positioned submentally, aligned in the mid-sagittal plane, and pointed cranially. This provided a lateral view of the tongue body, submental musculature, and mandible. Similar images of the tongue have been described in previous work on US imaging of the tongue during speech (50–52), measurement of GG depth (9, 19), and clinical imaging of upper airway (40).

The abdominal movement tracing was also recorded on the US images. Real-time B-mode images were collected for at least 5 consecutive stable breaths at a frame rate of ~40 Hz (termed a “sequence”). Three sequences were captured in each session. During scanning, time gain compensation, depth, and near gain were adjusted manually for best image quality. The validity of US measurements of muscle has been established when the US transducer is aligned perpendicular to skin surface or adjusted to optimize image quality (26). In our study, minor adjustment of the transducer position was performed for each subject to ensure the best image quality of the GG. The depth of the image acquisition was set to 6 cm. A scan of the surrounding tissues was also performed before recording to determine the position of the superior surface of the tongue, the mandible, and the posterior portion of the tongue.

Image sequences were analyzed offline using custom image correlation software developed in MATLAB (Mathworks). This tracked the movement of designated markers on the image throughout the video sequence (4, 16). For regions of suitable image quality, a rectangular grid containing three columns (4 mm apart) of five points (3 mm apart) was then placed over the tongue as inferoposteriorly as possible to include the inferior/posterior region of GG. This region was selected as previous studies have shown that it is the site of most local motion (12, 13) (Fig. 1A). Theoretically, motion in this region may also be due to the actions of the intrinsic tongue muscles (i.e., verticalis, transversus, and longitudinalis muscles) and/or to action of extrinsic tongue muscles (i.e., hyoglossus and styloglossus). Previous EMG studies in human subjects documented respiratory activity in

### Table 1. Characteristics of 20 subjects

<table>
<thead>
<tr>
<th></th>
<th>Men</th>
<th></th>
<th>Women</th>
<th></th>
</tr>
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<tbody>
<tr>
<td>Age, yr</td>
<td>26.0 ± 5.6 (21–38)</td>
<td>25.9 ± 5.6 (21–37)</td>
<td></td>
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<tr>
<td>BMI, kg/m²</td>
<td>21.8 ± 2.5 (18.5–26.1)</td>
<td>22.1 ± 2.3 (18.4–25.9)</td>
<td></td>
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<tr>
<td>Neck circumference, cm</td>
<td>37.2 ± 1.8 (35–40.6)</td>
<td>31.8 ± 1.5 (30–34.3)</td>
<td></td>
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<tr>
<td>Epworth sleepiness score</td>
<td>5.3 ± 3.1 (2–10)</td>
<td>6.3 ± 4.4 (0–12)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Berlin questionnaire</td>
<td>Low (n = 10)</td>
<td>Low (n = 10)</td>
<td></td>
<td></td>
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</table>

Values are means ± SD with the range given in parentheses; n, no. of subjects. BMI, body mass index.

Experimental protocol. The experimental setup is shown in Fig. 1. Measurements were made with subjects in the supine posture. Since flexion or extension of the head alters upper airway size (1), the head position was standardized with the Frankfort plane (defined by the lower borders of the bony orbits and the upper margin of the auditory meatus) perpendicular to the horizontal bed surface. In addition, the anteroposterior position of the head relative to the lower cervical spine was standardized. The angle between horizontal plane and a line from lateral angle of eye to tragus was constrained to 77–82°, and the angle between horizontal plane and a line from tragus to spinous process of C7 vertebrae to 37–42°. Angle measurements were made with the aid of two goniometers: one aligned along the horizontal plane and the other along the measurement plane. A digital photograph of the head position of each subject was also taken for further analysis. Padding for the head, neck, and shoulders maintained the desired head and neck posture. Subjects were asked to relax, remain awake, and to breathe through their nose throughout the study. Subjects were asked to position the tongue in its usual “resting” position, usually with its tip on the incisors. In this position, it is likely that the force-generating capacity of the tongue was high and has been described as the GG optimum length (45, 49). The resting ventilation of each subject was monitored using calibrated respiratory inductance bands (Inductotrace, Ambulatory Monitoring, Ardsley, NY) to ensure that consistent breathing could be achieved during ultrasonography.

![Image of tongue and grid](image_url)

**Fig. 1.** Schematic representation of ultrasound (US) image, grid and numbering system, and subject positioning. A: US image with red line outlining the tongue and the position of the grid. GG, genioglossus; M, mucosa; S, tongue surface; GH, geniohyoid; MH, myohyoid. B: numbering system used with the grid. C: subject positioning. Angle θ was between the horizontal plane and a line from lateral angle of the eye to tragus (A) and was set at 37–42°. Angle φ was between horizontal plane and a line from tragus to spinous process of C7 vertebrae and was set at 77–82°.
Innovative Methodology

GG (23, 43, 44, 56) and hyoglossus (31) and although previous studies in rodents indicate minimal activity in intrinsic tongue muscle during eupnea (2), similar studies in human subjects are yet to be conducted. For this grid, the three columns were placed in an anterior to posterior direction, with the five points placed from most inferior to most superior position. For analysis, points 1–5 constituted the “anterior” group, points 6–10 the “middle” group, and points 11–15 the “posterior” group. Points 4, 5, 9, 10, 14, and 15 made up the “superior” group. Points 1, 2, 6, 7, 11, and 12 made up the “inferior” group. The nomenclature for the grid points is given in Fig. 1B. Any sequence in which swallowing or jaw motion occurred was excluded. The sequence of five tidal breaths with the clearest images was then selected. Regional displacements over three of the five breaths in each sequence were analyzed, and then the average was calculated. The resultant displacements were calculated using Pythagoras’ theorem.

Repeatability. To assess repeatability of results within a measurement session, the same rater analyzed each US image sequence containing the 5 breaths for all 20 subjects. The mean peak resultant displacement of the “inferoposterior” region (mean of the displacement of points 11 and 12) was compared between the three selected breaths within the same sequence. This region was selected because a previous study using MRI imaging showed prominent displacement occurred in this region (13), and in the present study this region also showed the largest displacement in quiet breathing (see RESULTS).

To assess repeatability between different sessions due to variation in subject posture, probe positioning, and image analysis, two further studies were performed in a subset of 10 randomly chosen subjects (5 men and 5 women). One study was conducted in the same session, in which the subject stood up, walked around for 5 min, and was then repositioned and rescanned. The other study was conducted at least 1 week later. The mean peak resultant displacement of the inferoposterior region was compared between the three imaging sessions.

Finally, to assess intrarater reliability, the same rater analyzed 1 randomly chosen file from each of the 10 subjects on 3 different days, beginning with grid placement on the image sequence. The mean peak resultant displacement of the inferoposterior region was calculated, and this was compared between the three analysis sessions.

Statistical analysis. Means and standard deviations (SD) were used for descriptive purposes in the text and figures. To assess sex differences in subject characteristics, we used unpaired t-tests. To determine whether there were differences in the degree of motion for different regions of the grid of points (anterior, posterior, superior, and inferior regions), a one-way analysis of variance with repeated measures was used. Sphericity was not assumed, and the Greenhouse-Geisser correction was used. Bonferroni’s correction for multiple comparisons was applied. The correlation between the mean peak anteroinferior displacement of the posterior GG during the three separate tests was determined with the intraclass correlation coefficient (ICC) using the average two-way mixed-reliability model (54).

The internal consistency of the mean anteroinferior displacement of the “inferoposterior” region between the three measured breaths within one analysis session, and the internal consistency between the mean peak anteroinferior displacement of the posterior GG during the three analysis sessions of the intrarater reliability subtest, were determined by the Cronbach’s α-coefficient (27). We also performed correlation analysis between the resultant displacements and tidal volume, as well as between resultant displacement and ratio between tidal volume and inspiratory time (indirect measure of respiratory drive). This was performed using Pearson’s correlation analysis.

Statistical analyses were carried out using IBM SPSS version 20. Statistical significance was accepted at P < 0.05. An ICC > 0.70 and Cronbach’s α > 0.70 were considered to indicate acceptable reliability (36).

RESULTS

Subject characteristics are shown in Table 1. There was no difference between the sexes for age, BMI, Epworth sleepiness score, and Berlin questionnaire, but neck circumference was smaller in women (P < 0.01). Head position was standardized with a mean angle of 40 ± 2° between the horizontal plane and a line from lateral angle of eye to the tragus and 79 ± 2° between the horizontal plane and a line from the tragus to the spinous process of the C7 vertebrae.

Visualization of oral anatomy. With the transducer held in a midline sagittal position, the bulk of the tongue was clearly visualized (Fig. 1A). GG appeared as a fan-shaped muscle in the anterior portion of the tongue, and two components could be identified. The superior component terminated in the tongue body postero-superiorly, at which point it was difficult to distinguish from the other tongue muscles. The smaller inferior portion appeared to be directed posteriorly in a more horizontal band toward the hyoid bone.

The mylohyoid and geniohyoid muscles were less echogenic (darker) distinct bands lying underneath GG. The tongue surface could usually be seen cranially as an echogenic line, which indicated the junction between the superior surface of the tongue and air in the oral cavity. In most subjects, an echo-lucent band immediately beneath and parallel to the tongue surface can be seen, which represented the mucosal layer (e.g., Ref. 52). The posterior portion of the tongue could be visualized if the transducer was directed more posteriorly toward the hyoid bone. It gave a high-amplitude echogenic signal while the GG muscle usually would not be seen. The hyoid also produced an acoustic shadow.

Displacement during quiet breathing. Regarding grid placement for image analysis, point 1 of the 15 grid points was placed 18.7 ± 5 mm posterior (mean ± SD) and 9.1 ± 3 mm superior to the internal mental spine of the mandible (insertion of GG). The average distance between the grid columns was 3.6 ± 0.5 mm, and the average distance between the grid rows was 2.6 ± 0.3 mm. The mean tidal volume across the 20 subjects during one imaging session was 389 ± 133 ml, with a mean respiratory rate of 15 ± 4 breaths/min. For the breaths from which images were measured, the respiratory cycle averaged 4.27 ± 1.26 s, with a mean inspiratory time of 1.95 ± 0.57 s. US images from a single breath in one subject are shown in the video file (see supplemental video file GGlutrasound.avi; the online version of this article contains supplemental data). Figure 2 illustrates the anterior, superior, and resultant displacement of the inferoposterior region in a typical subject. To show the reproducibility of the movement, data are shown for the three imaging sessions (two on 1 day, and the third 1 wk later).

The maximal displacement during the inspiratory phase of the respiratory cycle averaged 0.44 ± 0.15 mm along the transverse plane (positive being in the anterior direction) and −0.10 ± 0.03 mm along the coronal plane (positive being in the superior direction). The mean resultant peak displacement was 0.45 ± 0.16 mm. Table 2 summarizes the results for the six subregions within the 15-point grid (Fig. 1A). There was a significant difference in the magnitude of the peak resultant movement between the different defined regions of the posteroinferior portion of the tongue (F1,1,23,43–13,47, P = 0.001). Overall, the largest displacement occurred in the inferoposte-
rior region of GG (~0.7 mm; Fig. 3; see also Table 3 for data from each point on the grid). Formal post hoc testing revealed that movement in the posterior region exceeded that in the anterior region ($P = 0.018$), and that movement in the inferior region exceeded that in the superior region ($P = 0.008$). There was no difference in the magnitude of GG motion between male and female subjects ($P = 0.05$, unpaired t-test). Figure 4 depicts the mean resultant displacement during inspiration in the tracked region across all subjects.

Timing of inspiratory displacement. Inspiratory displacements of the “inferoposterior” region detected with US occurred on average 140 ms before the onset of inspiratory airflow, as estimated from the respiratory inductance bands. One subject’s inductance band tracing on the US imaging was poor, and the result was not analyzable. In all but one subject, 

<table>
<thead>
<tr>
<th>Table 2. Average regional displacement of genioglossus</th>
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<tbody>
<tr>
<td>Anterior Region</td>
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<tr>
<td>-----------------</td>
</tr>
<tr>
<td>Resultant</td>
</tr>
<tr>
<td>Male resultant</td>
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<tr>
<td>Female resultant</td>
</tr>
<tr>
<td>$P$ value</td>
</tr>
</tbody>
</table>

Values are means ± SD (in mm) of the average regional displacement of each of the predetermined regions for 20 subjects. $P$ values are given for comparison of data from men and women.
anterior GG motion began before inspiration. Maximal resultant displacement of the inferoposterior group was reached relatively early in the inspiratory phase for all subjects at an average of 1.1 s after the beginning of inspiration (27.4% of the respiratory cycle). In all subjects, anterior displacement of the inferoposterior group was larger than the inferior displacement.

Using Pearson’s correlation analysis, there was no correlation between maximal resultant movement of the inferoposterior region of GG and tidal volume (Pearson’s coefficient = 0.129, P = 0.294). Similarly, no correlation was found between maximal resultant movement of same region with the ratio between tidal volume and inspiratory time (i.e., mean inspiratory flow; Pearson’s coefficient = −0.12, P = 0.308).

**Repeatability of US measure.** Within the same testing session, the consistency of peak displacement for all 20 subjects across three breaths was good (Cronbach’s α = 0.81). The ICC for repeatability of average peak displacement for the 10 subjects across 3 breaths in 3 separate imaging sessions over 2 separate days was 0.85. The intrarater reliability for repeated measurement of the displacement of the same sequence in 10 subjects for 3 separate image analysis sessions was excellent (Cronbach’s α = 0.99).

**DISCUSSION**

This study describes a novel method of using US to measure movement of the GG, the largest tongue muscle and upper airway dilator, during quiet breathing in wakefulness. It was visualized as a large fanlike muscle originating from the mandible and extending upward into the tongue body. As it contracted over the respiratory cycle, it moved the tongue forward and downward and would thus act to open the pharynx (28, 55). This action is consistent with its anatomical description (see 15, 17) and movement observed during quiet breathing with tagged MRI (12, 13). The US method is also demonstrated to be reproducible over different imaging sessions on different days. As noted in MATERIALS AND METHODS, contraction of both extrinsic and intrinsic muscles, along with local mechanical effects, may contribute to the measured motion within GG (for review see Ref. 3).

**GG displacement during quiet breathing.** As hypothesized, the US imaging analysis revealed that the inferoposterior region of GG was displaced anteroinferiorly by −0.70 mm during inspiratory phase of the normal respiratory cycle, with greater displacement in the anterior than the inferior direction. The inferoposterior portion of the GG moved more (in both anterior and inferior directions) than other parts of the GG. These findings extend those obtained in a small number of subjects by Cheng and colleagues (12, 13) with tagged MRI. They reported variable magnitude in anterior movement of posterior GG during inspiration among the subjects (1.02 ± 0.54 mm), with both the size of the movement and its variability being larger than in the present study. The inferior part of GG moved largely in the anteroposterior direction, consistent with the direction of the lower GG fibers, with minimal movement of surrounding tissues.

This study also demonstrated GG movement begins before inspiratory airflow, typically by ~150 ms, although there is potentially some imprecision in the indirect measure of the timing of onset of inspiratory airflow of the order of ~100 ms. The maximal displacement of GG occurred ~1 s into inspiration, consistent with the phasic motion previously described by Cheng and colleagues (13). It is also consistent with studies in which noninvasive sublingual electrical stimulation of GG was demonstrated to maintain upper airway patency in awake humans (47), and invasive electrical stimulation of GG increased inspiratory airway patency and reduced apnea severity in patients with obstructive sleep apnea during sleep (37). Both multiunit (19, 29, 32, 46) and single motor unit studies (43, 44, 57) show GG EMG has both inspiratory phasic and a sustained tonic activity. The inspiratory phase activity increases ~100 ms before inspiratory airflow (23, 39, 43, 44, 56) and continues with recruitment and rate modulation of phasic motor units of GG throughout the first one-half of inspiration. The onset of GG activity precedes that of inspiratory pump muscles (43). There is also a correlation between the increase in GG EMG and negative airway pressure (39), and hence the observed inspiratory anterior movement of GG will counteract the effects of negative inspiratory pressure at the level of the epiglottis.

**Application of US method.** This simple noninvasive novel US method quantified the GG movement in human subjects.

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**Table 3. Average displacement of each grid points for 20 subjects**

<table>
<thead>
<tr>
<th>Grid Points</th>
<th>Mean Anterior Displacement</th>
<th>Mean Inferior Displacement</th>
<th>Resultant Displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.45 ± 0.33</td>
<td>0.26 ± 0.19</td>
<td>0.54 ± 0.35</td>
</tr>
<tr>
<td>2</td>
<td>0.45 ± 0.32</td>
<td>0.18 ± 0.14</td>
<td>0.51 ± 0.32</td>
</tr>
<tr>
<td>3</td>
<td>0.40 ± 0.23</td>
<td>0.14 ± 0.13</td>
<td>0.43 ± 0.23</td>
</tr>
<tr>
<td>4</td>
<td>0.33 ± 0.23</td>
<td>0.10 ± 0.12</td>
<td>0.37 ± 0.22</td>
</tr>
<tr>
<td>5</td>
<td>0.30 ± 0.22</td>
<td>0.09 ± 0.13</td>
<td>0.35 ± 0.20</td>
</tr>
<tr>
<td>6</td>
<td>0.53 ± 0.39</td>
<td>0.26 ± 0.16</td>
<td>0.58 ± 0.41</td>
</tr>
<tr>
<td>7</td>
<td>0.69 ± 0.50</td>
<td>0.23 ± 0.18</td>
<td>0.71 ± 0.52</td>
</tr>
<tr>
<td>8</td>
<td>0.54 ± 0.38</td>
<td>0.19 ± 0.15</td>
<td>0.56 ± 0.40</td>
</tr>
<tr>
<td>9</td>
<td>0.42 ± 0.27</td>
<td>0.13 ± 0.13</td>
<td>0.43 ± 0.28</td>
</tr>
<tr>
<td>10</td>
<td>0.32 ± 0.20</td>
<td>0.11 ± 0.10</td>
<td>0.34 ± 0.20</td>
</tr>
<tr>
<td>11</td>
<td>0.52 ± 0.40</td>
<td>0.26 ± 0.19</td>
<td>0.60 ± 0.42</td>
</tr>
<tr>
<td>12</td>
<td>0.73 ± 0.55</td>
<td>0.25 ± 0.22</td>
<td>0.80 ± 0.56</td>
</tr>
<tr>
<td>13</td>
<td>0.59 ± 0.43</td>
<td>0.21 ± 0.16</td>
<td>0.65 ± 0.43</td>
</tr>
<tr>
<td>14</td>
<td>0.40 ± 0.29</td>
<td>0.16 ± 0.14</td>
<td>0.45 ± 0.29</td>
</tr>
<tr>
<td>15</td>
<td>0.30 ± 0.19</td>
<td>0.12 ± 0.11</td>
<td>0.34 ± 0.19</td>
</tr>
</tbody>
</table>

Values are means ± SD (in mm). For the analysis, points 1–5 constitute the anterior group, points 6–10 the middle group, and points 11–15 the posterior group. (Fig. 1B). Points 4, 5, 9, 10, 14, and 15 make up the superior group. Points 1, 2, 6, 7, 11, and 12 make up the inferior group.

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**Fig. 4.** Resultant displacement of all points on the grid for GG. The mean resultant displacement and direction of each of the 15 grid points for the 20 subjects are shown. The actual scale refers to the displacement of each grid point. Four points are numbered (1, 5, 11, and 15).
during quiet breathing. GG was easily visualized through submental position of the transducer. We propose that this can be done in subjects who are awake or during sleep, and the method is repeatable across different sessions on same and different days. The results show that it is a promising method for studies of GG movement (e.g., comparing healthy subjects to patients with upper airway or sleep disorders; patients with mandibular devices) because it provides quantification of tongue motion. Furthermore, there is evidence from MRI that respiratory motion of GG is markedly impaired in disorders such as OSA (6, 8). So far, no imaging method for the oral cavity has become routinely useful, probably due to radiation exposure, cost, or poor dynamic real-time correlation with quiet breathing. Our method, combined with physiological measures, should be broadly applicable to patients with upper airway and sleep disorders.

Limitations. As with all imaging techniques, US imaging of GG has limitations. Although resolution of the US image is excellent for air-tissue interfaces (e.g., upper and lower tongue surfaces), it is often difficult to visualize detailed intramuscular architecture of GG. Hence, improved linear probes and three-dimensional reconstructions may prove beneficial. Such technical developments may make it easier to position the 15-point grid in a more precise manner, in relation to a bony reference point (e.g., mandibular plane).

Images obtained by US are sensitive to movements of both the subject and the transducer. Here, as the quantification of GG displacement relies on tracking of grid points throughout the respiratory cycle, small movements during collection of image sequences can degrade image quality and affect the reproducibility of the imaging method. Therefore, standardizing the head position before US imaging and maintaining it during image capture is important. However, despite its limitations, reproducible measures of maximal inspiratory movement of GG were obtained within and across sessions, as indicated by high intrasession and intersession reliability analysis in this study.

Because the imaging data were gathered during wakefulness, it is unclear how applicable it is for sleep. Based on EMG measures, EMG activity of GG decreases during sleep onset, and thus GG movement may also differ (58). The measured GG motion shows that there can be apparent “drift” such that displacements do not always come back to zero at the end of each respiratory cycle. This could be due to breath-to-breath variability and/or errors by the program tracking points from frame to frame. Finally, image correlation analysis has been validated in other skeletal muscles, for instance good accurate results were demonstrated for small displacements (1.0–2.0 mm) in porcine muscle (11). The present method has not been validated in the human GG muscle, where it is also difficult to define a standard bony landmark under US imaging in a sagittal plane; however, the results are broadly consistent with the findings of Cheng and colleagues (13). Furthermore, US storage systems commonly store DICOM images at a default setting of 30 frames/s, which may underestimate deformation values (25, 30) and affect image correlation analysis.

In summary, this study demonstrated that US imaging is a repeatable and comparable method to existing imaging technique in measuring GG movement. Compared with existing imaging techniques, US does not emit radiation and is quick to perform. It can offer real-time imaging in both clinical and research setting. Its relative simplicity could provide a novel imaging technique for anatomical phenotyping in patients with upper airway disorder, such as obstructive sleep apnea.

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GRANTS

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS


REFERENCES