Dynamic change in hyoid muscle length associated with trajectory of hyoid bone during swallowing: analysis using 320-row area detector computed tomography

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Okada T, Aoyagi Y, Inamoto Y, Saitoh E, Kagaya H, Shibata S, Ota K, Ueda K. Dynamic change in hyoid muscle length associated with trajectory of hyoid bone during swallowing: analysis using 320-row area detector computed tomography. J Appl Physiol 115: 1138–1145, 2013. First published August 22, 2013; doi:10.1152/japplphysiol.00467.2013.—Research on muscle activation patterns during swallowing has been limited. Newly developed 320-row area detector computed tomography (320-ADCT) has excellent spatial and temporal resolution, which facilitates identification of laryngopharyngeal structures and quantitative kinematic analysis of pharyngeal swallowing. We investigated muscle activity patterns by observing the changes in length of hyoid muscles. 320-ADCT was performed in 26 healthy males while swallowing. The following parameters were analyzed three-dimensionally: 1) origins and insertions of the stylohyoid, anterior and posterior digastric, mylohyoid, geniohyoid, and thyrohyoid muscles; and 2) movement of the hyoid bone. The stylohyoid, posterior digastric, and mylohyoid muscles began to shorten simultaneously during the initial stage of swallowing. The shortening of these muscles occurred during the upward movement of the hyoid bone. Subsequently, the geniohyoid, thyrohyoid, and anterior digastric muscles began to shorten, synchronizing with the forward movement of the hyoid bone. A significant correlation was observed between the shortened muscle lengths of the stylohyoid, posterior digastric, and mylohyoid muscles and the upward movement of the hyoid bone ($r = 0.45–0.65$). A correlation was also observed between the shortened muscle length of the geniohyoid muscle and the forward movement of the hyoid bone ($r = 0.61$). In this study, the sequence of muscle activity during pharyngeal swallowing remained constant. Serial shortening of the hyoid muscles influenced the trajectory of the hyoid bone. The stylohyoid, posterior digastric, and mylohyoid muscles initiated the swallowing reflex and contributed to upward movement of the hyoid bone. The geniohyoid is a key muscle in the forward movement of the hyoid bone.

muscle; swallowing; movement; hyoid bone

THE HUMAN SWALLOWING REFLEX is a complex process involving the coordinated activity of swallowing-related muscles. It is imperative that we develop an understanding of the muscle activity pattern occurring during normal swallowing. Various techniques have been used to study the physiological and biomechanical aspects of swallowing. Well-known techniques such as videofluoroscopy (VF) and videendoscopy provide information on the movement of anatomic structures during swallowing. Manometry and electromyography (EMG) are used to study the pressure and muscle activation generated during pharyngeal swallowing, respectively.

Muscle activation patterns are best determined using EMG. Both animal and human experiments with EMG have contributed to the corpus of knowledge on swallowing. One of the early and most frequently cited studies on pharyngeal swallowing by Doty and Bosma (5) used wire electrodes to record intramuscular EMG activity in a large complex of oral, pharyngeal, and laryngeal muscles in anesthetized animals. The study documented an organized and relatively invariant sequence of muscle activation during swallowing. Additional EMG investigations of oral and pharyngeal swallowing in nonhuman species have been reported (15, 16, 21, 33, 34, 37). Data from these studies support the conclusion that the involuntary portion of the swallowing process is controlled by a central pattern generator, as stated by Doty and Bosma (5).

Because many muscles of deglutition tend to be located deep below the surface, needle or wire electrodes are typically used. This limits the quality and quantity of data obtained from simultaneously recorded muscle activity in humans. Therefore, many human studies using intramuscular EMG during pharyngeal swallowing focused on the activity of a single muscle or muscle pair (1, 6, 24, 35, 36). Studies that examined EMG activity on more than two muscles in humans (7, 9, 25, 26, 30, 32) have been somewhat limited and did not clearly quantify the temporal relationships of the activity between muscles. Furthermore, EMG does not provide information about the dynamics of swallowing whereas competent swallowing involves a complex sequence of oral and pharyngeal events resulting in the passage of a bolus into the esophagus.

Bolus passage occurs as a result of physiological and biomechanical changes in the anatomic structures involved in swallowing. VF has verified and quantified the upward and subsequent forward movement of the hyoid bone during swallowing (4, 31). Because the supra- and infrayoid muscles attach to the hyoid bone, it has been thought that supra- and infrayoid muscles play primary roles in controlling the hyoid movement (18, 19). Simultaneous VF and EMG data collection offer an opportunity to understand how muscle activity is related to the hyoid movement. However, synchronous VF and EMG recordings have been performed only in a few animal studies (10, 16). Thus the roles of the supra- and infrayoid muscles have not been explicitly or directly investigated (3, 14, 17). Most recently, Pearson et al. proposed that not only the supra- and infrayoid muscles but also the long pharyngeal muscles contribute to elevate the hyolaryngeal complex by using physiological cross-sectional areas of muscles taken from cadavers (28, 29) and muscle functional magnetic resonance imaging in healthy subjects (27).
The dynamic changes of muscle activity that occur with normal swallowing can be understood using a newly developed technology: 320-row area detector computed tomography (320-ADCT). 320-ADCT has excellent spatial and temporal resolution. It allows quantitative kinematic analysis of pharyngeal swallowing and sequential identification of laryngeal structures such as the hyoid bone and vocal cords (8, 12). This dynamic three-dimensional (3D) imaging technique displays target structures stereoscopically from multiple directions and enables precise quantitative and dynamic simultaneous measurement during swallowing (13, 23).

320-ADCT thus allows direct observation of musculature shortening and the movement of the hyoid bone. It enable us to measure the length of the supra- and infrahyoid muscles by identifying their origins and insertions. In this study, we hypothesized that individual hyoid muscles have specific roles for generating the hyoid upward and the following forward movement during pharyngeal swallowing. To verify it, we first evaluated sequential changes in length in six hyoid muscles. We then calculated the trajectory of the hyoid bone separately for the anterior-posterior and the superior-inferior directions. Finally, we analyzed the association between shortened muscle length and the upward vs. forward hyoid bone movements.

METHODS

Subjects. Healthy adult subjects over 20 years old with normal swallowing ability, without neurological diseases, and with no previous surgery in the upper gastrointestinal tract were recruited through advertisements at our university hospital. Judgment of having normal swallowing ability was done by a speech language pathologist and a physiatrist. All subjects gave informed consent for participation in this study that was based on a protocol approved by the institutional review board at Fujita Health University. To minimize the effect of body height, we analyzed the data for males in this study. Twenty-six healthy males with a mean age of 46 ± 16 (SD) yr were analyzed.

Procedure. A 320-ADCT scanner (Aquilion ONE; Toshiba Medical Systems, Otawara, Japan) was used in this study. A reclining chair specifically designed for this study (TOMEIBRACE, Seto and ASKA, Kariya, Japan) was placed on the opposite side of the CT table. The subject was seated on the reclining chair that was inclined at 45°. The reclining chair, which was designed to slide backward and forward, was inserted on the opposite side of the CT table and the CT scanning plane was inclined at 22° (Fig. 1). The scanning range was 160 mm from the skull base to the upper esophagus. The scanning parameters were set as follows: field of view = 240 mm and tube voltage/current = 120 kV/60 mA. The CT dose index (CTDI) and dose-length product (DLP) with these scanning parameters were 34.7 mGy and 554.9 mGy cm, respectively. One trial of the CT scanning was performed for each subject.

Subjects sat on the reclining seat while holding 10 ml of honey-thick liquid barium (5% vol/wt, Neohydromeal, FoodCare, Sagamihara-shi, Japan) in their oral cavity. They were then asked to swallow according to specific instructions. Images were acquired for 3.15 s with the tube rotating nine times per maneuver. For image generation, a half reconstruction technique, in which images were generated from data recorded at 0.17-s intervals, was employed for optimal temporal resolution. Multiplanar reconstruction (MPR) images and 3D-CT images were reconstructed from thin axial slices using scanner software. The 3D images were created in 29 phases at 0.10-s intervals for 2.9 s.

Measurement. Length, area, and volume can be measured threedimensionally without the limitations associated with cross-sectional images through software installed on a CT scanner. Muscle length is defined as the distance between the origin and insertion of a muscle. Muscles with origins and insertions on bony structures can be identified using 320-ADCT. Origins and insertions of the stylohyoid, posterior and anterior digastric, mylohyoid, geniohyoid, and thyrohyoid muscles were identified using 3D coordinates. The mylohyoid muscle is a unique muscle that has more circumferential shape with insertion along a raphe. As for the insertion of mylohyoid muscle, we first found the lateral posterior margin of mylohyoid muscle and eventually detected the lateral end of mylohyoid line. Origins and insertions for each muscle analyzed in this study are shown in Table 1 (2). The origin and insertion points of individual muscles were identified frame-by-frame from MPR images in 29 phases, and the changes in length between the origin and insertion points were calculated.

A typical example of identifying muscle origin, insertion, and length using a three dimensional CT image is illustrated in Fig. 2. Shortened length was defined as maximal length minus the minimal length over the duration of the image. Typically, maximal length was observed before swallowing or at very early phase of swallowing and minimal length was observed during mid-swallowing. The shortening ratio was defined as follows:

\[
\text{Shortening ratio (\%)} = \frac{\text{shortened length (mm)}}{\text{maximal length (mm)}} \times 100
\]

When a shortened length was less than 95% of the maximal shortened length, the muscle was described as “actively shortened.”

### Table 1. Measured superior and inferior hyoid muscles

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Origin</th>
<th>Insertion</th>
</tr>
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<tbody>
<tr>
<td>Stylohyoid</td>
<td>Tip of the styloid process</td>
<td>Tip of the lesser cornu of hyoid bone</td>
</tr>
<tr>
<td>Posterior</td>
<td>Muscle attachment of metapophysis</td>
<td>Tip of the lesser cornu of hyoid bone</td>
</tr>
<tr>
<td>Anterior</td>
<td>Muscle attachment of digastric fossa</td>
<td>Tip of the lesser cornu of hyoid bone</td>
</tr>
<tr>
<td>Mylohyoid</td>
<td>Lateral end in mylohyoid line</td>
<td>Midpoint and lower edge of lesser cornu of hyoid bone</td>
</tr>
<tr>
<td>Geniohyoid</td>
<td>Tip of spinous process</td>
<td>Anterior-most portion of body of hyoid bone</td>
</tr>
<tr>
<td>Thyrohyoid</td>
<td>Midpoint of greater cornu of hyoid bone</td>
<td>Midpoint of thyroid projection and inferior horn</td>
</tr>
</tbody>
</table>

Origins and insertions measured in this study are shown.
The timing of the hyoid bone movements (onset of upward and forward movement) was also measured. Onset of the upward movement of the hyoid was defined as the point at which the hyoid bone exceeded 5% of total possible vertical displacement just after it began to move upward. Onset of the forward movement of the hyoid was defined as the point at which the hyoid bone began to move forward and it exceeded 5% of total possible horizontal displacement. In this study, onset of the upward movement of the hyoid was labeled as time 0. The line passing through the anterior and posterior nasal spine was determined as “horizontal line” (Fig. 3). Upward movement of each muscle and the hyoid bone was defined as vertical to the horizontal line and forward movement was defined as parallel to the horizontal line.

Statistical analysis. Spearman’s rank correlation coefficient was used to test the relationship between the maximal muscle length, shortened muscle length, and shortening ratio. Spearman’s rank correlation coefficient was also used to test the relationship between shortened length of each hyoid muscle and the maximal displacement of upward and forward movement of the hyoid bone. SPSS ver. 19.0 J for Mac (SPSS, Chicago, IL) was used for the statistical analyses. The level of significance was set at <5%.

RESULTS

Maximal and minimal muscle length. The means and standard deviations of the maximal and minimal muscle lengths are shown in Table 2. In most cases, maximal muscle length corresponded to the length at rest. In some thyrohyoid and anterior digastric muscles, maximal muscle length corresponded to the beginning or middle of hyoid bone movement (cf. Fig. 5). The maximal length of the longest muscle, the posterior digastric muscle, was 85.2 ±
Muscle shortening and hyoid trajectory. The average upward movement of the hyoid bone was $16.5 \pm 9.2$ mm and the average forward movement was $12.8 \pm 5.0$ mm. Figure 6 illustrates the relationships between minimal muscle lengths of the six hyoid muscles and upward movement distance of the hyoid bone during swallowing. The correlation coefficients for individual muscles are shown in Fig. 6. Significant correlations were observed for the stylohyoid, posterior digastric, and mylohyoid muscles with the distance of upward movement of the hyoid bone ($r = 0.652$, $0.452$, and $0.625$, respectively). Figure 7 illustrates the relationships between shortened muscle lengths of six hyoid muscles and forward movement distance of the hyoid bone during swallowing. The correlation coefficients are also shown in Fig. 7. A significant correlation was observed between the geniohyoid and forward movement distance of the hyoid bone ($r = 0.611$). Although not significant, moderate correlation coefficients were observed for the anterior digastric and thyrohyoid muscles ($r > 0.30$).

**DISCUSSION**

Activity of the hyoid muscles. Muscle contraction involved in swallowing can be evaluated using EMG. Some EMG...
experiments have been reported in the past 50 years. Animal studies using EMG have suggested that the swallowing reflex is initiated by the contraction of certain suprahyoid muscles (5, 34). The work of Doty and Bosma (5) led to a consensus that the mylohyoid muscle is a key muscle in the sequential pattern of muscle activation. However, they found wide variation in the duration of activity in various muscles; no two EMG measurements of deglutition from the same electrodes gave identical or even similar unit patterns (5). Thexton et al. (34) reinvestigated EMG activity during reflex pharyngeal swallowing. They suggested that the mylohyoid muscle was not activated before other muscles and that the geniohyoid muscle was not a part of the “leading complex.” However, they also stated that the recorded EMG signals showed both the intramuscular and interanimal variations, whereas the movements were highly stereotyped (34). Some of this variation could be attributed to slight displacements of the electrodes during muscle movement (5, 34).

In humans, needle EMG of the swallowing musculature is more challenging than that of the limb muscles because hyoid muscles inserting into the hyoid bone are located deep to the surface. Although needle EMG appears to be a safe procedure (17, 22), patient discomfort may be a problem; time may be required to

Table 3. Onset of upward and forward movement of the hyoid bone and actively shortened time of individual muscles during swallowing of a 10-ml honey-thick liquid

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Average, s</th>
<th>SD, s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upward movement</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Posterior digastric</td>
<td>0.34</td>
<td>0.10</td>
</tr>
<tr>
<td>Stylohyoid</td>
<td>0.01</td>
<td>0.05</td>
</tr>
<tr>
<td>Mylohyoid</td>
<td>0.03</td>
<td>0.06</td>
</tr>
<tr>
<td>Geniohyoid</td>
<td>0.04</td>
<td>0.09</td>
</tr>
<tr>
<td>Thyrohyoid</td>
<td>0.27</td>
<td>0.12</td>
</tr>
<tr>
<td>Anterior digastric</td>
<td>0.29</td>
<td>0.09</td>
</tr>
<tr>
<td>Geniohyoid</td>
<td>0.39</td>
<td>0.18</td>
</tr>
</tbody>
</table>

The onset of upward movement of hyoid bone was set as 0 s. The average and SD for each muscle were relative to onset of the upward movement of the hyoid bone.

Fig. 5. Changes in muscle length and the trajectory of hyoid bone movement during swallowing of a 10-ml honey-thick liquid. Onset of the upward movement of the hyoid bone was set as 0 s. The graphs are averaged data from 26 subjects. An arrow indicates the point when a shortened muscle length became <95% of the maximal shortened length at which the muscle is considered as actively shortened. Positive value indicates the upward and forward directions in the graph below.
manipulate the needle to locate the muscle of interest, which may be deeply embedded in other overlapping muscles not directly related to swallowing. Thus human studies investigating EMG activity in swallowing-related muscles have been limited. EMG studies of the stylohyoid or digastric posterior muscles have been very rarely conducted in humans (17).

The general consensus is that sequential muscle shortening represents muscle activity during concentric contraction (11, 20). Thus muscle shortening has been measured two-dimensionally for evaluation of hyoid muscle activity during swallowing (20). In this study, changes in the distance between the origins and insertions of supra- and infrahyoid muscles were measured three-dimensionally using a 320-ADCT scanner. We demonstrated that the supra- and infrahyoid muscles changed in length during pharyngeal swallowing and that the overall sequence of muscular activity remained constant and stereotypical.

**Role of hyoid muscles in hyoid bone movement.** A crucial event in the pharyngeal phase of swallowing is the elevation and subsequent anterior movement of the hyoid bone. VF has verified and quantified the upward and subsequent forward movement of the hyoid bone during the passage of a bolus into the esophagus (4, 31). The 3D dynamic ADCT technique used in this study allowed calculation of the total upward and forward movement distances of the hyoid bone.

Muscles attached to the hyoid bone presumably affect hyoid bone movement, but their roles have not been explicitly investigated (3, 14, 17). In a recent study by Pearson et al. (28), a cadaver model was used to evaluate the architecture of muscles positioned to move the hyoid upward and forward. Based on structural properties, the geniohyoid muscle may have the most potential to displace the hyoid in the forward direction, and the mylohyoid may have the most potential to displace the hyoid in the upward direction. However, as Pearson et al. (28) stated, anatomic data while suggestive of function must be corroborated by functional studies to ensure its clinical usefulness. In the current study, we demonstrated not only the role of the geniohyoid and mylohyoid muscles but that of other hyoid muscles using the 3D dynamic ADCT technique.

In the analysis of hyoid muscle activity, shortening of the stylohyoid, posterior digastric, and mylohyoid muscles was observed before that of other suprahyoid muscles during swallowing (Fig. 5, Table 3). The shortening of these muscles synchronized and significantly correlated with the upward movement of the hyoid bone (\(r = 0.45 - 0.65\)) (Fig. 6). The correlation of timing and distance between the shortening of these three muscles and the upward movement of the hyoid bone provides absolute evidence that the stylohyoid, posterior digastric, and mylohyoid muscles cause this upward movement (Fig. 8). Following the shortening of these three muscles, the geniohyoid, thyrohyoid, and anterior digastric muscles began to shorten, synchronizing with the forward movement of the hyoid bone. The shortening of the thyrohyoid muscle correlated significantly with this forward movement (\(r = 0.61\)) (Fig. 7). The shortening of the thyrohyoid and anterior digastric muscles was moderately but insignificantly correlated with this forward movement (\(r > 0.3\)). Although the thyrohyoid shortened associated with onset of the forward movement, the primary of this muscle is to pull the larynx closer to the hyoid bone. These results indicate that the geniohyoid is the key...
muscle that moves the hyoid bone forward and that the anterior digastric muscle is secondary muscle contributing to the forward movement of the hyoid bone (Fig. 8).

In summary, serial shortening of hyoid muscles significantly influenced the trajectory pattern of the hyoid bone. Most importantly, as hypothesized, the hyoid muscle group can be divided into two groups on the basis of functional influences on hyoid bone movement. The stylohyoid, posterior digastric, and mylohyoid muscles constitute the first group of muscles that shorten in the initial stage of swallowing and are instrumental in moving the hyoid bone upward. The second group comprises the geniohyoid and anterior digastric muscles, which shorten subsequently and are instrumental in moving the hyoid bone forward.

Limitation of this study and potential of ADCT for swallowing study. Target structures can be displayed stereoscopically from multiple directions using 320-ADCT. Multiphase 3D images are reconstructed in 29 phases at intervals of 0.1 s, allowing a kinematic analysis of swallowing (8). CT is inferior to magnetic resonance imaging with regard to the contrast resolution of soft tissues, thus making muscle identification difficult. However, hyoid muscles with their origins and insertions within the bone can be accurately identified and measured using 320-ADCT. The hyoid bone and larynx move very quickly during swallowing. Nevertheless, images created at short intervals (0.1 s) and continuous multisectional observation on MPR permitted comfortable morphologic examination and kinematic analysis of the target structures in the current study. Thus this 3D dynamic ADCT technique was a good tool for identifying changes in muscle length.

There were some limitations in this study. First, other variables such as the bolus consistency were not examined simultaneously to minimize the potential risk associated with radiation exposure. The effective dose was 1.08 mSv at one time, about the same dose for a clinical videofluoroscopic swallowing study (1.05 mSv for 5 min). The second limitation was the 45 degree reclining position because the CT procedure cannot be performed with the subject in the upright position. There is a possibility that the inclined and sitting positions might have produced different results. Third, to generalize the current findings, it is necessary to increase the number of volunteers to assess the variations potentially caused by age and sex.

Compared with VF, the biggest advantage of 320-ADCT is the recording technology of the 3D dynamic image. It has great potential for further research on swallowing. Further studies measuring upper esophageal sphincter, oropharyngeal cavity, and pharyngeal muscles are recommended. As for a possible
clinical use, measurement of changes in hyoid muscle length may be useful for evaluating the effects of rehabilitation in dysphagia. Referring to rehabilitation approaches based on limited movement of the hyoid in pharyngeal dysphagia, the effectiveness of strategies such as electrical stimulation or muscle strengthening exercises may be evaluated. From the viewpoint of the cost-benefit ratio and the risk exposing individuals to a certain amount of radiation in the process of conducting a swallow assessment, however, it remains unknown in patients with dysphagia whether the 3D information offers further benefit in addition to 2D information provided by VF.

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

AUTHOR CONTRIBUTIONS

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