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The effect of pleural fluid layers on lung surface wave speed measurement: Experimental and numerical studies on a sponge lung phantom

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ABSTRACT

Pleural effusion manifests as compression of pleural fluid on the lung parenchyma contributing to hypoxemia. Medical procedures such as drainage of plural fluid releases this compression and increases oxygenation. However, the effect of pleural effusion on the elasticity of lung parenchyma is unknown. By using lung ultrasound surface wave elastography (LUSWE) and finite element method (FEM), the effect of pleural effusion on the elasticity of superficial lung parenchyma in terms of surface wave speed measurement was evaluated in a sponge phantom study. Different thicknesses of ultrasound transmission gel used to simulated pleural fluid were inserted into a condom, which was placed between the sponge and standoff pad. A mechanical shaker was used to generate vibration on the sponge phantom at different frequencies ranging from 100 to 300 Hz while the ultrasound transducer was used to capture the motion for measurement of surface wave speed of the sponge. FEM was conducted based on the experimental setup and numerically assessed the influence of pleural effusion on the surface wave speed of the sponge. We found from FEM experiments that the influence of thickness of ultrasound transmission gel was statistically insignificant on the surface wave speed of the sponge at 100 and 150 Hz.

1. Introduction

Pleural effusion, frequently encountered in critically ill patients hospitalized in intensive care units (ICU), is the accumulation of excess fluid in the pleural cavity, which is the fluid-filled space that surrounds the lungs. It induces restrictive syndromes and increases the intrapulmonary shunt by compressing the lung parenchyma. Study has showed that pleural effusion may contribute to hypoxemia under mechanical ventilation (Balik et al., 2006). In order to increase oxygen delivery and oxygen consumption, medical procedures such as drainage of pleural fluid are performed to increase functional residual capacity and improve oxygenation. Hemodynamic and pulmonary parameters, such as blood pressure, systemic vascular resistance, peak airway pressure, were collected before and after the fluid was drained (Ahmed et al., 2004). However, no technique is able to evaluate the degree of restoration of the function of lung parenchyma.

In the ICU, the diagnosis of pleural effusion relies on the anteroposterior chest radiography obtained at bedside (Lichtenstein et al., 2004; Prim et al., 2016). However, it exposes patients to a high dose of radiation. Pleural sonography is an alternative imaging modality. It is a highly portable and widely accepted diagnostic technique for identifying pleural disease (Remérand et al., 2010; Mayo and Doelken, 2006; Twal et al., 2014). It permits imaging of pleural effusion and other pleural pathologies. In addition, ultrasonography is able to guide thoracentesis for pleural interventions. Normal visceral and parietal pleura are supposed and estimated at 0.2–0.3 mm thick. Pleural effusions with parietal pleural thickness > 10 mm, and diaphragmatic thickness > 7 mm predict underlying malignancy with high specificity. It has been shown that a minimum pleural effusion depth of 1.2 cm between the visceral and parietal pleura has been recommended to perform diagnostic thoracentesis (Soni et al., 2015; Shazly et al., 2015).

Thoracentesis is usually performed to relieve the compression of pleural effusion on the lung parenchyma. Few studies evaluated the restoration of lung parenchyma after drainage of pleural fluid. Function of lung parenchyma is heavily dependent on its elasticity. In order to noninvasively evaluate the elasticity of lung parenchyma for patients with interstitial lung disease (ILD), we recently developed a lung ultrasound surface wave elastography (LUSWE) to measure the surface wave speed of lung, which is correlated with lung elasticity (Zhang et al., 2017a, 2017b; Kalra et al., 2017; Clay et al., 2018). No pleural effusion was observed for ILD patients so ultrasound propagation can penetrate the thoracic muscle, and motion of lung surface can be captured by ultrasound imaging. For the patients with pleural effusion, the effect of pleural fluid on the surface wave speed of lung parenchyma in LUSWE is unknown. Therefore, there is a pressing need to develop a phantom model to systematically investigate the effect of pleural fluid

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on the measurements of LUSWE.

Wet foam dressing material has been used for lung ultrasound simulation models to teach novice physicians to perform lung ultrasound in clinical situations (Lee et al., 2015). An economical sponge phantom was used for understanding and researching reverberation artifacts in lung ultrasound given its similar microstructure with lung parenchyma (Blüthgen et al., 2017). Moreover, with its availability, relevant phantom models for a systemic study of induced disease states, such as pulmonary edema, can be generated.

The objective of this study was to develop a phantom model for evaluating the effect of pleural fluid on surface wave speed in LUSWE. Ultrasound transmission gel to simulate pleural fluid was squeezed into a condom that was placed between the acoustic standoff pad and sponge phantom. In LUSWE, a shaker was used to generate a vibration on the surface of the standoff pad, and wave propagation on the surface of the sponge phantom was measured by using ultrasonic imaging and analysis. A FEM model was developed to simulate the wave propagation in the sponge phantom according to the experimental setup and compare with experimental measurements.

The rest of the paper is structured as follows: we describe the setup for the sponge phantom model in the Section 2; we present results that evaluate the effects of thickness of ultrasound transmission gel in the Section 3; we finalize the paper with Sections 4 and 5.

2. Materials and methods

2.1. Experimental setup

The experimental setting consisted of the following parts: (1) household sponge (Ocelo utility sponge, 3M, St. Paul, MN); (2) ultrasound transmission gel (Aquasonic 100, Parker Laboratories Inc, Fairfield, NJ); (3) an acoustic standoff pad (Aquaflex; Parker Laboratories Inc, Fairfield, NJ). The acoustic standoff pad is made of a gel matrix free of air bubbles eliminating the air-filled space between the transducer and the sponge phantom. Without a standoff pad, extrathoracic tissues will not be satisfactorily imaged. The fluid component of a pleural effusion may have echogenicity, which is characteristic of the presence of cellularity. Air bubbles within pleural fluid, which may occur with esophageal-pleural fistulas or a gas-forming infection will exhibit multiple mobile echogenic foci within pleural fluid that represent air bubbles (Cardenas-Garcia et al., 2015). Ultrasound transmission gel has a similar echogenicity as pleural fluid and can contain air bubbles in it. A sponge has been shown to have similar microstructure as lung parenchyma. Ultrasound transmission gel was squeezed into a condom that was placed between the standoff pad and sponge phantom. The condom was used to maintain the required thickness for the gel. The condom should not affect the acoustic properties of ultrasound transmission gel given its negligible weight and stiffness. The thickness of gel in the condom was measured using ultrasound imaging and also taking pictures with a ruler placed aside as reference. The thickness of ultrasound transmission gel was varied at 4 levels: 0 (base), 2 mm (level 1), 7 mm (level 2) and 12 mm (level 3). A sinusoidal vibration signal of 0.1 s duration was generated by a function generator (Model 33120A, Agilent, Santa Clara, CA). The vibration signals were used at five frequencies of 100, 150, 200, 250, and 300 Hz (Kubo et al., 2018a). The 100 Hz wave motion is stronger than the wave motion of higher frequency waves. The higher frequency waves have smaller wave length but decay rapidly over distance than the lower frequency waves. The frequency ranges chosen in this study consider the wave motion amplitude, spatial resolution, and wave attenuation. The excitation signal at a frequency was amplified by an audio amplifier (Model D150A, Crown Audio Inc., Elkhart, IN). This signal then drove an electromagnetic shaker (Model: FG-142, Labworks Inc., Costa Mesa, CA 92626) mounted on a stand. The shaker applied a 0.1 s harmonic vibration on the surface of the acoustic standoff pad using an indenter with 3 mm diameter. 0.1 s is selected to exclude most of the

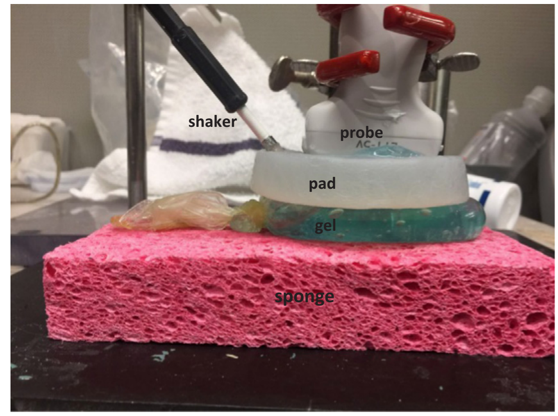

Fig. 1. Experimental setup of sponge phantom, transmission gel in a condom, and acoustic standoff pad.

reflections from the data collection window while keeping the detected wave as a continuous wave. The propagation of the vibration wave in the sponge was measured using a linear array transducer (L11-5v, Philips Healthcare, Andover, MA) transmitting at default 6.4 MHz center frequency mounted on the acoustic standoff pad (Cheng et al., 2018). The transducer was connected to the ultrasound system (Vantage 1, Verasonics Inc., Kirkland, WA) (Fig. 1) (Zhang et al., 2018). The measurements were repeated three times at each frequency and each gel thickness.

2.2. Statistical analysis

An unpaired, two-tailed *t*-test of the differences in surface wave speed of the sponge phantom among different levels of gel thickness was conducted to compare sample means. Differences in mean values were considered significant at $p < 0.05$.

2.3. Numerical modeling

A FEM model was developed in ABAQUS (VERSION 6.14, 3DS Inc., Waltham, MA). The sponge phantom, acoustic standoff pad, and transmission gel in the condom were simulated as a 2D planar model of elastic medium (Fig. 2). Length and height of the acoustic standoff pad were 9 and 1.5 cm. Length and height of the sponge phantom were 12 and 2 cm. Ultrasound transmission gel thickness was predefined based on the measurements from experiments. The densities of the acoustic standoff pad and transmission gel were assumed to be 1000 kg m^{-3}. The structural constituent of the sponge phantom is cellulose, which has a density of 1500 kg m^{-3}. The sponge was modeled using a linear poro-viscoelastic model assuming the void ratio of the sponge is 0.7. The standoff pad was assumed an incompressible, linear elastic material

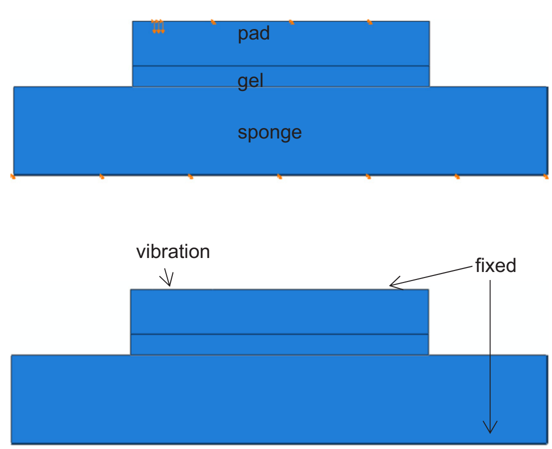

Fig. 2. Geometrical configuration of sponge phantom model.