Comparison of accuracy of multi-component media evaluation for higher-order amplitude enveloping statistics models

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1. Introduction

Amplitude envelope statistics of echo signal is one kind of the quantitative ultrasound (QUS) method and has been applied for evaluation of biological tissue properties such as hepatic steatosis grades. Several statistical models and high-order models were suggested to evaluate the relationship between echo signal characteristics and tissue structure[1,2]. However, in order to find the model described metabolic dysfunction associated steatohepatitis (MASH) liver the most accurately, it is necessary to compare the evaluation accuracy between different models with high-resolution liver echo data.

In this study, ouble Nakagami (DN) model, which has been proposed as an evaluation model for hepatic steatosis[3,4], was applied to high-resolution echo data of MASH liver-mimicking phantoms acquired with high-frequency ultrasound. The evaluation accuracies of DN model, Generalized Nakagami (GN) model and Homodyned-K (HK) model were compared.

2. Targets and methods

2.1 Numerical phantom

The 5 μm diameter scatterer was randomly placed in the simulation field at 0.1% volume fraction to mimic a normal liver with homogeneous structure. And 25 μm diameter scatterer mixed inside the normal liver in silico phantom with a volume fraction of 0.25% mimicked fat droplets in fatty liver. In addition, fibrosis-mimicking and MASH-mimicking in silico phantoms were generated by adding fibrous structures extracted from pathological images of hepatitis B patients. The acoustic impedance ratios of the liver, fat, and fibers were set to approximate those of the actual human livers. All the scatterers were placed in the simulation field which size was 60 × 60 mm in lateral and depth direction. **Figure 1** shows the pattern of scatterer distribution in tissue-mimicking phantoms. The fibrosis-mimicking phantom was the MASH model without fat droplets.

The echo simulation was performed with ultrasound development platform (Vantage256, Verasonics) and a linear array probe (L39-21gD, Daxsonics) in compound plane-wave imaging (CPWI) method. The T/R condition was shown in **Table. 1.**

Table 1. Transmit/Receive condition

Tx elements	128
Tx angles	0°,±5°, ±10°, ±15°
Tx frequency	31.25 MHz
Sampling frequency	125 MHz

2.2 Amplitude envelope analysis

The relationship between the amplitude envelope probability density function (PDF) of the echo data and the one-component scatterer distribution can be approximated by the Nakagami model, given as,

$$p(x) = \frac{2\mu \cdot x^{2\mu-1}}{\Gamma(\mu) \cdot \omega^{\mu}} \exp\left\{-\frac{\mu x^2}{\omega}\right\} \qquad (1)$$

where x is amplitude envelope, Γ is the gamma function, ω is echo signal energy and μ is related to the number density of scatterers.

DN model is composed of two Nakagami model to evaluate the statistical characteristics of echo signal from scatterers with different variance. It was given as,

$$p_{mix}(x) = (1-\alpha)p_L(x|\mu_L, \omega_L) + \alpha p_F(x|\mu_F, \omega_F) \qquad (2)$$

when p_* are the probability distribution functions (PDFs) which expressed as Nakagami distribution of each component with relative echo amplitude distributions of low and high variance, independently. Parameters μ_* represent number density of each component, $\alpha\omega_F$ is related to the echo signal energy of high variance component.

The PDF of Generalized Nakagami model and Homodyned-K was given as equation (3) and (4), respectively.

$$p(x) = \frac{2smm^m \cdot x^{2ms-1}}{\Gamma(m) \cdot \Omega^m} \exp\left\{-\frac{mx^{2s}}{\Omega}\right\} \qquad (3)$$

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$$p(x) = \frac{1}{2\pi}\int_0^\infty \frac{uJ_0(us)J_0(uA)}{(1+\frac{u^2\sigma^2}{2\mu})^\mu}du \quad (4)$$

J_0 is the Bessel function of zeroth order.

Kullback-Leibler (KL) divergence was used to describe the similarity between 2 probability distribution function. The accuracy of evaluation between different models were compared by KL divergence. Two probability distribution functions are more similar with a lower KL divergence.

3. Results and discussion

Figure 2 shows the echo data of Fibrosis, Fatty and MASH liver superimposed with (a) B mode image, (b) $\alpha\omega_F$, the signal intensity of high variance echo component and (c) μ_F, the number density of high variance scatterer. Since MASH phantom had both fatty droplets and fibrous, $\alpha\omega_F$ is higher in the entire evaluation region when compare MASH with Fibrosis or Fatty. Compare Fatty with Fibrosis or MASH, μ_F was higher in fibrous region, which corresponds to the scatterer structure.

Figure 3 shows the mean and standard deviation of KL divergence for different evaluation models and phantom cases. In Fibrosis, Fatty and MASH phantom, DN model has lower KL divergence than GN and HK model. Since DN model was a higher-order model it can describe echo signal characteristics from different components and be more fit to raw data PDFs. In contrast, DN model's KL divergence was higher than GN and HK models in Healthy phantom case. The error was caused by the DN model's separation into two components, even though in a healthy liver, only hepatocytes were homogeneously distributed and there was only one component. We have confirmed that this issue can be resolved by adding the judgment conditions we used in similar studies.

4. Summary

The application of the DN model to high-frequency ultrasound data confirmed that the echo characteristics can be analyzed with higher accuracy than the mathematical model used for general amplitude envelope statistics. This means that the DN model is able to discriminate and evaluate echo components from different scatterers.

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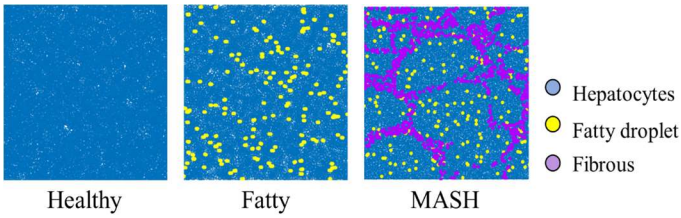

Fig. 1 Scatterer distribution pattern in tissue-mimicking in silico phantoms.

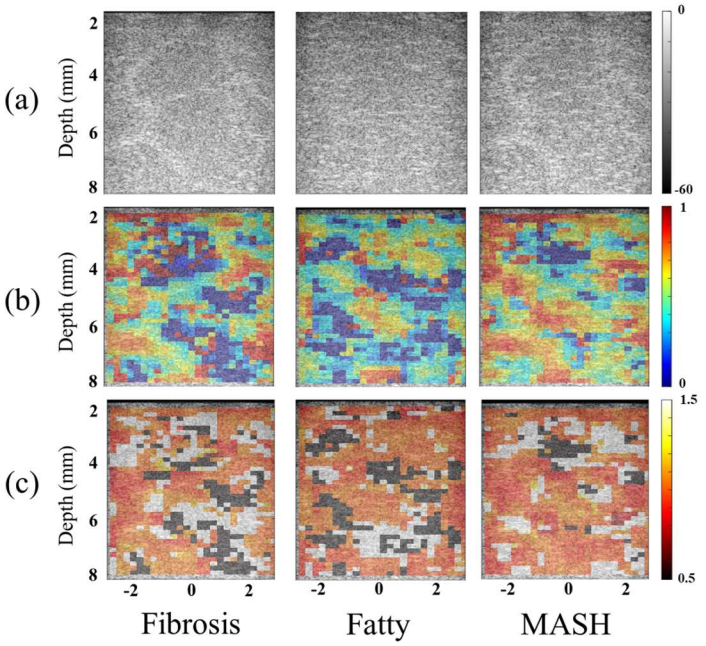

Fig. 2 B mode image (a) signal intensity (b) and number density (c) of high variance component of in silico phantoms evaluated by DN model.

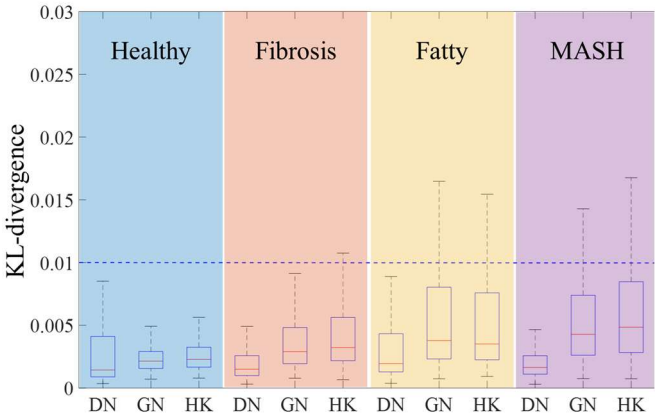

Fig. 3 Fitting accuracy between different models in different simulation phantom.