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Simulation of ultrasound B-mode image in heterogeneous media using FDTD method

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1. Introduction

A quantitative estimate technique of liver fibrosis has been developing. The finite-difference time-domain (FDTD) method is to simulate the process of ultrasound propagation in tissues with various acoustic property. The simulated radio frequency (RF) data at transducer is used to form B-mode image, in which the behaviors of different tissue are statistically analyzed by using the multi-Rayleigh model.

2. Method

2.1 FDTD simulation method

The spatial impulse responses based method is widely used in the simulation of ultrasound propagation in human tissue, howerver it falls into drawbacks as the sound speed is fixed, the process of propagation is not really simulated, instead, the reflection is caculated with the spatial postion of the reflecting scatterer and the reflection coefficient, phenomenon as multi-reflection, refraction, etc. cannot be observed. While in the FDTD based method, ultrasound propagation is appoxmated by actually solving the propagation equation, phenomenon unprecedented in the traditional one can thus be properly reappeared.

2.2 Process of B-mode image formation

Simulation is conducted in a confined field, where media with different property are placed inside. Transducer transmits the carrier wave with a Hanning window into the field, where reflections occur when the wave propagates between media with different specific acoustic impedances, and the reflections are received by the same transducer as RF data. The RF data is then processed with a technique called dynamic focus, and the lateral resolution is raised. Finally after the quadrature detection, the envelope is acquired as the amplitude information in the form of B-mode image.

3. Estimation of liver disease progress

3.1 Random scatters and Rayleigh distribution model

In our previous studies[1], the multi-Rayleigh distribution model frame has been proposed as a quantitative diagnosis tool in inspecting B-mode image of liver disease, due to the fact that the distribution of amplitude of reflections from random distributed homogeneous scatters fit Rayleigh distribution. And the case of heterogeneous scatters (with different characteristic acoustic impedance) can be express as the combination of multiple homogeneous scatters, only that their combination contribute to the heterogeneousness as shown below:

$$P(x)_{mix} = \alpha P(x)_{fibrosis} + (1-\alpha)P(x)_{normal}$$

$$P(x)_i = \frac{2x_i}{{\sigma_i}^2}\exp\left(-\frac{{x_i}^2}{{\sigma_i}^2}\right), i = normal, fibrosis$$

$$V = {\sigma_{fibrosis}}^2/{\sigma_{normal}}^2$$

$$x = \frac{x_{ori}}{\sqrt{mean({x_{ori}}^2)}}$$

,

where x_{ori} is the original amplitude in B-mode image, x the amplitude normalized about the mean power of x_{ori}, P the probability density function of x; normal and fibrosis the index for corresponding tissue, since the variance σ_i^2 differs for the different tissues; variance V the severity of disease and mixture rate α the occupancy of fibrosis tissue in all.

3.2 Moments

Moments of the amplitude are defined as below:

$$Moment_i = E(x^i), i = 1,3$$

,

where the 1st and 3rd moments are used in the process of estimation. Corresponding to each combination of different V and alpha of the multi-Rayleigh distribution model, a look up table of the theoretical first and third moment is created in advance.

3.3 Estimation of liver disease parameters

In the process of estimation disease process, a particular region of interest (ROI) is firstly selected from the B-mode image. 1st and 3rd moments are calculated from the normalized ROI, and are used as initial values. The expectation–maximization (EM) algorithm then use the initial value in the estimate of severity and occupancy of liver diseases. To assess the correctness of the estimation, Kullback-Leibler (KL) divergence[2] is used to assess the similarity between distribution of ROI and that of the inferred multi-Rayleigh model.

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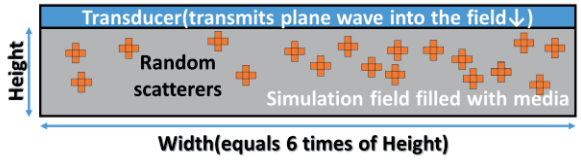

Fig. 1 Scheme of simulation configuration.

Table. 1 Simulation configuration parameters

Carrier wave	Two sine wave
Frequency	5 MHz
Window	Hanning
Points per wavelength	40
CFL Number	1
Density of media/scatter	1050 kg/m^3
Sound speed of scatter	1775 m/s
Sound speed of media	1555.3 m/s
Vertical length	15 mm
Horizontal length	90 mm
Number of scatters/mm^2	100
Number of scatters/mm^2	400
Pixels/scatter	5 (cross-like)
Space grid size	7.7765 μm

4. Simulation

4.1 Configuration

As can be seen from **Fig. 1**, a 2-period-sine plane wave with Hanning window is transmitted at the transducer (2nd vertical grid) into the field. Reflection occurs at the boundary media and scatter, to record which, sound pressure at the same transducer is recorded as radio frequency (RF) data until the time reaches the preset span. Scatters, each consisting of 5 pixels, are random distributed into two areas, left and right separately, representing tissue with low or high reflection rate (normal tissue or fibrosis tissue). Currently, the variance ratio V for the tissue is controlled by the ratio of scatters number per unit area, the sound speed of scatterers are automatically set, so as to keep the average sound speed of normal tissue at 1560 m/s while that of fibrosis tissue 1580 m/s. After removing the carrier wave in the first 2 period in time axis of the RF data, aperture synthesis and quadrature detection is performed and the data is used as the B-mode image.

4.2 Simulation results and analysis

Figure 2 is an example of B-mode image. Normal and fibrosis tissue is on the left or right side, and the speckle-like pattern can be seen. The estimation is carried out in the combination of ROIs on the left and right side. The basic size of the ROI is 5mm (W)*3mm (H), the mixture is changed by extending the horizontal width of either the ROI on the left or right side. By combining the two ROIs

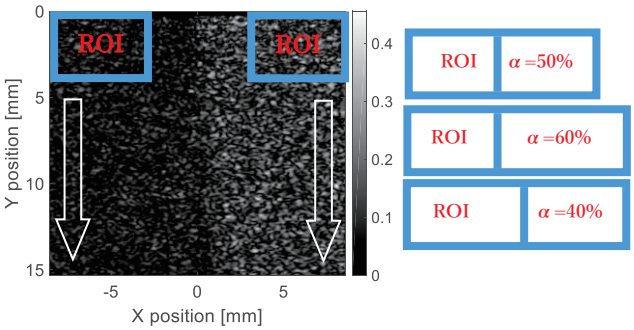

Fig. 2 B-mode image heterogeneous tissue, the combination of ROIs with various mixture rate α.

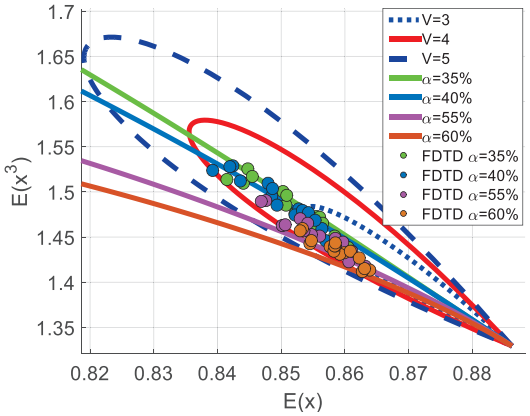

Fig. 3 Analyzed moments, and corresponding mixture rate and variance ratio in moments loop up table

together, a heterogeneous fibrosis tissue is obtained. Moved from the top to the bottom in vertical direction, each ROI is analyzed with the multi-Rayleigh distribution model. For the configured V=4 and α=35% to 60% in **Fig. 3**, where the horizontal axis is the 1st moment, vertical the 3rd moment, the circles the variance ratios, the curves the mixture rates. The dots are the analyzed data from the ROIs in the depth direction, and they are fluctuating around the theoretical values.

5. Conclusion and Future work

In this study, an ultrasonic heterogeneous B-mode image simulation method based on FDTD method is realized. By applying analysis tools like KL divergence, moments and multi-Rayleigh distribution model, tissue with disease can be qualitatively and then quantitatively inspected. The analysis shows the simulation method is feasible. In the meantime, the detection accuracy of liver disease in the early stage with low V and α needs to be improved.

References

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2. T. Higuchi, et al.: Jpn. J. Appl. Phys., **52** (2013) 07HF19.