Food appropriate for evaluation of tongue dynamics during swallowing using ultrasonography

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Dysphagia is most often diagnosed using video fluorography, video endoscopy, and ultrasonography. Ultrasonography is superior for imaging soft tissue, and enables real-time evaluation of the dynamics of the tongue and pharyngeal region. Since tongue dynamics plays an important role in swallowing in the preparatory and oral stages, the oral cavity function has been evaluated by measuring tongue movement and morphology using the B or M mode of ultrasonography. Evaluation of oral cavity function in D mode using the Doppler method has also recently been reported. However, ultrasonography is not common compared to video fluorography and endoscopy because of a problem with the clarity of the test food images. In this study, we performed basic experiments to investigate appropriate test food for the observation of M-mode images and D-mode flow rate measurement. We also observed images of the oral cavity and measured the speed of food mass transport from the oral cavity to pharynx.

Measurements were made using a Prosound SSD-5500 an ultrasonography system, and UST-9126 electronic convex sounding probe (both from Hitachi Aloka Medical, Tokyo, Japan). Five types of test food with different physical properties were prepared in 100 cc portions: tap water, carbonated water, and tap water combined with 1, 2 or 3 g of thickener (Toromi Perfect®, Nisshin Oillio, Tokyo, Japan) (Toromi 1, 2 and 3, respectively). A silicon tube was horizontally fixed in deaerated water and adjusted so that the test food flowed in the tube. Test food flow in the tube was imaged using B-mode echo, and the image clarity was observed. In addition, the test food flow rate in the tube was measured employing the pulse Doppler method and compared with the measured rate calculated from piston movement of the opposite syringe. The subject’s oral cavity while swallowing the test food was imaged using the B/D mode, and differences in the image clarity and oral-pharyngeal passage time among the test foods were investigated.

With B-mode imaging thickened water was the most easily observed in the silicon tube. The flow rate spectrum was also clearly displayed in the D mode when the test food was thickened water. However, when the subjects were tested, many light spots were present in the thickened water and there was weakened contrast between the test food and surrounding tissue, making it difficult to observe tongue dynamics and confirm the test food flow. When carbonated water was swallowed, air bubbles were produced and imaged as light spots adhering to the dorsum of the tongue and palate. Echo images concentrated on these regions and made the flow of the test food and the tongue dynamics readily observable. The speed of oral-pharyngeal passage measured in the D mode was fastest for carbonated water, followed by tap water, and Toromi 1, 2 and 3, in that order. (J Osaka Dent Univ 2012; 46: 137-146)

Key words: Ultrasonography; Tongue dynamics; Swallowing; Test food
INTRODUCTION

Currently, dysphagia is diagnosed mainly using video fluorography, video endoscopy, and ultrasonography. Although video fluorography is capable of evaluating the flow sequence in the oral cavity-pharynx-esophagus, the test involves radiation exposure. Video endoscopy is advantageous in that the procedure is simple and actual food ingestion can be evaluated. However, insertion is painful, showing that these methods have problems. Ultrasonography is superior in imaging soft tissue and enables real-time evaluation of the dynamics of mainly the tongue and pharyngeal region. Although the image clarity is poor, it is relatively non-invasive for the patient and is frequently used in clinical practice. Since tongue dynamics play an important role in the preparatory and oral stages of swallowing, tongue movement and morphology are frequently measured to evaluate the oral cavity function employing B- or M-mode ultrasonography. Evaluation of the oral cavity function using the D-mode Doppler method has also recently been reported.

In the D mode, liquid flow rates can be measured utilizing Doppler effect-induced changes in the frequency. Applying this to the oral cavity, food flow from the oral cavity to the pharynx can be investigated and the speed of transport can be determined, which may be utilized in evaluation of swallowing function. We performed basic experiments to investigate appropriate test food for observation of M-mode images and D-mode flow rate measurements. In addition, using the test foods, we observed the intraoral images and measured the food mass transport velocity from the oral cavity to the pharynx.

MATERIALS AND METHODS

Experiment I

Objective

We employed B-mode tomography on different test foods that were flowed through a silicon tube, to investigate differences in the resulting images. In addition, the test food flow rate in the tube was measured employing the pulse Doppler method and compared with the actual rate calculated from the piston movement.

Methods

Measurements were made using a Prosound SSD-5500 ultrasonography system at frequency of 7 MHz and a pulse frequency of 20 kHz, and UST-9126 electronic convex sounding probe at 3 MHz. A $26 \times 26 \times 15$-cm water bath was filled with deaerated water prepared by boiling and cooling tap water. A SAFEED silicon joint tube with an inner diameter of 6.9 mm (Terumo, Tokyo, Japan) was fixed horizontally in deaerated water and both ends were attached to 50 mL catheter tip type Terumo syringes. The syringes and silicon tube were filled with the test food. This system was adjusted so that the test food flowed when the piston of one syringe was pushed at a constant rate. Test food flow in the tube was visualized using B-mode echo, and the image clarity was observed.

Using the pulse Doppler method, the test food flow rate in the tube was measured and compared with the actual rate calculated from the piston movement of the opposite syringe. Block diagrams of these experiments are shown in Figure 1. The actual rate was calculated as follows: Movement of the opposing piston was recorded at about 30 frames/sec using an NV-GS 400 K-S digital camera (SONY, Tokyo, Japan) while the active piston was pushed. The piston movement was read from graduations on the syringe. The number of frames

![Fig. 1 Block diagram of Experiment 1.](image-url)
required to fill a specific volume was measured to determine the water volume filled per unit time, and the calculated volume was divided by the cross-sectional area of the silicon tube to determine the liquid flow rate in the silicon tube.

The pulse Doppler method is capable of measuring the flow rate at a specific point. The B-mode tomography and D-mode spectral images were simultaneously displayed, and the flow rate measurement site in the D mode was confirmed and established in the B-mode display. The angle formed by the ultrasonic waves and flow direction is important for D-mode fluid measurement. The probe inclination was adjusted as much as possible to direct ultrasonic waves along the direction of the flow. To avoid detecting multiple reflections produced on the lateral surfaces and bottom of the water bath, the angle formed by the probe inclination and silicon tube horizontally fixed in water was adjusted to 45 degrees. In addition, the angle mark was adjusted to the flow rate direction to correct the angle. The sample volume was set at the same width as the inner diameter of the silicon tube. D-mode measurement was repeated five times for each test food.

100 cc samples of five test foods with different physical properties were prepared: 1. tap water, 2. carbonated water, and 3. tap water combined with 1, 2 or 3 g of Toromi Perfect® thickener (Nisshin Oil, Tokyo, Japan) (Toromi 1, 2 and 3).

Experiment II
Objective
The oral cavity was imaged while swallowing the test food employing B/D modes of the ultrasonography system in the subjects, and the image clarity and oral-pharyngeal passage time were investigated.

Methods
The subjects were 5 healthy males aged 25–30 years with no morphological or functional abnormality in their stomatognathic system. The experiment was sufficiently explained and consent was obtained from each subject. Similar to experiment I, five types of test food were used (tap water, car-
bonated water, and 3 types of thickened water (Toromi 1, 2 and 3).

Tests
Each subject sat upright in a dental chair, and the head in a fixed position. They were interested to swallow a test food volume of 15 cc, which was confirmed not to be difficult to do in one gulp. The probe was placed at about 3 cm right of the median of the submandibular region and directed left and upward to image the root of the tongue. And the sagittal view of the tongue was imaged employing the B mode, followed by adjustment of the angle formed by the dorsum of the root of the tongue and the echo beam to 45 degrees. Differences in B-mode images among the test foods were investigated. At the same time, the test food flow rate from the oral cavity to the pharynx was measured using the D mode, and the spectral waveforms were displayed. The sample volume was set at the width between the palatal region and the tongue. Block diagrams are shown in Figure 2. The experiment was repeated five times for each test food.

RESULTS
Experiment I
Images
The images on B-mode tomography are shown in Figure 3. The flow direction was from the upper left side toward the right lower side in each image.

(a) Tap water
Some air bubbles adhered to the inner wall, particularly the upper wall. Tap water appeared black
in the image and it was difficult to confirm the flow of the test food on the ultrasonography display.

(b) Carbonated water
Many air bubbles that were formed by gas dissolved in the carbonated water appeared white in the image, allowing observation of the air bubble flow in the tube. However, the size and distribution of air bubbles were heterogeneous, and they concentrated on the upper wall. Some air bubbles adhered to the inner wall of the tube and did not flow, even though the carbonated water did flow.

c) Thickened water
The image while swallowing Toromi 2 is shown as an example of thickened water. Air bubbles were naturally formed when the thickener was added and mixed, and were homogeneously present in the tube. Since these air bubbles flowed as the thickened water flowed, it was easy to observe the test food dynamics in the image.

**Relationship between the flow rate determined from the spectrum and measured flow rate**

The FFT waveforms determined by employing the pulse Doppler method are shown in Figure 4. The envelope of the spectrum with the pulse Doppler method represents the maximum speed of fluid in the sample volume at the time point, termed Vmax. The relationship of the flow rate determined by Vmax was compared with the measured flow rate. The vertical and horizontal axes represent the flow rate and time, respectively. The spectra above and below the baseline indicate flow rates entering and leaving the probe, respectively. The sample volume filled the inner diameter of the silicon tube. Although the FFT waveforms indicated that the flow rate in the silicon tube showed essentially constant stationary waves for all test foods, the thickness of the spectrum varied. The vertical axis represents the flow rate. The spectrum thickens when the distribution is wide, whereas it thins and the luminance
Fig. 4  FFT waveforms.

Fig. 5  Vmax determined employing the pulse Doppler method and scattered plots of the actual flow rate.
increases as the distribution narrows.
(a) Tap water: A laminar flow was noted. The spectrum was sparsely displayed.
(b) Carbonated water: The spectrum was lower than the baseline.
(c) Thickened water: The flow rate spectrum of Toromi 2, representing thickened water, is shown. A similar laminar flow was observed, but the waveform line was thick on the spectrum display.

Figure 5 shows the Vmax determined employing the pulse Doppler method and scattered plots of the actual flow rate calculated from the video of (a) tap water, (b) carbonated water, (c) Toromi 1, (d) Toromi 2, and (e) Toromi 3. The actual flow rate was 0.50 Vmax for tap water, 0.45 Vmax for carbonated water, and 0.35 Vmax thickened water. The correlation coefficients, $R^2$, were 0.97, 0.93, and 0.88, respectively, indicating a strong correlation in all test foods.

Experiment II
Images
Figure 6 shows schematic diagrams and images of the oral cavity retaining the test foods on B-mode tomography. The strong reflection shaped like a downward arc in the lower region of the diagram represents the palatal region, and the upward arch slightly above that represents the surface of the dorsum of the tongue. The slightly dark image present between these is the echo image of the retained test food.
(a) Tap water: Although air bubbles were incorporated when tap water was held in the oral cavity, the echo image was mostly black, whereas the palate and dorsum of the tongue appeared white.
(b) Carbonated water: Since air bubbles appeared as white light spots adhering to the dorsum of the tongue and palate, the reflected echo image of these regions could be observed by these spots.
(c) Thickened water: The image of Toromi 2 is
shown as a representative of thickened water. Many air bubbles were incorporated when it was held in the oral cavity, as seen in the silicon tube, and the air bubbles appeared as many light spots that were widely distributed in the test food.

**Speed of the oral-pharyngeal passage of the test food**

Figure 7 shows the schematic diagrams and flow rate spectra of (a) tap water, (b) carbonated water, and (c) Toromi water. As in Experiment 1, the speed of transport was compared among the test foods using Vmax as the flow rate determined from the spectrum. Figure 8 shows the speeds of oral-pharyngeal passage of the test foods in the root of the tongue region measured employing the pulse Doppler method (input speed). The mean speed was highest for carbonated water, followed by tap water, Toromi 1, Toromi 2 and Toromi 3 in that or-
der. Significant differences were noted in the input speed between tap water and Toromi 2, between tap water and Toromi 3, between Toromi 1 and carbonated water, between Toromi 2 and carbonated water, and between Toromi 3 and carbonated water ($p < 0.01$).

**DISCUSSION**

**Images in Experiment I**

**B-mode**

The test foods in the silicon tube were (a) tap water, (b) carbonated water, and (c) thickened water. The flow of thickened water was most clearly observed on the B-mode display. White light spots were assumed to be air bubbles contained in the test food. The most important factor influencing observability of the images is probably the number of air bubbles in the test food. Many white light spots were observed when thickened water was used, suggesting that air bubbles were most abundant in this medium. Thickened water was prepared by adding thickener and stirring. The bubbles were likely incorporated while stirring. The carbon dioxide dissolved in carbonated water readily produces air bubbles, facilitating observation of the flow in the tube.

**D-mode**

(a) Tap water

The D mode of medical ultrasonic waves is mainly used to analyze the blood flow rate, which is measured using the red blood cells as reflectors. Measurement of the test food flow rate in the silicon tube may have been facilitated by the air bubbles in the test food which acted as reflectors. As observed in the above images, tap water may have contained fewer air bubbles, resulting in the low flow rate spectrum.

(b) Carbonated water

Unlike tap and thickened water, the spectrum of carbonated water was displayed below the baseline, suggesting that turbulence occurred in the tube. Since the test food was carbonated water, air bubbles were irregularly produced at various sites in the tube and influenced the test food flow rate.

(c) Thickened water

Although the spectrum showed a laminar flow similar to tap and carbonated water, the waveform line was thick. Since the waveform thickness represents the flow rate distribution, the distribution of the flow rate in the tube was wide, which may have been due to the viscosity of the thickened water. The flow rate in the tube was heterogeneous, and may have been slightly faster in the central region and slower at the periphery near the inner wall. It was also possible that this was due to the sample volume set at the same width as the inner diameter.

**Images in Experiment II**

**B-mode**

Factors influencing observability of the images may have been the number of air bubbles contained in the test food, similar to that in Experiment I, and the contrast between the test food and surrounding tissue. In the oral cavity, the surrounding tissue is mainly the tongue and hard palate. The dorsum of the tongue and hard palate appeared white in the echo image.

(a) Tap water

Although the tap water flow in the silicon tube was unclear and the spectrum acquired using the Doppler method was weak, the contrast with tissue was clear when it was viewed in the oral cavity, and the flow could readily be observed.

(b) Carbonated water

Air bubbles generated from carbonated water in the oral cavity were also visualized as white light spots in the image. Since air bubbles adhered to the dorsum of the tongue and palate, appearing white in the image, reflection of the echo image concentrated in these regions. Accordingly, in the echo images of the test foods swallowed by the subjects, the flow and tongue dynamics could be most readily observed when the test food was carbonated water.

(c) Thickened water

Test food flow in the silicon tube in Experiment I could be readily observed when the test food was thickened water. However, in the oral cavity, when thickened water containing many light spots was
present between the white reflected images of the palate and dorsum of the tongue, the contrast between the test food and surrounding tissue was weakened, and observation of the tongue dynamics and confirmation of test food flow were somewhat difficult. Thickened water may be the best test food for clinical application with patients has eating and swallowing disorders because it is safe for swallowing. So, when confirmation of the test food flow and tongue dynamics is required, if we use thickened water for test food, some consideration is necessary to observation. From now on, more detailed analysis is needed about thickened water.

Speed of the oral-pharyngeal passage of test food
D-mode
The Vmax with the pulse Doppler method and the actual flow rate were strongly correlated in Experiment I, suggesting that the test food flow rate in the oral cavity during swallowing can be measured. The maximum speed of oral-pharyngeal passage was observed when carbonated water was swallowed, followed by tap water, Toromi 1, Toromi 2 and Toromi 3. When 1, 2 and 3 g of thickener are dissolved in 100 cc of water, the viscosities of the combination are expressed as like French dressing, like ‘Tonkatsu’ sauce, and like ketchup, respectively. The input speed slowed as the amount of thickener in the test food increased. Hara et al. reported that the maximum speed of the test food was influenced by its physical properties, particularly adhesiveness. They also stated that the addition of thickener increased adhesiveness confirming our findings.

The carbonated water flow rate was the fastest. It has a characteristic physical property of effervescence. Karahō et al. reported that the swallowing reflex was rapidly induced when carbonated water flowed into the pharynx as a test food, compared to saline and distilled water. This suggests that carbonated water might be useful for training of patients with an impaired swallowing response. Our experiment using the ultrasonography system also revealed that carbonated water is superior for observing the tongue and test food dynamics in the oral cavity. However, as Nagatoishi et al. reported, generic food as known as hard to be aspirated passes through the pharynx slowly. Further investigation is necessary using carbonated water with a high passage rate from the oral cavity to pharynx as a test food in patients with eating and swallowing disorders.

We performed basic experiments to investigate the appropriate test food for observation on M-mode ultrasonography and flow rate measurement in the D mode. In addition, using the test foods, we observed intraoral images and measured the speed of food mass transport from the oral cavity to pharynx. Carbonated water was appropriate for observation of the oral cavity on B-mode ultrasonography, suggesting its possible use as a test food. However, the maximum speed of oral-pharyngeal passage of carbonated water was high in the D mode, suggesting the necessity of further investigation of its applicability as a test food.

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