

ACOUSTICAL LETTER

Fundamental study of numerical simulation of ultrasound wave propagation in microcalcification for analysis of twinkling sign

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1. Introduction

Rahmouni *et al.* first introduced the twinkling sign (TS), which is a phenomenon displayed as a rapidly changing mixture of red and blue behind a strongly reflecting structure [1]. The potential of the TS in calcification diagnoses (e.g., that of thyroid cancer) has been reported [2]. Calcifications can become larger than 10 mm. It is very important to detect microcalcifications (≤ 1 mm) for the early detection of lesions. However, the mechanism of the TS is still unresolved.

The TS appears when echo signals change in successive frames. To investigate why and how the TS occurs, most investigators used final images displayed on the monitor of commercial medical ultrasound equipment with various parameters and factors [1–3]. Although a few simulations were conducted previously, the simulation models did not satisfy the acoustic and mechanical characteristics of tissue [4,5]. Moreover, the acoustic behavior of a small sphere in soft tissue has been investigated theoretically [6]. However, Taki *et al.* indicated that the experimental echo signal differs from the theoretical one [7]. There has been little research on how ultrasound penetrates calcifications in soft tissue.

In this study, we conducted a three-dimensional numerical simulation using the FEM simulator PZFlex (Weidlinger Associates, Inc., CA, USA) and visualized the way that ultrasound propagates in a microcalcification for the first time.

2. Simulation conditions

We modeled a tissue-mimicking phantom (cubic with dimensions: $6 \times 4 \times 4\,\text{mm}^3$, density: $900\,\text{kg/m}^3$, longitudinal velocity: 1,426 m/s, and shear velocity: 2.58 m/s) containing a microcalcification (spherical with diameter: 1 mm, density: $2{,}250\,\text{kg/m}^3$, longitudinal velocity: 5,640 m/s, and shear velocity: 3,280 m/s) placed at the focal point of a linear phased array probe, as shown in Fig. 1. The center of the sphere was located at $x = 3.5$ mm, $y = z = 2$ mm. We investigated how the ultrasound excited by the probe propagates around the microcalcification. The mesh size was set to $10 \times 10 \times 10\,\mu\text{m}^3$. The center frequency of the incident pulse was 7 MHz and its negative maximum pressure was 2.5 MPa. Therefore, its mechanical index was approximately 0.9. The ultrasound replicating the sound around the focal point, was excited at $x = 1$ mm and $0.5 \leq (y, z) \leq 3.5$ mm. The distance between the excitation area and the microcalcification was 2 mm.

3. Results

Snapshots of particle velocities of the sphere in the x-y plane ($z = 2$ mm) at 50 μm intervals are shown in Fig. 2. Each arrow represents the vector of the particle velocity at each point, and the length of the arrow corresponds to the magnitude of the particle velocity. From another view point, particle velocities at the front surface ($x = 3$ mm, $y = 2$ mm), upper surface ($x = 3.5$ mm, $y = 2.5$ mm), and rear surface ($x = 4$ mm, $y = 2$ mm) of the microcalcification are shown in Fig. 3. Furthermore, the x-directional particle velocities at the front and rear surfaces when the longitudinal and shear velocities of the microcalcification were varied, are shown in Fig. 4.

4. Discussion

The obtained results implied what a complex phenomenon occurs around the microcalcification. As shown in Fig. 3(a), the emitted ultrasound reached the microcalcification at 1.4 μs, then the x-directional particle velocity of the front surface started to increase rapidly. This is clear from the longitudinal velocity of the soft tissue (1,426 m/s) and the propagation distance (2 mm). After that, however, a long and complex signal appeared. The complexity of the signal should be caused by not only multiple reflections inside the microcalcification but also the surface acoustic wave around the microcalcification. As shown in Fig. 3(b), the y-directional velocity at the upper surface increased at approximately 1.5 μs. Moreover, as shown in Figs. 4(a) and 4(c), the time difference from the peak at the front surface to that at the rear surface was approximately 0.5 μs, which was considered reasonable from the shear velocity of the microcalcification (3,280 m/s) and the length of the half circle of the microcalcification (1.57 mm). These findings indicated that a surface acoustic wave occurred around the microcalcification.

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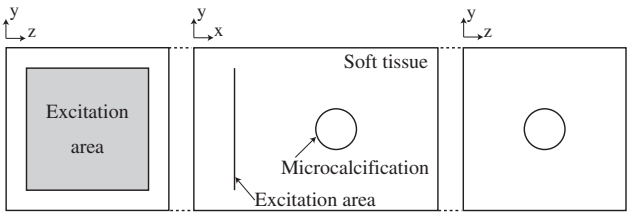

Fig. 1 Simulation model.

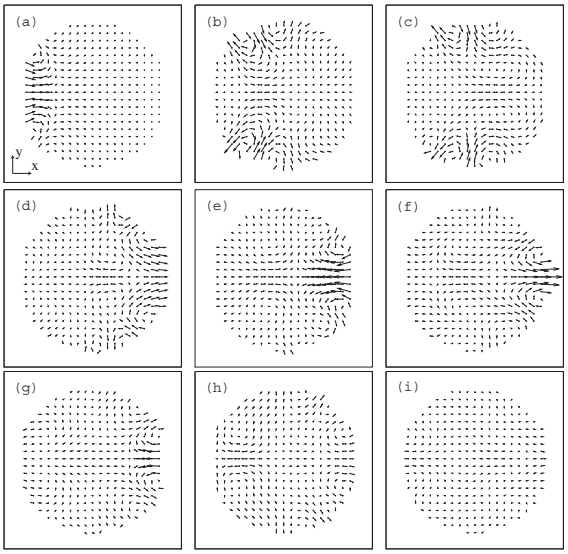

Fig. 2 Snapshots of two-directional particle velocities at 50 μm intervals at (a) 1.54, (b) 1.68, (c) 1.73, (d) 1.84, (e) 1.94, (f) 2.01, (e) 2.09, (f) 2.16, (g) 2.30, (h) 2.43, and (i) 2.55 μs.

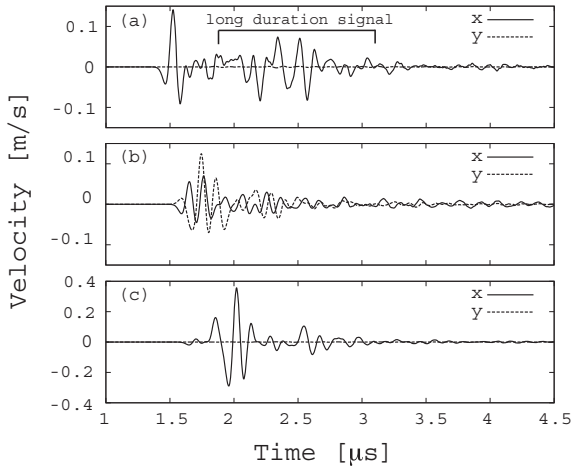

Fig. 3 Two-directional particle velocities at (a) front surface, (b) upper surface, and (c) rear surface.

When we varied the longitudinal velocity of the microcalcification, the shape of the long signal at the front surface did not change markedly, as shown in Fig. 4(a). However, when the shear velocity of the microcalcification was varied, the peak time changed depending on the shear velocity, as

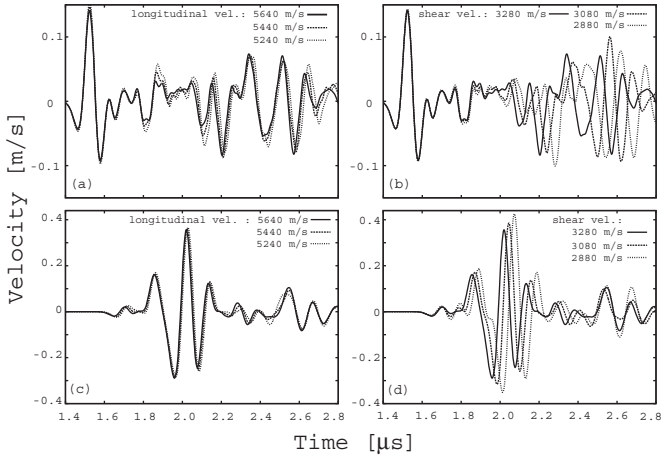

Fig. 4 *x*-directional particle velocities in microcalcification at (a) front surface with various longitudinal velocities, (b) front surface with various shear velocities, (c) rear surface with various longitudinal velocities, and (d) rear surface with various shear velocities.

shown in Fig. 4(d). As a result, the long and complex signal changed abruptly from approximately 2 μs, as shown in Fig. 4(b).

Rahmouni *et al.* presumed that the surface roughness induced multiple reflections in the medium, increased the pulse duration of the received RF signal, and caused the only slight variation of the incident beam generated for a completely different acoustic pattern [1]. However, it has already been revealed that a smooth surface also generates the TS [8]. Furthermore, this study strongly indicated that the long-duration signal is caused by a surface acoustic wave around the microcalcification.

5. Conclusion and future work

In this study, we examined how ultrasound propagates in a microcalcification by FEM simulation. It was found that a surface acoustic wave was generated around the microcalcification, which finally caused a long-duration echo signal. However, it is difficult to assert that the long-duration signal itself generates the TS. As a future work, we will investigate the change in the echo signal between successive excitations.

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