A proposal of compound amplitude envelope statistical analysis model considering low scatterer concentration

低散乱体密度状態に着目した複合型振幅包絡統計解析モデルの提案

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1. Introduction

In order to evaluate the echo signal, some methods had been proposed which were focusing on the frequency dependency[1] and the amplitude envelope statistics[2]. In particular, the amplitude envelope statistics can evaluate the back scattering wave from multiple types of scatterers, and it can be applied to various diseases such as diffuse liver disease and cancer metastasis diagnosis of lymph nodes. In recent years, high-performance ultrasound diagnostic equipment can obtain with high spatial resolution. It means that the number and scale of scattering sources in tissue structures lose the concept of existing probability density function (PDF) described envelope statistics. Therefore, it is concerned that the conventional amplitude envelope statistics models can not sufficiently evaluate the biological structure.

In this study, we developed a new envelope statistics model that can evaluate tissue structures with high accuracy in high resolution measurment. Specifically, we proposed a multi amplitude envelope statistics model assuming physical structure of fatty liver. Each PDF relats to individual structures and which were evaluated independently. The Nakagami distribution was used as each PDF model because the PDF can evaluate the number of scatterer density.

2. Assumption of scattering sources

The structure of fatty liver was supposed as a mixture of normal liver structure and lipid droplets. The structure of normal liver was composed hepatocytes and luminal structure. In the case of normal liver, the percentage of hepatocytes is over than 80 % of liver whole volume. The number density of hepatocyte is sufficient larger than the luminal structure.

Generally, the shape of nucleus and lipid droplets are spherical, and that of luminal is cylinder. Scattering amplitude of a nucleus in hepatocytes is weaker than luminal. On the other hand, the size of the lipid droplets varies depending on the degree of fatty depositon with disease state, relating the impedance contrast with the surrounding tissues strongly affects the backscattering intensity to large, the backscattered wave from of faty liver becomes stronger than the normal liver structure. In this study, in order to model these features, echo signal was supposed two different amplitude characteristics. The amplitude envelope distribution p_L and p_F were derived from the normal liver structure and the lipid droplets, respectively. $p_{mix}(x)$ is computed with weighted(α) and added together as Eq. 1. When the number of scatterers in the spatial resolution (R_{vol}) is small (e.g, < 10 sc/R_{vol}), it is known that the distribution is biased to the lower amplitude side than the Rayleigh distribution. Nakagami distribution[3] (eq. 2) can approximat[4] those situation. Echo signals of each structure $p_L(\mu_{\mathrm{L}}, \omega_{\mathrm{L}})$ and $p_F(\mu_{\mathrm{F}}, \omega_{\mathrm{F}})$were modeled with each Nakagami distributions.

$$p_{mix}(x) = (1-\alpha)\, p_L + \alpha\, p_F. \tag{1}$$

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

3.Methods

3.1 RF echo simulation

A computer simulation was performed with Field II (J.A. Jensen, Technical University of Denmark) using MATLAB (The MathWorks Inc., Natick, MA) in a three-dimensional space of 6 mm in depth, 2.5 mm in lateral and 2.5 mm in slice. A single element concaved transducer was simulated with a diameter of 10 mm and F-number of 2. The transmission and reception frequency were 15.0 MHz, and the sampling frequency was set to 250 MHz using 16-bit accuracy. The speed of sound was assumed to be 1560 m/s for each tissue. The scatterers ware distributed on the area from 17 mm to 23 mm in depth. An ultrasound wave with a center frequency of 15.0 MHz was used to radiate each of the simulated computational domains. The simulation mimicking the mechanical two dimensional scan every 30 μm and computed 31 line by 31 line. The number of scatterers for lipid droplets were 0, 1, 1.5, 2, 3, 4, 5, and 10 sc/R_{vol} for 4 sc/R_{vol} of luminal structure. Scattering amplitude

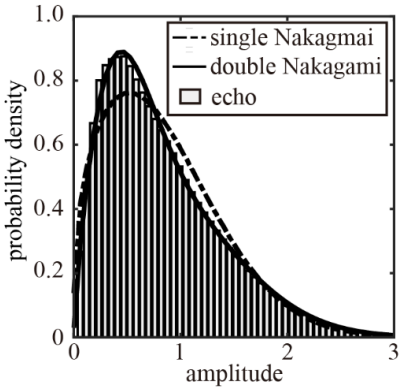

Fig. 1 PDF of the echo amplitude envelope when the lipid droplets is 2 sc/R_{vol}.

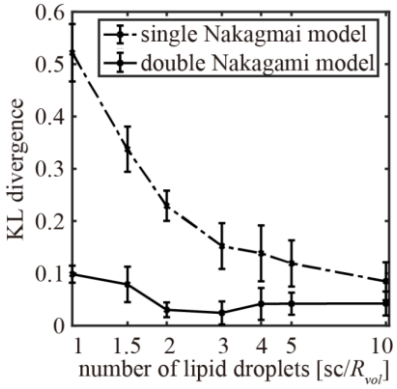

Fig. 2 D_{KL} of previous and proposed methods in each number of lipid droplets per R_{vol}.

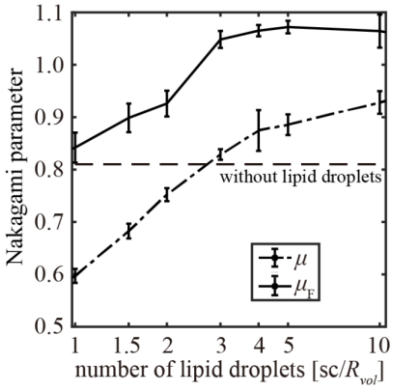

Fig. 3 Nakagami parameters (μ and μ_{F}) in each number of lipid droplets per R_{vol}.

of lipid droplet was ten times of luminal scattering amplitude. Five different scatterer distribution for each scatterer number were computed.

The statistical characteristics of the simulated echo signal envelope from the same depth range (19.5 to 20.5 mm) in each simulated domain were analyzed. The analyzed depth range was based on three times of axial spatial resolution of the simulated imaging system. The analyzed areas are sufficient for stable statistical analysis.

3.2 distribution parameter estimation

The distribution parameter was estimated from the envelope amplitude of RF echo signal. Nakagami parameter μ_{L} (i.e., the normal liver structure part) was fixed a *priori*. the parameters $\mu_{\mathrm{F}}, \omega_{\mathrm{L}}, \omega_{\mathrm{F}}$, and α are optimized based on the Kullback-Leibler (KL) divergence in Eq. 3.

In Eq. 3, $q(x)$ and $p(x)$ were the PDF of the simulated echo amplitude envelope and the fitted distribution model (i.e., double Nakagami model function (Eq.1) or single Nakagami models (Eq.2). Eq.3 indicates that when the two functions are similar, then D_{KL} is small. The parameter combination of smallest D_{KL} was computed with 'fminserch' (in Matlab) which is the optimization method without a derivative function.

$$D_{\mathrm{KL}}(p||p_{mix}) = \sum_{x=0}^{\infty} q(x) \log \frac{q(x)}{p(x)}. \quad (3)$$

4.Results and discussions

Figure 1 shows the PDF of the echo amplitude envelope when the lipid droplets is 2 sc/R_{vol}. The echo amplitude envelope was normalized with the root mean square of the amplitude envelope. The best fitted single and double Nakagami model are superimposed. Double Nakagami method is fitted better from low amplitude to high amplitude than singe Nakagami model.

Figure 2 illustrates D_{KL} of previous and proposed methods in each number of lipid droplets per R_{vol}. In the proposed method, fitting accuracy is stably higher than single Nakagami model for all the number of lipid droplets.

Figure 3 illustrates the estimated Nakagami parameters (μ and μ_{F}) in each number of lipid droplets per R_{vol}. The horizontal dashed line shows μ (μ_{L} in the double Nakagami method) estimated from the distribution structure by single model. In the single Nakagami model, μ decreases is supposed to enhance a small number of lipid droplets, especially it becomes impossible to distinguish from the luminal structure alone around 3 sc/R_{vol}. On the other hand, the double Nakagami method has a positive correlation with the number of lipid droplets and it can be confirmed that μ_{F} gradually increases stepwise from normal liver structure continuously. Therefore, this results suggest that the double Nakagami method can quantify number of lipid droplets from low to high lipid droplet density in various condition of livers.

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