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Original Article

Swallowing maneuver analysis using 320-row area detector computed tomography (320-ADCT)

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ABSTRACT
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Objective: Our objective was to examine whether swallowing maneuvers such as the Mendelsohn maneuver (MM) and the super-supraglottic swallow (SSGS) can be analyzed three-dimensionally and kinematically by using 320-row area detector computed tomography (320-ADCT).
Methods: The subject was instructed to lean against a seat reclined at a 45° angle, hold 4 ml of 5% thickened liquid barium in the oral cavity, and then swallow normally or using the MM or the SSGS. Data were acquired for 3.15 s by using 320-ADCT, and images were reconstructed using a half-reconstruction method. The timing of each swallowing event was compared among the 3 swallowing methods.
Results: We were able to determine the timing of vocal-cord closure and pharyngoesophageal segment (PES) opening during the normal swallowing method, the MM, and the SSGS.
Conclusion: Swallowing maneuvers can be analyzed three-dimensionally and kinematically by using 320-ADCT.
Keywords: 320-ADCT, swallowing maneuver, Mendelsohn maneuver, super-supraglottic swallow

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Introduction

Swallowing maneuvers are important compensatory techniques that improve safety during ingestion in patients with dysphagia. In 1972, Larsen et al. [1] first reported that swallowing function was improved by using a breath-holding technique and maintaining the neck in a flexed position. In the 1980s, additional swallowing maneuvers were developed. However, these swallowing maneuvers were analyzed by videofluorography (VF) or by endoscopic evaluation, not by three-dimensional (3D) analysis. In 2010, Fujii et al. [2] described 320-row area detector computed tomography (320-ADCT), a new method for evaluating swallowing movements that can acquire a volume data set covering a maximum range of 16 cm and can generate axial images of 0.5-mm thickness at 0.5-mm intervals. A 3D image can be reconstructed from these axial images. However, it is not yet clear whether 320-ADCT can kinematically analyze swallowing maneuvers adequately, because its time resolution (10 frames/s) is inferior to that of VF. This study aimed to examine whether it is possible to kinematically analyze 2 typical swallowing maneuvers, the Mendelsohn maneuver (MM) and the super-supraglottic swallow (SSGS), using 320-ADCT.

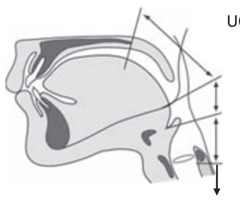
Methods

This study was approved by and performed in accordance with the guidelines of our institution's Ethics Review Board. The subject was a healthy 32-year-old female, who was familiar with the swallowing maneuvers and submitted written consent to participate in the study. Images were acquired on a 320-ADCT scanner (Aquilion ONE; Toshiba Medical Systems, Otawara-shi, Japan). The patient was seated

Table 1. Measured events and definitions of the oropharynx areas

Measured events		Definition
Complete closure of the soft palate		
	initiation	Time of complete closure of the rhinopharynx following elevation of the soft palate
	termination	Time of reopening of the rhinopharynx
Closure of the laryngeal vestibule		
	initiation	Time of closure of the laryngeal vestibule following contact between the arytenoid cartilage and the epiglottis
	termination	Time of reopening of the laryngeal vestibule
Closure of the glottis		
	initiation	Time of adduction of the vocal cords and complete closure of the airway
	termination	Time of reopening of the airway at the vocal cord level
Opening of the PES		
	initiation	Time when air is first present at the PES
	termination	Time of passage of contrast medium bolus and elimination of air or bolus
Stage transition duration (STD)		Duration from the time at which the leading edge of the bolus was defined by the inferior margin of the lower jaw until the time at which the rear end of the bolus passed the PES

The oropharynx area	Definition
Upper oropharyngeal area (UOP)	From the plane at the border of the hard palate and the soft palate and perpendicular to the hard palate to the plane made by the inferior margin of the lower jaw
Valleculae area (VAL)	From the plane made by the inferior margin of the lower jaw to the valleculae
Hypopharyngeal area (HYP)	Beyond the valleculae area to the plane where the inferior margin of the thyroid cartilage is parallel to the vocal cord plane
Esophageal area (Eso)	Beyond the plane parallel to the vocal cord at the inferior margin of the thyroid cartilage



on a reclining seat, specifically designed for this study, positioned at a 45° angle (Tomei brace; Seto-shi, Japan, and Asuka Corporation, Kariya-shi, Japan). The reclining seat, which was designed to slide backward and forward, was inserted on the opposite side of CT table, and the CT scanning plane was tilted to 22°. The subject leaned against the reclining seat, held 4 ml of 5% thickened liquid barium in the oral cavity, and then swallowed according to the instructions. The subject performed the normal swallowing method, the MM, and the SSGS once each. Images were acquired for 3.15 s with the tube rotating 9 times per maneuver. Images were reconstructed with a half-reconstruction method to obtain multi-planar reconstruction (MPR) images at 0.1-s intervals as well as 3D images. The obtained images were analyzed by 2 researchers who were familiar with oral anatomy and with diagnostic imaging using 320-ADCT.

Measured events: The soft palate, hyoid bone, epiglottis, vocal cords, arytenoid cartilage, and pharyngoesophageal segment (PES) opening during swallowing were observed on the mid-sagittal and axial images obtained by MPR. A list of the measured events and their definitions are provided in Table 1. We measured the timing of laryngeal vestibule closure, vocal cord closure, and PES opening as previously reported by Inamoto et al. [3]. The duration of complete soft-palate closure was defined as the period during which the rhinopharynx was closed by the elevation of the soft palate, starting from when the area from the base of the soft palate to the tip of the uvula came into contact with the pharyngeal wall and lasting until the rhinopharynx was opened again. The onset of hyoid elevation was set as time zero, and then the timing of each initiation and termination was measured. The airway surface, contrast medium, and bones were visualized on the 3D images by employing the volume-rendering method. The images displayed these features in blue, yellow, and white, respectively and were then used to determine the extent of airway closure and the location of the contrast medium bolus. To indicate the location of the leading edge of the bolus, the oropharyngeal area was divided into the upper oropharyngeal (UOP), valleculae (VAL), hypopharyngeal (HYP), and esophageal (Eso) areas; each area is defined in Table 1. The time to transport the bolus of contrast medium was measured by the stage transition duration (STD), starting from when the leading edge of the bolus was located at the inferior margin of the lower jaw (i.e., VAL) and ending when the rear edge of the bolus passed the PES, as described by Lof and Robbins [4].

The movement of the hyoid bone was traced using ImageJ software (v1.44o; NIH, Baltimore, MD, USA). In the mid-sagittal images obtained by MPR, the Y-axis was defined as the line between the anteroinferior margin of the second cervical spine and the anteroinferior margin of the fourth cervical spine. The X-axis was defined as the line running to the anteroinferior margin of the second cervical spine to the Y-axis direct. The image was rotated so that the Y-axis was vertical. The intersection of the 2 axes was defined as the origin; the superior direction was defined as positive Y-axis values, and the anterior direction was defined as positive X-axis values. The superior margin of the hyoid bone was defined as the measure point to measure the trace.

Results

Visualization of swallowing movements using 320-ADCT

In the normal swallowing method (Figure 1), at the beginning of the swallowing reflex, the arytenoid cartilage started to incline forward as the hyoid bone moved forward at the beginning of the swallowing reflex. Complete closure of the soft palate and laryngeal vestibule occurred 0.3 s later. Glottis closure occurred at 0.4 s, and at 0.6 s, the air layer was eliminated from the hypopharynx because of the complete inversion of the epiglottis and contraction of the pharynx.

In the MM (Figure 2), complete soft-palate closure and simultaneous initiation of the anterior tilt of the arytenoid cartilage occurred 0.2 s before the hyoid

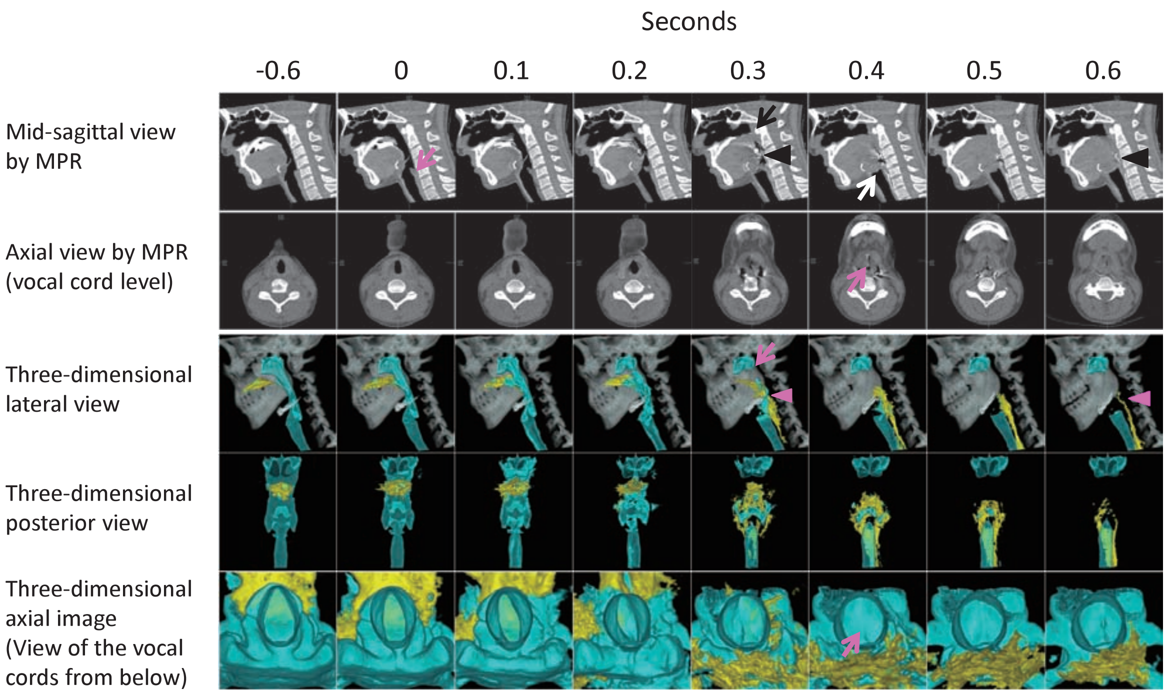


Figure 1. Normal swallowing method.
The time at which the hyoid bone moved forward at the beginning of the swallowing reflex was defined as 0 s in the time series.
0 s : Initiation of anterior tilt of the arytenoid cartilage (←)
0.3 s : Initiation of complete closure of the rhinopharynx following elevation of the soft palate (←); initiation of closure of the laryngeal vestibule (∇)
0.4 s : Initiation of glottis closure (←); this persisted for 0.4 s.
0.6 s : Elimination of the air layer from the hypopharynx by complete inversion of the epiglottis and contraction of the pharynx (∇)

bone started to move forward. Closure of the laryngeal vestibule and glottis occurred at 0.2 and 0.3 s, respectively. The elimination of the air layer from the hypopharynx by the complete inversion of the epiglottis and contraction of the pharynx occurred at 0.5 s.

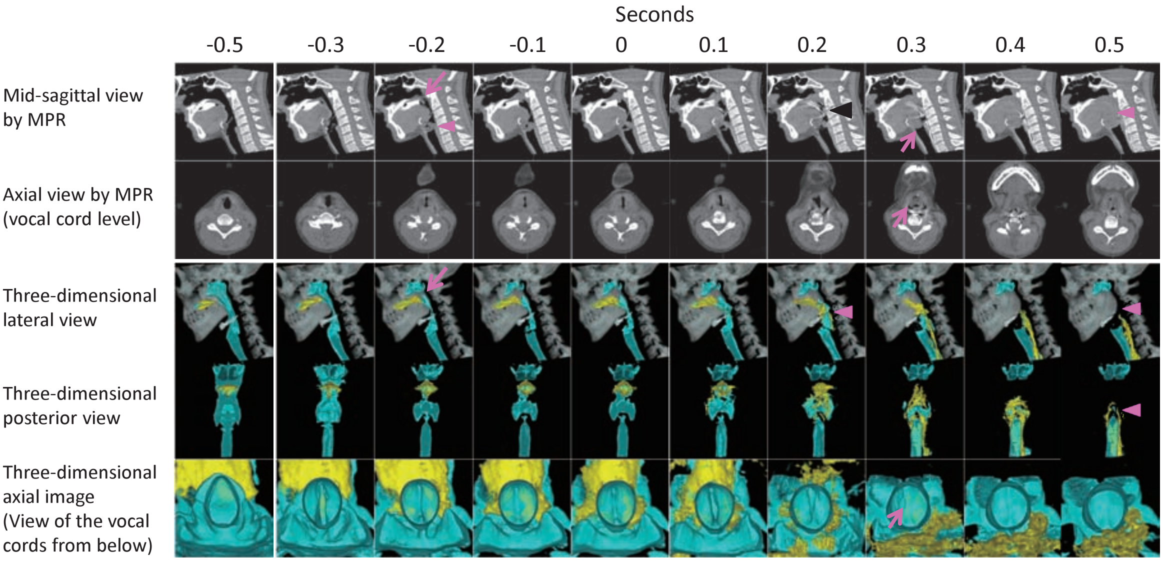


Figure 2. Mendelsohn maneuver.
The time at which the hyoid bone was moved forward at the beginning of the swallowing reflex was defined as 0 s in the time series.
-0.2 s: Complete closure of the rhinopharynx following elevation of the soft palate (⟵); Beginning of forward inclination of the arytenoid cartilage (∇)
0.2 s : Initiation of closure of the laryngeal vestibule (∇)
0.3 s : Initiation of glottis closure (⟵); this persisted for 2.0 s.
0.5 s : Complete inversion of the epiglottis and elimination of the air layer from the hypopharynx by contraction of the pharynx (∇)

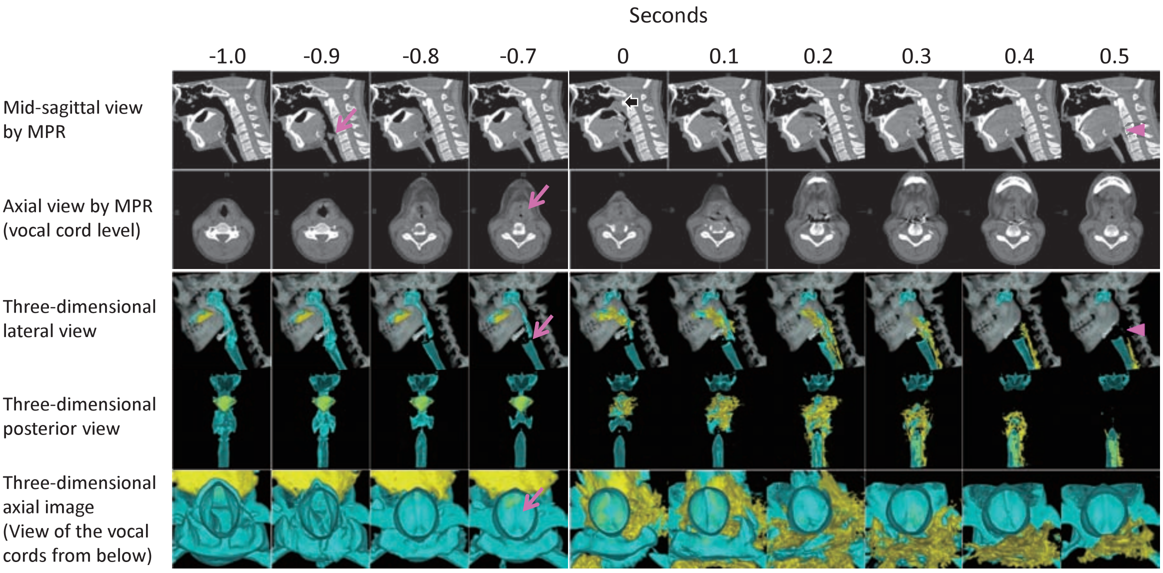


Figure 3. Super-supraglottic swallow.
The time at which the hyoid bone moved forward at the beginning of the swallowing reflex was defined as 0 s in the time series.
-0.9 s: Beginning of forward inclination of the arytenoid cartilage (⟵)
-0.7 s: Initiation of glottis closure (⟵); this persisted until termination of swallowing.
0.5 s : Complete inversion of the epiglottis and elimination of the air layer from the hypopharynx by contraction of the pharynx (∇).

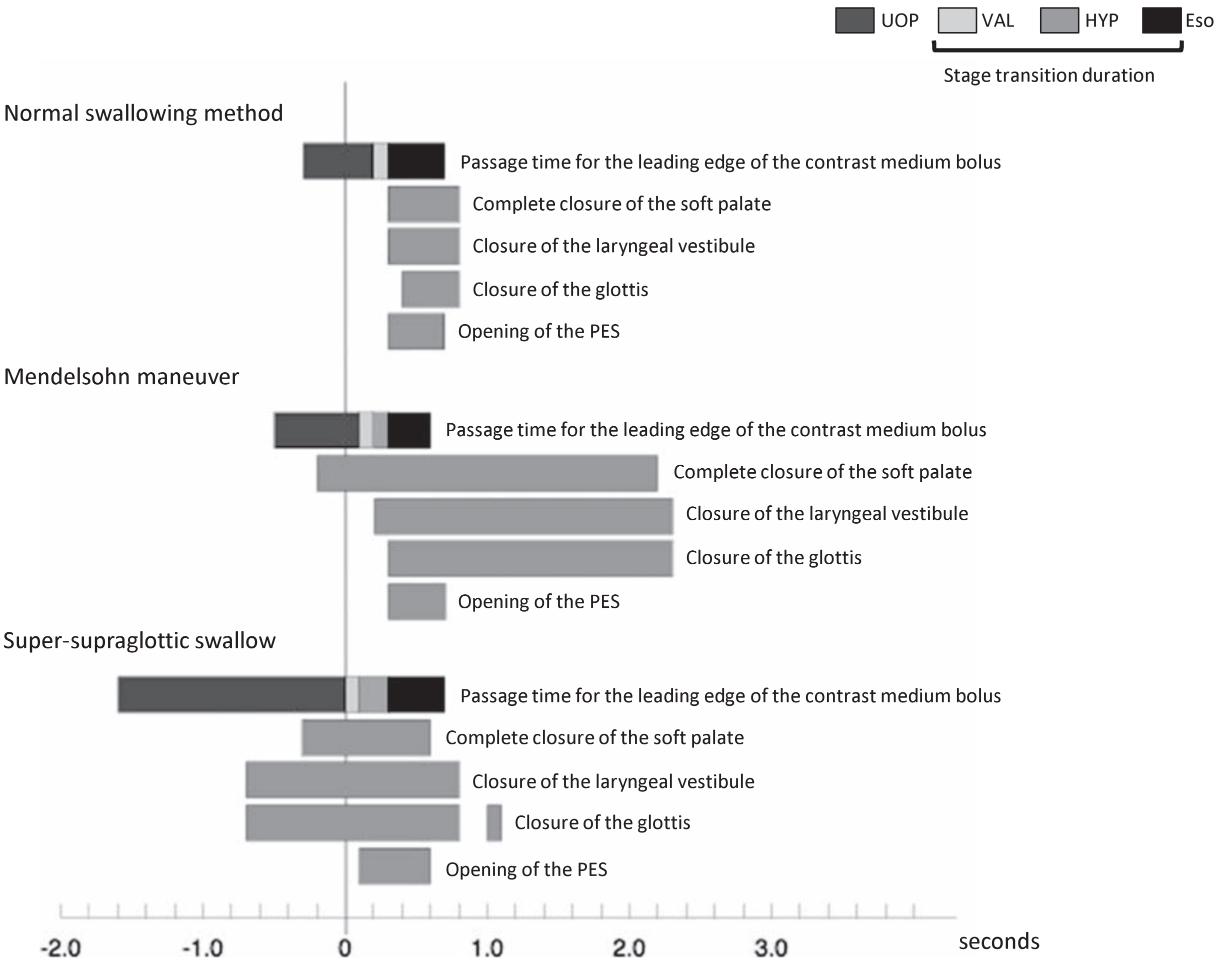


Figure 4. Phase graph.
The time at which the hyoid bone moved forward at the beginning of the swallowing reflex was defined as 0 s. The time course is shown on the horizontal axis. The graph shows the passage time of the leading edge of the bolus (the first line of the figure) in each of the upper oropharyngeal areas as well as the 4 events associated with the swallowing movement, from initiation to termination.
The graph shows the passage time of the leading edge of the bolus at the UOP, the VAL, and the HYP, measured from the time the front end of the bolus first reached each area until it reached the next area, and the time from the passage of the leading edge of the bolus to the passage of the rear end of the bolus at the border between the HYP and the Eso.

In the SSGS (Figure 3), initiation of the anterior tilt of the arytenoid cartilage occurred 0.9 s before the hyoid bone started to move forward at the beginning of the swallowing reflex, and glottis closure occurred 0.7 s before that. Closure of the glottis persisted until the swallowing movement was terminated. Elimination of the air layer from the hypopharynx by the complete inversion of the epiglottis and contraction of the pharynx occurred 0.5 s after the hyoid bone started to move forward.

Each event is represented graphically for each of the swallowing maneuvers in Figure 4. The time of initiation for each event was similar in the normal swallowing method and the MM; each event started at the same time as or just after forward movement of the hyoid bone. On the other hand, in the SSGS, each event started before the forward movement of the hyoid; in particular, closure of the laryngeal vestibule and glottis occurred before complete closure of the soft palate.

Initiation of each swallowing event

We examined the onset of each swallowing event relative to the time at which the hyoid bone started to move forward at the beginning of the swallowing reflex (Figure 5). The initiation of complete soft-palate closure was at 0.3 s, -0.2 s, and -0.3 s, respectively, for the normal swallowing method, the MM, and the SSGS. As indicated by the negative values, this event occurred before the hyoid bone started to move forward in the MM and the SSGS. The initiation of laryngeal-vestibule closure occurred at 0.3 s, 0.2 s, and -0.7 s, respectively, in the normal swallowing method, the MM, and the SSGS; in the SSGS, this event occurred

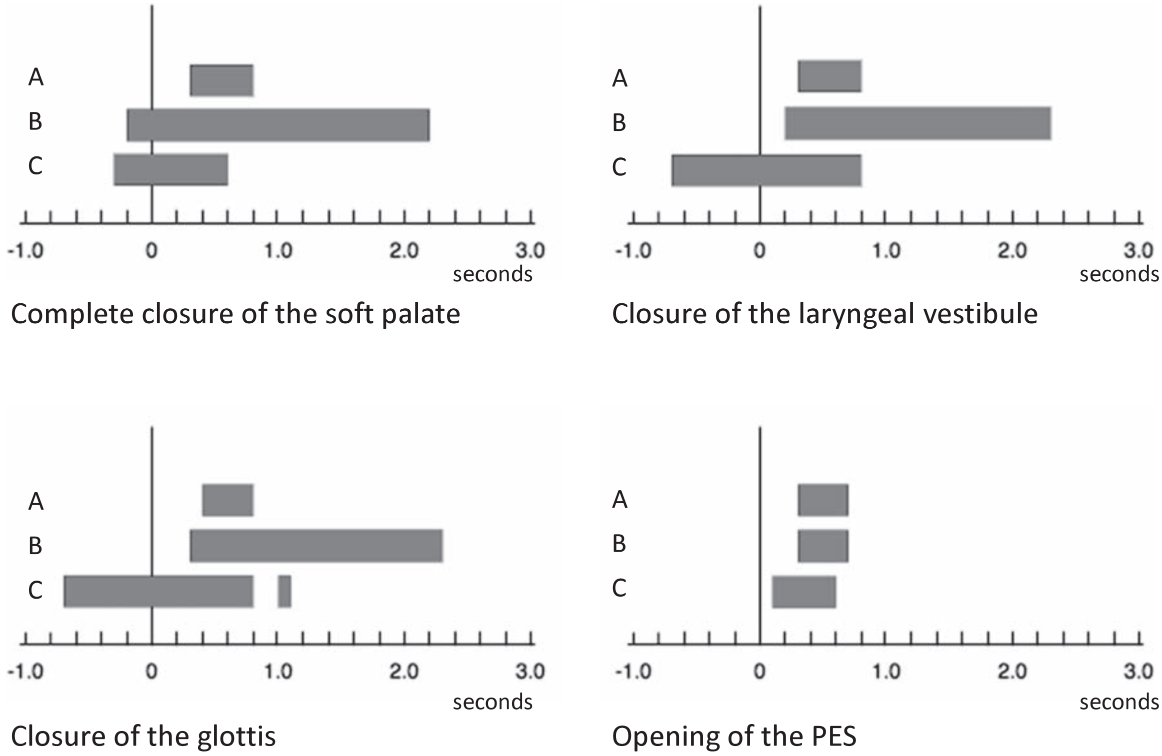


Figure 5. Comparison of the phases of each event between the swallowing maneuvers.
The time at which the hyoid bone moved forward at the beginning of the swallowing reflex was defined as 0 s, and the time course is shown in the horizontal axis. The 4 events associated with the swallowing movement, from initiation to termination, are shown on the graph in order to compare the differences between the swallowing maneuvers.
A, Normal swallowing method; B, Mendelsohn maneuver; C, Super-supraglottic swallow.

0.1 s before the hyoid bone started to move forward. The initiation of glottis closure occurred at 0.4 s, 0.3 s, and -0.7 s, respectively, in the normal swallowing method, the MM, and the SSGS; for the normal swallowing method and the MM, this occurred simultaneously with the forward movement of the hyoid bone. At the same time, closure of the laryngeal vestibule occurred in the SSGS. The initiation of PES opening occurred at 0.3 s, 0.3 s, and 0.1 s, respectively, in the normal swallowing method, the MM, and the SSGS; this occurred earlier in the SSGS than in the other 2 swallowing maneuvers. For the normal swallowing method and the MM, the front end of the contrast bolus was at the UOP when the hyoid bone started to move forward; for the SSGS, the front end of the contrast bolus had already reached the VAL when the hyoid bone started to move forward.

Duration of each movement

The time required for complete soft-palate closure was 0.5 s, 2.4 s, and 0.9 s, respectively, for the normal swallowing method, the MM, and the SSGS; this event was significantly longer in the MM than in the other 2 methods. The time required for laryngeal-vestibule closure was 0.5 s, 2.1 s, and 1.4 s, respectively, for the normal swallowing method, the MM, and the SSGS; this event was longer in the MM and the SSGS than in normal swallowing. The time required for glottis closure was 0.4 s, 2.0 s, and 1.5 s, respectively, for the normal swallowing method, the MM, and the SSGS; this event was longer in the MM and the SSGS than in the normal swallowing method. Additionally, glottis closure occurred simultaneously with laryngeal-vestibule closure in the SSGS and was observed during coughing after swallowing. The time required for PES opening was 0.4 s, 0.4 s, and 0.5 s, respectively, for the normal swallowing method, the MM, and the SSGS; this event was 0.1 s longer in the SSGS than in the other maneuvers. The STD was 0.5 s, 0.5 s, and 0.7 s, respectively, for the normal swallowing method, the MM, and the SSGS; the STD was 0.2 s longer in the SSGS than in the normal swallowing method and the MM.

Movement of the hyoid bone

For the normal swallowing method and the MM, the hyoid bone started to move upward before moving forward at the beginning of the swallowing reflex (Fig. 6). At this point, in the normal swallowing method, the hyoid bone moved backward; in contrast, in the MM, the hyoid bone did not move backward, but progressed steadily upward. In the SSGS, the hyoid bone moved

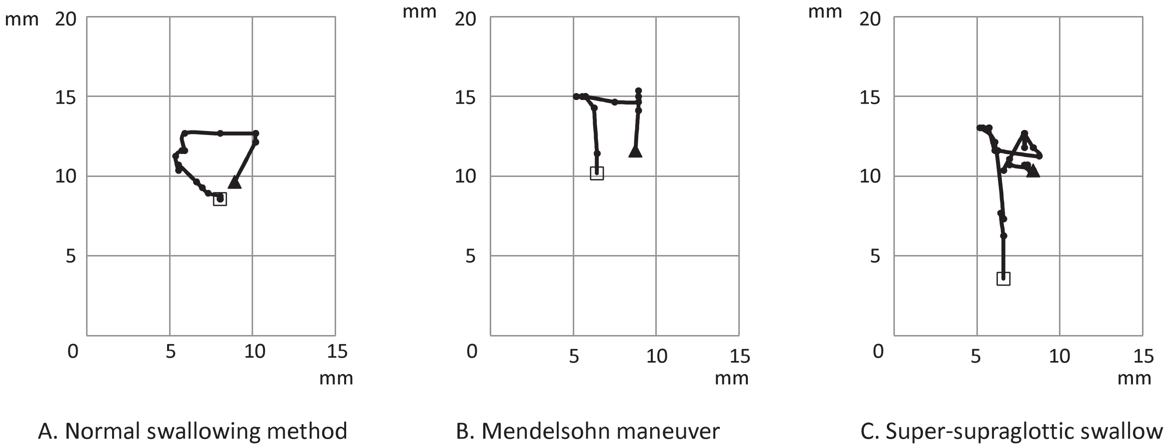


Figure 6. Trace of the hyoid bone.
▲: Initiation □: Termination
Normal swallowing method: The hyoid bone moved backward to its highest elevation and then moved forward horizontally at the beginning of the swallowing reflex.
Mendelsohn maneuver: After the hyoid bone reached its highest elevation, it moved forward horizontally at the beginning of the swallowing reflex to maintain the elevation, and then moved downward.
Super-supraglottic swallow: The hyoid bone moved forward and then upward at the beginning of breath holding. Subsequently, the hyoid bone was gradually repositioned, but did not return to starting position completely, and moved maximally in an anterosuperior direction at the beginning of the swallowing reflex.

forward and then upward when the subject held her breath firmly and strained herself. Following this, the hyoid bone gradually returned to its original position, but was not completely repositioned; it moved in an anterosuperior direction again at the beginning of the swallowing reflex.

The migration length of the hyoid bone at the beginning of each swallowing maneuver was compared with that at maximal migration. Forward migration length of the hyoid was 7.2 mm, 7.2 mm, and 6.5 mm, respectively, in the normal swallowing method, the MM, and the SSGS; among the 3 swallowing maneuvers, the migration length was shortest in the SSGS. The upward migration length of the hyoid was 6.1 mm, 7.6 mm, and 5.4 mm, respectively, in the normal swallowing method, the MM, and the SSGS; again, the migration length was the shortest in the SSGS of the 3 swallowing maneuvers.

Discussion

This study demonstrated that 320-ADCT can be used to three-dimensionally analyze swallowing maneuvers and to identify kinetic differences between different swallowing maneuvers. The subject was able to keep the larynx elevated for 2 or more seconds during the MM, in accordance with Logemann's definition [5]. The SSGS is believed to be the most difficult swallowing maneuver to acquire and execute; however, in our study, the subject maintained the closure of the glottis from the initiation of breath-holding through the termination of the swallowing maneuver. Therefore, this suggests that all the maneuvers were performed precisely.

Although the time resolution of the images obtained with 320-ADCT (10 frames/s) is inferior to that obtained with VF, it was possible to compare the timing of swallowing events in a similar manner as with VF. From cross-sectional MPR images, 320-ADCT revealed the structure and movement of the swallowing organs, particularly closure of the vocal cords on the axial image. This visualization is not possible via VF. The sagittal images distinguished various conditions, including the anterior tilt of the arytenoid cartilage, the approach to the base of the epiglottis, and the inversion of the epiglottis. The CT values of the 3D images could be adjusted to display air in blue and contrast medium in yellow, facilitating the visualization of contrast bolus movement and pharynx contraction; these images were therefore suitable for observing the entire swallowing movement. In addition, the open airway, which is difficult to visualize in MRP images, was clearly visualized in these 3D images, allowing for precise determination of the timing of vocal cord closure.

The MM was designed to improve PES opening for patients with impaired larynx elevation during swallowing. The following effects have been reported in conjunction with the MM: prolonged duration and quantity of larynx elevation, increased time and width of PES opening, and improved coordination of swallowing movements [5−7]. In addition, an extended period of time for the food bolus to be transferred from the oral cavity to the esophagus has been reported [8]. In the present study, we observed an extension of upward migration length and of migration time;

however, we found no differences in the time for PES opening between the MM and the normal swallowing method. This could result from the following possibilities: our method more precisely measured PES opening due to the superior spatial resolution of CT, or we were unable to visualize the difference due to low time resolution. The STD was equally long in the MM and the normal swallowing method. We believe that this is because the contrast bolus was only 4 ml, and because the subject may have swallowed rapidly because of her reclined position. The duration of the swallowing event was similar in both the normal swallowing method and the MM, where the hyoid bone moved upward and then forward. The contrast bolus moved from the oropharynx into the hypopharynx after the hyoid bone started to move forward in the normal swallowing method. On the other hand, soft-palate elevation occurred before forward movement of the hyoid bone in the MM. Further, glottis closure occurred 0.1 s after PES opening in the normal swallowing method, but occurred simultaneously with PES opening in the MM. Further studies using larger sample sizes may provide more information on the coordination of swallowing movements in the MM, particularly if combined with an electromyogram of the suprahyoid muscles or measurement of the internal pressure of the pharynx.

The SSGS was designed for dysphagia caused by reduced airway closure. In the SSGS, the airway is closed by holding one's breath tightly and bearing down; the arytenoid cartilage approaches the base of the epiglottis on the upper side of the vocal cords [5]. In our study, the MPR lateral view showed that the arytenoid cartilage moved forward to approach the base of the epiglottis when the subject held her breath. The blue portion of the 3D images, representing air in the laryngeal part of pharynx, disappeared at that time, confirming that the airway was closed.

Ohmae et al. [9] compared the normal swallowing method, the SGS, and the SSGS in healthy people. They reported that, although the hyoid bone was in the same location for the SSGS and the other swallowing maneuvers, the distance between the hyoid bone and the larynx was shortened by the thyrohyoid muscle early during swallowing using the SSGS. This helps the hyoid bone move forward during the swallowing reflex and produces earlier PES opening. PES opening is caused by larynx elevation and by the hyoid bone pulling the anterior wall of the cricopharyngeus muscle forward [10, 11]. Relaxation of the cricopharyngeus muscle occurs synchronously with larynx elevation prior to PES opening [12]. Our results showed that the hyoid bone moved forward during breath holding and then moved upward. Thereafter, the hyoid bone gradually returned to its original position while maintaining glottis closure, but moved forward and upward at the beginning of the swallowing reflex. In the SSGS, PES opening occurred 0.1 second after the hyoid bone started to move forward at the beginning of the swallowing reflex, which was earlier than in the other maneuvers. When the contrast medium bolus was held in the oral cavity, the maximal forward migration length was equal in the SSGS and the other swallowing maneuvers, whereas the upwards migration length was shorter in the SSGS than in the normal swallowing method and the MM. This might be because, in the SSGS, tightly holding one's breath and straining oneself enhances the muscular activity of the thyroarytenoid muscle and the thyrohyoid muscle to elevate the larynx, effectively allowing the hyoid bone and the larynx to move as one unit and thereby accelerating PES opening when the hyoid bone was moved forward at the start of the swallowing reflex. In the SSGS, the leading edge of the contrast medium bolus was already located at the VAL at the beginning of the swallowing reflex; this might indicate improved efficiency in transporting the bolus in order to accommodate the early PES opening. Further studies with more cases are required to examine these events. Additionally, it is necessary to confirm whether this bolus transport mechanism occurs in patients with dysphagia who exhibit impaired tongue movement, which affects bolus transport.

320-ADCT is superior technique for spatial resolution and facilitates the observation of hyoid bone movement and the position of the bolus in the pharyngeal space. Additionally, 320-ADCT can visualize cross-sectional images and vocal cord and PES movements, which are difficult to visualize with VF. In terms of radiation exposure, dynamic volume scanning for 3.15 s using 320-ADCT resulted in an effective radiation dose of 1.65 mSv. This corresponds to ~1.6 times the radiation dose received during VF for 5 min but is lower than the 2.8 mSv dose resulting from a single neck CT scan, which is considered a relatively low dose [13]. Consequently, 320-ADCT is not suitable for evaluation of chewing or longer durations of swallowing kinetics. However, with adequate investigation and evaluation, 320-ADCT might be beneficial in clinical practice, providing important information that VF cannot. Because each measurement was performed only once, our study cannot provide a comprehensive description of each organic movement of each swallowing maneuver; however, we have demonstrated that 320-ADCT can be used to evaluate the effects of the swallowing maneuvers in healthy people and even in patients with impaired ingestion and swallowing.

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