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● *Technical Note*

A LUNG PHANTOM MODEL TO STUDY PULMONARY EDEMA USING LUNG ULTRASOUND SURFACE WAVE ELASTOGRAPHY

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Abstract—Lung ultrasound surface wave elastography (LUSWE) is a novel technique used to measure superficial lung tissue stiffness. A phantom study was carried out in the study described here to evaluate the application of LUSWE to assess lung water for pulmonary edema. A lung phantom model with cellulose sponge was used; various volumes of water were injected into the sponge to model lung water. Shaker-generated surface wave propagation on the sponge surface was recorded by a 10-MHz ultrasound probe at three shaker frequencies: 100, 150 and 200 Hz. Surface wave speeds were calculated but did not exhibit dependence on the volume of injected water. However, the shear viscosity of the sponge increased with water content, and shear elasticity also exhibited a subtle increase. This study suggests that sponge viscoelasticity might change with the water content, which can be detected by LUSWE. (E-mail: zhang.xiaoming@mayo.edu) © 2018 World Federation for Ultrasound in Medicine & Biology. All rights reserved.

Key Words: **Lung ultrasound surface wave elastography, Surface wave speed, Pulmonary edema, Lung phantom, Viscoelasticity.**

INTRODUCTION

Pulmonary edema is a fundamental feature of congestive heart failure and inflammatory conditions such as acute respiratory distress syndrome (Picano and Pellikka 2016). A high extravascular lung water (EVLW) level predicts severe prognosis in critically ill patients (Sakka et al. 2002) and increased risk of death or rate of heart failure re-admission (Coiro et al. 2015). Assessment of EVLW, however, is challenging. Chest X-ray and chest computed tomography (CT) have been the historical standards in the assessment of EVLW, but these imaging studies require ionizing radiation and radiology facilities and pose a significant logistic burden. Because of the high levels of X-ray absorption by bones, the image quality of chest X-ray is also mediocre. Researchers are actively searching for other methods.

Ultrasound is not traditionally used to evaluate the lung. In normal aerated lungs, most of the ultrasound energy is reflected from the lung surface because of the large acoustic impedance difference between the pleural lining of the lung and the air within the lung. In the presence of EVLW, however, the ultrasound beam finds subpleural interlobular septa thickened by edema (Gargani 2011). The reflection of the ultrasound beam produces reverberation artifacts, called “B-lines,” in wet lungs. These B-lines start from the plural line and extend to the edge of the screen looking like comet tails. The location and amount of B-line artifacts in ultrasound images (Corradi et al. 2016; Lichtenstein and Mezière 1998) are used to evaluate pulmonary edema (Picano et al. 2006) and congestive heart failure (Cardinale et al. 2014). A recent multicenter trial found that lung ultrasound (LUS) was more sensitive than chest X-ray for the diagnosis of cardiogenic pulmonary edema (Pivetta et al. 2015). However, analysis of B-line artifacts is qualitative and relies on visual interpretation, which is subject to inter-operator variability (Corradi et al. 2016).

We have developed a novel technique, lung ultrasound surface wave elastography (LUSWE), to measure superficial lung tissue elastic properties (Zhang et al. 2011, 2016, 2017, 2018). LUSWE measures the lung surface wave by recording thousands of lung ultrasound images. In addition to lung ultrasound’s qualitative evaluations, LUSWE can also quantitatively characterize the lung. In LUSWE, a 0.1-s harmonic vibration at a given frequency is generated by the indenter of a handheld vibrator on the chest wall of a subject. The ultrasound

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probe is positioned about 5 mm away from the indenter in the same intercostal space to measure the surface wave propagation generated on the lung in that intercostal space. The surface wave speed of lung is determined from the change in wave phase with distance and is not dependent on the location of wave excitation. LUSWE has been reported to successfully differentiate the lung elastic properties of patients with interstitial lung disease and healthy controls (Zhang et al. 2017). The objective of this research was to evaluate preliminarily whether LUSWE could be used to measure the EVLW level for pulmonary edema through a lung phantom model study.

METHODS

Sponges have been used as a lung phantom in past research studies (Molinari et al. 2014; Soldati et al. 2011). In particular, Blüthgen et al. (2017) reported that sponges can reproduce nicely the commonly observed lung ultrasound A- and B-line artifacts and can be used for relevant lung studies. In our experiment, we used a rectangular cellulose sponge for our lung phantom model. Tap water was injected by syringe at three locations approximately 2 cm apart in the middle of the sponge surface. The experimental setup is illustrated in Figure 1. The purple sponge (Ocelo Utility Sponge, 3M, St. Paul, MN, USA), with a labeled size of $15.2 \times 9.1 \times 2.2$ cm, is the lung phantom sponge for measurement. Diameters of the pores on this sponge vary from sub-millimeter to a few millimeters. Tiny sub-millimeter pores are distributed all over the walls of larger pores. Beneath the purple sponge, a large pink sponge and a piece of black rubber were added as cushions to reduce the strength of the wave reflected from the boundaries. This setup can help generate the surface wave propagation and avoid other types of waves such as the Lamb wave in a contained structure. We previously proposed a concept of start frequency for generating the surface waves in a finite phantom structure (Zhang 2016). We found that different standing wave modes were generated below the start frequency because of wave reflection. However, pure symmetric surface waves were generated from the excitation above the start frequency. By use of the wave speed dispersion above the start frequency, the viscoelasticity of the phantom can be correctly estimated. By reduction of the wave reflection and measurement of surface wave speed above the start frequency, surface wave propagation can be generated in a finite structure. A shaker (Model FG-142, Labworks Inc., Costa Mesa, CA, USA) was placed in contact with the sponge to generate harmonic vibrations on the sponge surface. Three vibration frequencies (100, 150 and 200 Hz) were used, and the duration for each was 0.1 s. An ultrasound probe (Verasonics linear transducer L11-4 V, Verasonics Inc., Kirkland, WA, USA) with a frequency of 10 MHz was placed about 0.5 cm away from the shaker to detect the waves propagated on the sponge surface. An Aquaflex ultrasound gel pad (04-02, Parker Laboratories, Inc. Fairfield, NJ, USA) was placed between the ultrasound probe and the purple sponge to create a separation for wave detection, because ultrasound locates an object by multiplying the speed of sound by the length of time it travels to the object. The ultrasound measurement and shaker vibrations were synchronized by a vantage ultrasound system (Vantage 256, Verasonics Inc.), and the B-mode images generated were collected for further analysis.

Fig. 1. Experimental setup. An ultrasound probe was placed atop an ultrasound gel pad to measure the surface wave speed of the lung phantom—the purple sponge. The pink sponge and the black rubber were placed under the purple sponge to reduce the reflection of the sound wave from harder surfaces. A shaker was in contact with the purple sponge surface to generate harmonic vibrations on the sponge surface. The bars behind the shaker and the ultrasound probe are the holder frames used to keep the equipment in place.

The waves generated by the shaker will travel at the shaker frequency. Through analysis of the phase change $\Delta\phi$ over a distance of Δr at the sponge surface, the surface wave speed C_s can be determined with the known angular shaker frequency ω: $C_s = \omega|\Delta r/\Delta\phi|$ (Zhang et al. 2016). The accuracy of calculation can be greatly improved by incorporating multiple locations.