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ULTRASOUND IMAGE OF THE MONTH

# Measurement of displacement and strain in biological tissue generated by ultrasonic dual acoustic radiation force

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**Keywords** Acoustic radiation force · Phased tracking method · Strain

## Introduction

The tenderness of muscle tissue is decreased by aging and excessive exercise, potentially leading to disorders such as injuries and decreased supply of nutrients due to poor blood circulation. It is therefore important to diagnose muscle condition, but quantitative and noninvasive diagnostic methods have not yet been established.

In recent years, some remote actuation methods based on acoustic radiation forces have been reported. Fatemi and Greenleaf proposed an imaging modality that uses the acoustic responses of an object, which are closely related to the mechanical frequency response of the medium. By measuring the acoustic emission with a hydrophone, hard inclusions such as calcified tissues in soft material were detected experimentally [1, 2]. However, the spatial resolution in the depth direction corresponds to the size of the intersectional area of the ultrasound beams at slightly different frequencies and is not particularly high.

Nightingale et al. proposed an alternative imaging method in which focused ultrasound is employed to apply a radiation force to soft tissue for short durations (less than 1 ms). The viscoelastic properties of the tissue were investigated from the magnitude of the transient response, which was measured as the displacement, $d(t)$, of the tissue [3–5]. In order to generate measurable displacement by several ultrasonic pulses, high-intensity pulsed ultrasound (1,000 W/cm$^2$) was employed. However, according to safety guidelines for the use of ultrasound, it is recommended that the intensity be below 240 mW/cm$^2$ ($I_{\mathrm{SPTA}}$) for pulsed waves and 1 W/cm$^2$ for continuous waves [6]. The intensity of the pulsed ultrasound employed by Nightingale et al. is therefore far greater than that indicated in the safety guidelines.

The aim of our study was to evaluate muscle condition by noninvasively measuring its viscoelasticity. To evaluate muscle viscoelasticity, muscle needs to be deformed. In this study, two ultrasonic acoustic radiation forces from different directions were shown to be able to deform muscle tissue effectively. Furthermore, the resultant regional displacement and strain in the muscle tissue were measured using a different ultrasonic probe.

## Method

When a single acoustic radiation force is applied to biological tissues, strain (deformation) is not generated effectively, because one acoustic radiation force generates not only strain but also a change in the position of the tissue that has zero spatial gradient in displacement (no strain). In this study, for effective generation of strain in an object, two acoustic radiation forces, which were induced by two continuous ultrasound beams at frequencies of $f_0$ and ($f_0 + \Delta f$), were synchronously applied to two different positions in the object from two different directions, as shown in Fig. 1 [7]. The region pinched by two acoustic

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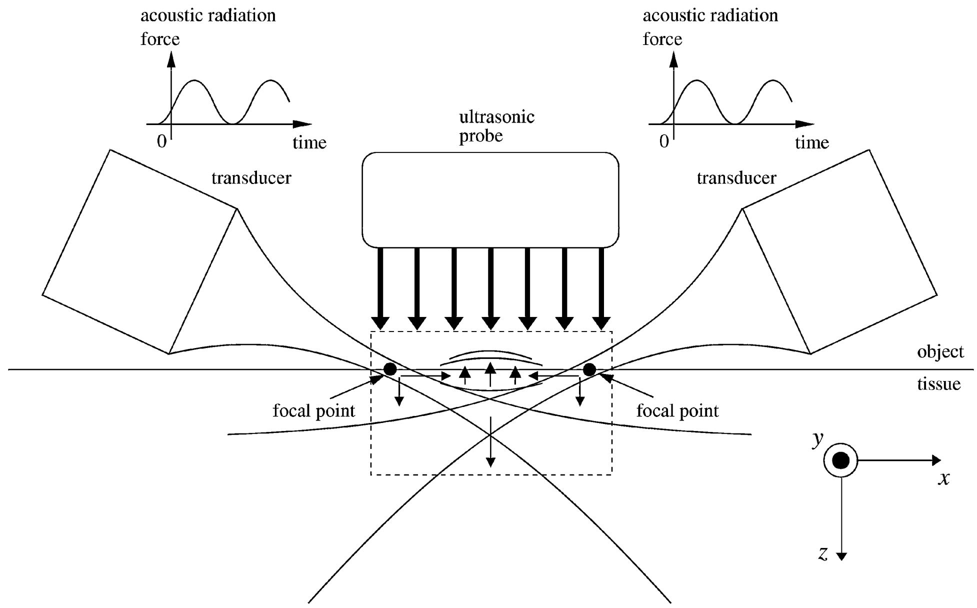


**Fig. 1** Schematic of deformation generation in an object using two ultrasonic acoustic radiation forces and ultrasonic measurement of the resultant displacement and strain

radiation forces oscillating at a frequency of $\Delta f$ was therefore compressed along the horizontal axis. In the case of biological tissues, such as muscle and tendons, vertical expansion occurred due to their incompressibility.

With respect to the low-frequency component, the acoustic radiation pressure, $P_R(t)$, acting on the interface between the medium and the tissue is given by [7]

$$\begin{aligned} P_R(t) &= (1+R^2)\frac{p_0^2}{\rho c^2}(1+\cos 2\pi\Delta f t) \\ &\cong \frac{p_0^2}{\rho c^2}(1+\cos 2\pi\Delta f t), \end{aligned} \tag{1}$$

where $R$, $p_0$, $\rho$, and $c$ are the pressure reflection coefficient at the interface between the medium and the object, the sound pressure of the transmitted ultrasound, the density of the medium, and the sound speed in the medium, respectively. The pressure reflection coefficient is defined by the speed of sound and the densities of the medium and the object. For example, the speed of sound in muscle and fat is 1,568 m/s and 1,465 m/s, respectively. By assuming the density of soft tissue to be $1.0 \times 10^3$ kg/m$^3$, the reflection coefficient $R$ is 0.034. Thus, the squared reflection coefficient $R^2$ in Eq. (1) is assumed to be zero. The resultant displacement in the vertical direction was measured by our ultrasonic phased tracking method [8, 9]. In the present study, the center frequency, $f_0$, of ultrasound for actuation generated by the two transducers and the actuation frequency, $\Delta f$, were set at 1 MHz and 5 Hz, respectively. The two transducers used for generating acoustic radiation forces were single-element focused transducers. The sound pressure of the continuous ultrasonic wave used for actuation was 180 kPa, which corresponds to 1.08 W/cm$^2$ ($I_{SPTA}$) in ultrasonic intensity (safe level of continuous wave is 1 W/cm$^2$ [6]) and 7.4 Pa in acoustic radiation force. The intensity of the ultrasonic pulse for measurement was 11.2 mW/cm$^2$ ($I_{SPTA}$), which was smaller than the safe level (240 mW/cm$^2$).

## In-vitro experimental results

In this study, an in-vitro experiment using chicken breast muscle was conducted to investigate whether the proposed method could generate the presumed deformation in biological tissue. Figures 2a and b show the instantaneous displacement and the strain, respectively, in the vertical direction inside the object during one cycle of acoustic radiation forces. Figure 2c shows waveforms of the acoustic radiation forces (black line), the instantaneous displacement (green line), and the strain (blue line) at $(x, z) = (1.4$ mm, $1.0$ mm$)$ during one cycle of the acoustic radiation force. As shown in Fig. 2, the region between the two focal points of the ultrasound beams for actuation expanded in the vertical direction when the region moved downward due to the increase in acoustic radiation forces. The horizontal components of the applied acoustic radiation forces should have increased when the region moved downward, because this downward motion occurred due to the vertical components of the acoustic radiation forces. Consequently, this result suggests that the proposed method successfully generated the deformation in biological tissue that was expected, as illustrated in Fig. 1, i.e., the targeted region expanded vertically, due to the horizontal compression by two acoustic radiation forces.

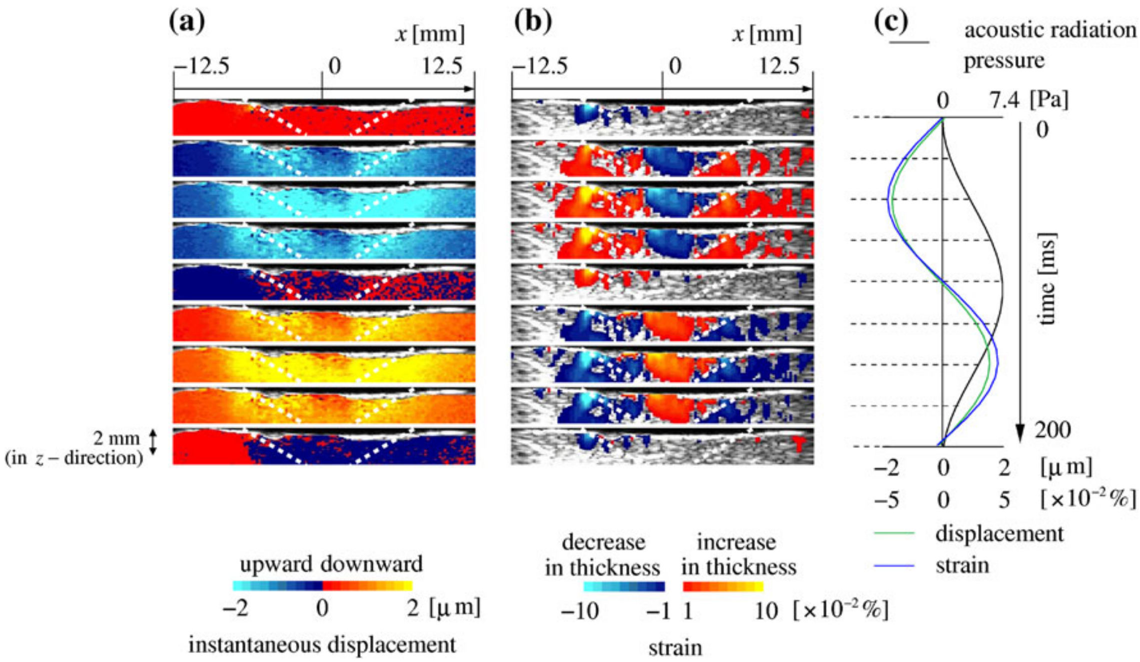


**Fig. 2** Distributions of **a** instantaneous displacement and **b** strain in the vertical direction in each frame during a cycle of radiation force. **c** Waveform of instantaneous displacement and strain at ($x$, $z$) = (1.4 mm, 1.0 mm) during one cycle of acoustic radiation force. The *black line*, the *green line*, and the *blue line* show the acoustic radiation force, the instantaneous displacement, and the strain, respectively

## Discussion and conclusion

In this study, it was confirmed that strain was successfully generated in muscle tissue using two synchronous acoustic radiation forces, and that the strain generated could be measured by our ultrasonic phased tracking method. Skeletal muscle is composed of muscle fibers that show significant elastic anisotropy. However, such elastic anisotropy was not considered in the present study. The elastic anisotropy of muscle tissue will be investigated in a future work by applying acoustic radiation forces from different directions.

In addition, there were phase delays in the displacement and strain from the applied acoustic radiation forces, as shown in Fig. 2c. These phase delays depend on the viscoelasticity (not only on elasticity) of the tissue. By analyzing such phase delays, it would be possible to assess the viscosity, which would be a useful marker for diagnosis of the physiological status of muscle tissue.

**Conflict of interest** None.

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