Fundamental study on high frequency application of multicomponent amplitude envelope statistics

Mami Shirai[1†], Taisei Higa[2], Tingzhen Zhang[2], Shinnosuke Hirata[3], Kenji Yoshida[3], Tadashi Yamaguchi[3] ([1]Eng. Chiba Univ.; [2]Grad. School of Sci. and Eng. Chiba Univ.; [3]Center for FrontierMedical Engineering, Chiba Univ.)

1 Introduction

Many methods for the quantitative evaluation of biological tissue properties have been proposed by analyze the amplitude envelope analysis of ultrasound echo signals, primarily applied to evaluating hepatitis and fatty liver. The possibility of fat mass evaluation has been suggested in phantom studies simulating fatty liver using a low frequency probe and MRA model. However, the low frequency resolution showed limitations in evaluation as the fat mass increased[1)]. Therefore, we examined the accuracy of fat volume evaluation by observing liver-simulating phantom using 20-30 MHz radiofrequency waves, which have recently begun to be used for skin and body surface tissues in clinical practice. In this study, fatty liver phantom was measured using a high frequency linear array probe and evaluated using MRA model, and the relationship between tissue structure and evaluation parameters was examined.

2 Evaluation target and data acquisition

A fatty liver mimicking phantom (phantom A) was prepared by mixing Orgasol 2001 (Arkema) with an average particle size of 5 μm at a volume fraction of 0.5% and MX-1000 (Soken) with an average particle size of 10 μm at a volume fraction of 0.25% in 2.0 wt% agar gel (A1296; Sigma-Aldrich) and ultrapure water. The acoustic impedances of Orgasol and MX-1000 are 2.22×10^6 kg/m^{2}s and 3.25×10^6 kg/m^{2}s, assuming cell nuclei and fat droplets in the liver, respectively.

Echo signals were acquired using a Vantage 256 (Verasonics) and a high frequency linear array probe (L38-22v, Verasonics). The center frequency is 31 MHz, and the sampling frequency during the observation was set to four times the center frequency. Echo data were obtained by steering the probe to 11 angles between -15° and 15° of the plane waves, transmitting and receiving at each angle. The data were processed by compound plane wave imaging (CPWI) using synthetic aperture and compounded for analysis. In order to reproduce blood vessels and portal veins observed in the actual liver, Gaussian distributions of low intensity components were superimposed on a portion of the acquired echo signals to create a hybrid phantom (phantom B) of actual measurements and computer simulations.

†shiraimami1101@chiba-u.jp, *yamaguchi@faculty.chiba-u.jp

3 Amplitude Envelope Analysis

3.1 MRA model

It is known that the probability distribution of the amplitude envelope of an echo signal obtained from a homogeneously distributed medium of one type of scatterer can be approximated by the Rayleigh distribution. In this distribution, 'x' represents the amplitude envelope of the echo signal, and 'σ²' is a parameter corresponding to the echo signal power.

$$p_{RA}(x) = \frac{2x}{\sigma^2} exp\left(-\frac{x^2}{\sigma^2}\right)$$

On the other hand, since biological tissues are distributed with multiple types of scatterers, Multi-Rayleigh (MRA) model, which combines multiple Rayleigh distributions, was proposed for their evaluation. In this study, three components MRA (3-MRA) model with the following equation was used.

$$p_{MRA}(x) = \alpha_L p_L(x) + \alpha_M p_M(x) + \alpha_H p_H(x)$$

where α_L, α_M and α_H represent the mixing rate of the corresponding Rayleigh distributions, and p_L, p_M, and p_H are Rayleigh distributions with different scale parameters σ_L^2, σ_M^2, and σ_H^2 respectively. The scale parameters are constrained to be $\sigma_L^2 < \sigma_M^2 < \sigma_H^2$, where the echo signal components from normal liver tissue correspond to $\alpha_M p_M$ and those from low or high echo tissue compared to normal liver tissue to $\alpha_L p_L$ and $\alpha_H p_H$, respectively.

3.2 Evaluation of the number of components of the organization

MRA model determines the number of scatterers in the medium from the analytical signal, and the number of components is evaluated by a component number model that matches the actual

tissue structure[2]. In this study, phantom B includes high echo scattering source that simulates fat in the scatterer that simulates normal liver. Consequently, 2-MRA model is estimated as follows.

$$\alpha_M p_M(x|\sigma_M^2) + \alpha_H p_H(x|\sigma_H^2)$$

α_H corresponds to the mixing rate of high echo scatterers and σ_H^2/σ_M^2 to the reflection intensity ratio of high echo scatterer. And non-Rayleigh is defined as a point where the mixing ratio is biased toward one or all dispersions are equal, the moment is large although it is actually one component, and the estimation accuracy is degraded due to inconsistency between the results of the component number determination and the estimated parameters.

4. Results

Figure 1 shows the B-mode and probability density distribution (PDF) of the region of interest (ROI) around 8 mm depth, which is the elevation focus. The phantom A was evaluated as containing two components, liver tissue components and high echo components from fat droplets as Fig. 2(a). The phantom B was evaluated as containing three components with additional low echo tissue components as Fig. 2(b). Both results consistent with the scatterer structure in each phantom.

Figure 2 shows the results of the number of the component evaluation superimposed on the B-mode. Blue dot indicates one component, green dot indicates two components (L+M) of low echo and liver tissue components, yellow dot indicates two components (M+H) of liver tissue and high echo components, red dot indicates three components, and light blue indicates the ROI evaluated to be non-Rayleigh (amplitude distribution could not statistically modeled). In the evaluation result of the phantom A (Fig. 2(a)), the amplitude characteristics of the echo signals are evaluated to be two components (yellow) over a wide area, except near the probe where the sound field characteristics are complex and at the deepest part where the effect of attenuation is large. This indicates the presence of strong scatterers mixed in a homogeneous medium, which is consistent with the characteristics of fatty liver. In the evaluation results for the phantom B, only low echo portions with sparse scatterers are evaluated as three components (red), which is consistent with the mathematical theory. Our previous study using the clinically equivalent frequency band (around 5 MHz) gave similar results, but in the present study, a mixture of smaller hypoechoic regions could also be evaluated.

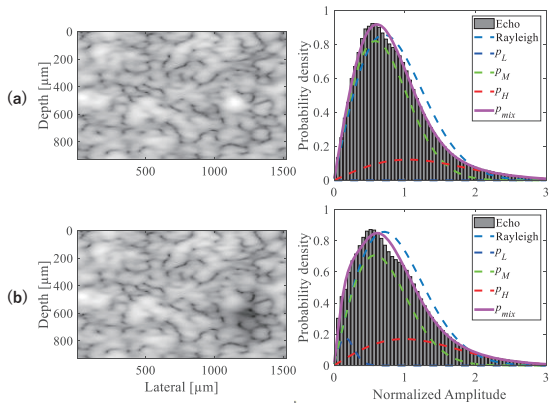

Fig. 1 B-mode and PDF at the elevation focus point for the phantom (a) A (b) B

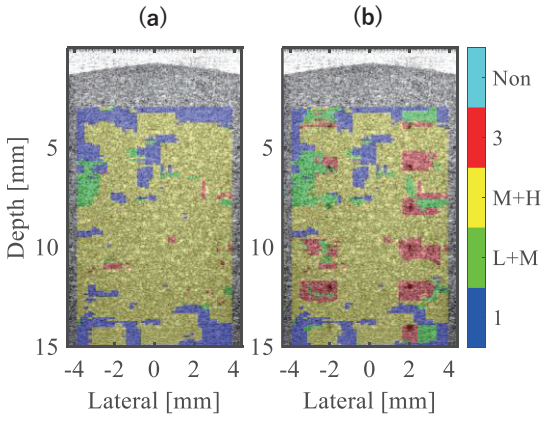

Fig. 2 Evaluation of the number of components by MRA model for the phantom (a) A (b) B

5. Conclusions

In the phantom with multiple types of scatterers and low echo areas, the component number evaluation in MRA model worked effectively. The evaluation resolution was improved to the sub-millimeter order by targeting the echo data at high frequencies, compared to the previous results at low frequencies. In future works, we will examine the evaluation accuracy of MRA model when fibrous structure is added in addition to the fat components.

Acknowledgments

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References

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