Noninvasive aspiration detection using through-transmission ultrasound

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Abstract— **We investigate the potential of through-transmission ultrasound in noninvasive aspiration detection for bedside rehabilitation. In the present study, we used through-transmission ultrasound to investigate the waveform change in received signals caused by an aspirated object located at the posterior wall of the larynx, the most difficult type of case in the detection of aspiration. In a simulation study based on an X-ray CT image of the neck of a patient, the aspirated object adhered at the posterior wall of the larynx resulted in the waveform change of the received signal with a maximum amplitude of 4.3% compared with that of the received signal with aspiration. In an experimental study using a swine larynx ex vivo, an aspirated object resulted in the waveform change of the received signal with a maximum amplitude of 43.3%. These results indicate the high potential of through-transmission ultrasound in aspiration detection.**

Keywords-component; aspiration, dysphagia, through-transmission ultrasound

I. Introduction

Dysphagia is an impairment of food intake that leads to pneumonia, choking, and malnutrition and can be caused by stroke, neuromuscular disease, dementia, hospital-acquired disability, and head and neck cancers. In an aging society, the number of such patients is increasing because these issues are most common in elderly people, and thus it is now a serious medical problem not only in Japan but also in many developed countries. In the United States, for example, the number of dysphagia inpatients grew from 408,000 in 2009 to 657,000 in 2013. Dysphagia causes 3.8 days of additional hospital stay, 34% higher total hospital charges, and 1.7-fold mortality rate in the hospital [1].

Primary treatment of dysphagia is rehabilitation, which is classified as direct therapy using food and indirect therapy without using food. In direct therapy, the earlier beginning of oral food intake [2, 3, 4] and dysphagia screening and management [5, 6, 7] are said to be important. Fiberoptic endoscopic evaluation of swallowing (FEES) and videofluoroscopic swallowing study (VFSS) are useful methods for understanding disease state, screening, and management of dysphagia [8]. However, these examinations are invasive and inappropriate for daily use. They are not useful for supporting direct therapy by managing to prevent pneumonia and selecting appropriate food style, resulting in increased length of hospital stay.

For the detection of dysphagia, several researchers have reported on a screening test [9], an oxygen concentration monitor [10], respiratory sounds and clinical insights of speech language therapists [11], and neck auscultation [12] as potential solutions. Voice or respiratory sound analysis [13], acceleration sensors [14], and ultrasound [15, 16] are also said to be potential solutions. However, these existing solutions and technologies have insufficient sensitivity in detecting aspiration [17], because it is difficult to detect silent aspiration [18]. Aspiration is a phenomenon in which food or liquid pass through the airway by mistake. In cases of decreased sensation of the larynx, the patient cannot cough up and expel aspirated objects, causing silent food arrival to the lung; this results in aspiration pneumonia. As a result, nurses and speech language therapists suppose that direct therapy applied to patients with decreased sensation has a large risk of pneumonia. This supposition leads to delayed rehabilitation process. The delayed rehabilitation process also causes gastrostomy induction which cause worsened quality of life of a patient. A noninvasive easy aspiration detection is strongly desired for the effective bedside training of dysphagia patients. Additionally, the realization of data collection about aspiration information at home is expected to enable a novel internet of things (IoT) approach that brings a clinical indicator for determination of therapy and management of rehabilitation.

One notable solution among these technologies is ultrasound. Ultrasound has a remarkably advantageous high spatial resolution for observing structures of the airway [19, 20]. It can contribute to higher sensitivity and detecting smaller food particles. The previous study [16] showed an aspiration detection method using B-mode sonography, with sensitivity and specificity of 64% and 84%, respectively. The

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reason for low sensitivity may be the difficulty to receive the echo returned from aspirated objects located at the posterior wall of the larynx. In the present study, we employ through-transmission ultrasound to detect aspirated objects. The through-transmission method is used for the assessment of bone quality [21, 22, 23]. In comparison with B mode ultrasonography using an echoic method, this method has much higher signal-noise ratio and is suitable for quantitative measurement of tissue [24]. We investigate the potential of the ultrasound through-transmission method in the detection of aspirated objects located at the posterior wall of the larynx, the most difficult location for the detection of aspiration.

II. MATERIALS & METHODS

Principle of the aspiration detection method using through-transmission ultrasound

An aspirated object adhered at the airway lumen should change ultrasound propagation characteristics passing through the adhesion site of the airway cartilages. Therefore, we estimate the occurrence of aspiration from the change in ultrasound propagation characteristics passing through the airway cartilages using through-transmission ultrasound.

Fig. 1 shows a schematic illustration of the proposed method in a cross-section of the human neck at the height of the cricoid cartilage, which is a ring-shape structure located at the boundary between the larynx and the trachea. We use a pair of ultrasonic transducers placed on the neck skin, with the transducers are set on both sides, as shown in Fig. 1.

Through-transmission ultrasound measurement is performed continuously during and after a meal. When the aspiration occurs, an aspirated object changes ultrasound propagation characteristics passing through the cricoid cartilage, resulting in the waveform change in the received signal.

To show the potential of the proposed method, we conducted a two-dimensional (2D) computer simulation study and an *ex-vivo* experiment using a swine larynx.

A. *Two-dimensional computer simulation setting*

The system model of the 2D computer simulation is shown in Fig. 2. The model is based on an X-ray CT image of the neck of a dysphagia patient. A commercial software based on finite-difference time domain method, PZFlex Ver. 3.0 (Weidlinger Associates, Inc. CA, USA) was used in this study. The grid size was set to 0.1 mm × 0.1 mm and the lateral and horizontal calculation ranges were 120 mm and 100 mm, respectively. The sound velocity and mass density of each tissue were shown in TABLE I. A 10.4-mm diameter ultrasound transmitter and receiver were put on the left side and the right side of the neck skin, respectively. The distance between the center of each transducer was set to 30 mm. The transmitted signal was a 30-cycle burst wave with the center frequency of 1 MHz.

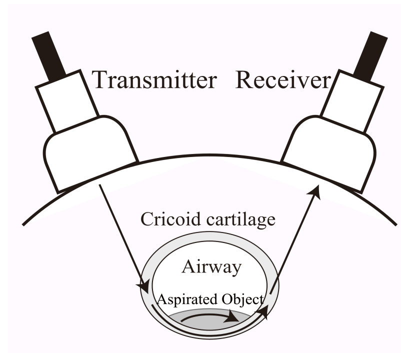

Figure 1. A schema of the proposed method using through-transmission ultrasound.

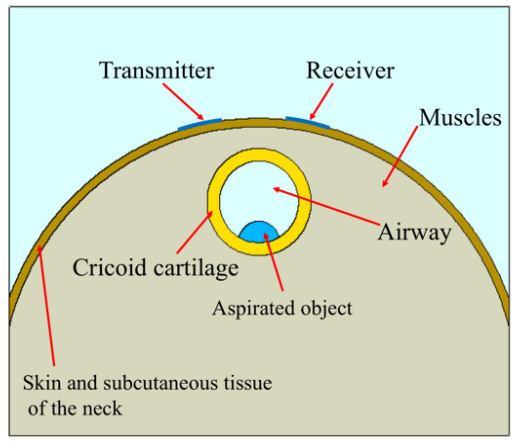

Figure 2. A schema of the proposed method using through-transmission ultrasound.

TABLE I. MASS DENSITIES AND SOUND VELOCITIES OF MATERIALS.

Material	Mass density (kg/m^3)	Sound velocity (m/s)
Air	1.293	340
Skin and subcutaneous tissue	1120	1611
Muscle	1050	1547
Cartilage	1000	1665
Aspirated object (water)	1000	1500

Detecting aspiration of water is one of the most difficult problems, and it is also clinically important because the chance of water aspiration is more frequent than other objects which have higher viscosity. In the present study, we thus employ water as the aspirated object. We investigated two conditions: with and without an aspirated object adhered at the posterior wall of the airway, because it is difficult to detect an aspirated object in this position. To simplify, we used the acoustic properties of the water as those of the aspirated object.

B. *Experimental setting*

A bench model experiment using a fresh swine larynx was conducted. The upper edge of the hypopharynx was cut to the topmost part, the cervical esophagus and the trachea were cut to the lowermost part, and anterior cervical muscles and the thyroid were detached. A pair of transducers was attached to both sides of the cricoid cartilage, and the distance between the center of each transducer was set to 30 mm. Transducers and the larynx were fixed on a wooden board, as shown in Fig. 3. Because a dysphagia patient who has just started direct therapy usually reclines on the bed during meals, the board was tilted to 45 degrees. An 18-gauge intravenous catheter was inserted into the posterior wall of the larynx just under the true vocal cords.

We used a pair of ultrasonic transducers (Okusonic, Saitama, Japan) that were 15 mm in diameter with a central frequency of 1.5 MHz as a transmitter and a receiver. The transmitted signal was a 35-cycle burst wave with a center frequency of 1.5 MHz. The maximum voltage applied to the transmitter was 20 V peak-to-peak. The pulse repetition interval was 10 ms.

After 3 s from beginning of the measurement, 2 mL of water were injected at the flow rate of about 1 mL/s. It was confirmed that water reached the level of the cricoid cartilage after 5 s from beginning of the measurement.

III. Results

A. Simulation study

Fig. 4 shows the received signals under the conditions with and without aspiration. This result indicates that an aspirated object adhered at the airway lumen results in the waveform change acquired by the proposed method. In the temporal region from 50 to 70 µs, the maximum amplitude of the subtraction between two signals was 4.3% compared with that of the received signal under the condition with aspiration.

B. Experimental study

Fig. 5 shows the temporal change in intensity of the received signals caused by an aspirated object. Because ultrasound measurement was performed repeatedly with the pulse repetition interval of 10 ms, ultrasound measurement during 10 s included 1,000 transmit and receive events. In the ultrasound transmission time from 5 to 9 s, the intensity of the received signal changed significantly during the reception time from 50 to 70 µs. Fig. 6 shows the received signals at the transmission time of 5 s and that of 1 s as the received signals of with and without aspiration, where the white broken line and red broken line in Fig. 5 show the intensity of the received signals with and without aspiration, respectively. The maximum amplitude of the subtraction between two signals was 43.3%, compared with that of the received signal under the condition with aspiration.

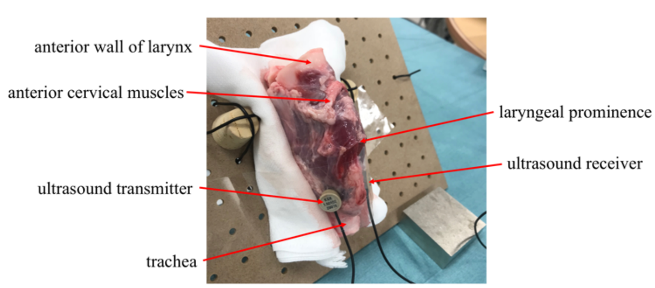

Figure 3. Aspiration measurement of a swine larynx.

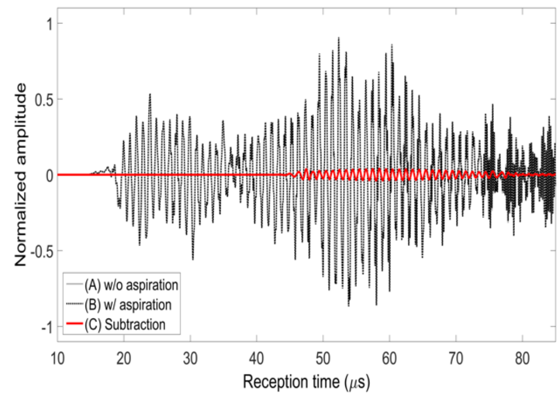

Figure 4. Waveform change caused by an aspirated object in the simulation study.

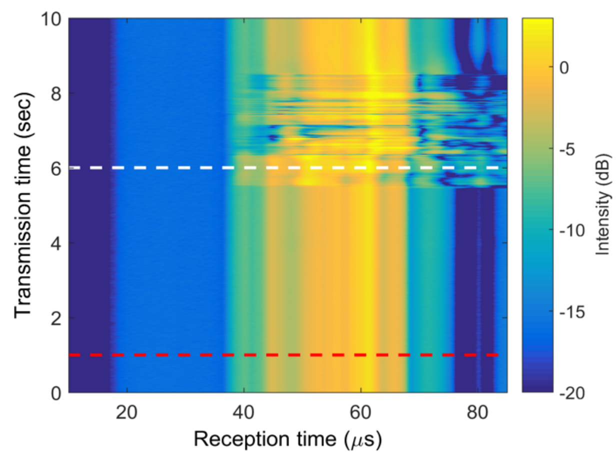

Figure 5. Temporal change in intensities of the received signals. Longitudinal axis shows the ultrasound transmission time. Lateral axis shows the reception time based on each transmission time.

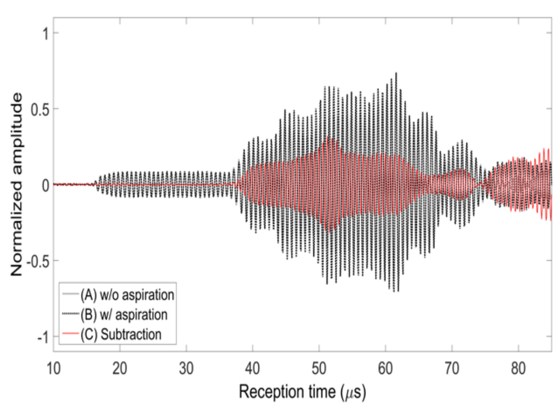

Figure 6. Waveform change caused by an aspirated object in the experimental study.

IV. DISCUSSION

In the present study, we investigate the potential of the proposed method in the detection of an aspirated object located at the posterior wall of the larynx, which is the most difficult case in the detection of aspiration. In the simulation study based on an X-ray CT image of the neck of a patient, the aspirated object adhered at the posterior wall of the larynx resulted in the waveform change of the received signal with the maximum amplitude of 4.3% compared with that of the received signal with aspiration. In the experimental study using a fresh swine larynx, the aspirated object adhered at the posterior wall of the larynx resulted in a large waveform change compared with that in the simulation study. This large change compared with that in the simulation study may originate from the direct attachment of the transducers to a swine larynx. These results indicate the high potential of the proposed method in aspiration detection.

Future work should include simulation and experimental studies that is close to a clinical situation. We believe that an experimental study in vivo will bring about the development of a novel aspiration detection algorithm based on through-transmission ultrasound.

V. CONCLUSION

We investigate the potential of through-transmission ultrasound in the detection of an aspirated object located at the posterior wall of the larynx, the most difficult case in the detection of aspiration. In the simulation study based on an X-ray CT image of a patient's neck, the aspirated object adhered at the posterior wall of the larynx resulted in the waveform change of the received signal with a maximum amplitude of 4.3% compared with that of the received signal with aspiration. In the experimental study using a swine larynx ex-vivo, an aspirated object resulted in the waveform change of the received signal with a maximum amplitude of 43.3%. These results indicate the high potential of the through-transmission ultrasound in aspiration detection.

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