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Novel method of lipid content quantification using double-Nakagami distribution model in rat liver steatosis

二成分仲上モデルを用いた ラット脂肪肝中の脂肪量定量手法の開発

Kazuki Tamura[1‡], Jonathan Mamou[2], Kenji Yoshida[3], Hiroyuki Hachiya[4], Tadashi Yamaguchi[3]([1]Hamamatsu Univ. School of Medicine; [2]Riverside Research; [3]Chiba Univ.; [4]Tokyo Institute of Technology)

田村和輝[1‡] Mamou Jonathan[2] 吉田憲司[3] 蜂屋 弘之[4] 山口匡[3] ([1]浜松医科大学 [2]Riverside Research [3]千葉大学 [4]東京工業大学)

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1. Introduction

Ultrasonography plays an important role in diagnostic imaging. However, ultrasound images are difficult for radiologists to use because the images include a lot of noise, known as a speckle pattern. A more specific diagnosis is required; more valuable information can be obtained using quantitative ultrasound (QUS) because the spatial resolution of the image is insufficient for observation at the tissue structure scale. An approach to quantifying the difference between the echo amplitude probability density and Rayleigh distribution was proposed by Burckhardt.[1)] Some probability density functions (PDFs) have been proposed for characterizing ultrasound echo signals. The multi-Rayleigh model is composed of several Rayleigh distributions that have different variances reflecting the scatter conditions in each type of tissue. The multi-Rayleigh model was mainly proposed for the evaluation of liver fibrosis.[2)] However, the PDF model is limited to structures at the same scale as the spatial resolution and requires a sufficient scatter density.

The spatial resolution of high-frequency ultrasound (HFU) has improved. The improvement in the resolution may change the relationship between the scattering structure and the PDFs. Our group developed the Double Nakagami (DN) PDF model for adopting HFU RF echo signals.[3)] This study proposes a steatosis area enhancement filter which is based on dissociation from a healthy liver parameter distribution.

2. Method

i. Double Nakagami distribution model

This model can be expressed using the following PDF: [3)]

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

where p_L and p_F are two Nakagami distributions used to model the luminal structure in a healthy liver and the distribution of lipid droplets, respectively. μ_L was given the Nakagami parameter[4)] of a healthy liver obtained from healthy rat livers.

Parameter estimation was applied to a normalized echo by replacing ω_{L} with $\omega_{\mathrm{L}} = 1 - \omega_{\mathrm{F}}\alpha \,/\, (1-\alpha)$. Then, Nelder-Mead optimization was applied to estimate the remaining three parameters of the model: μ_{F}, α and ω_{F}. The proposed algorithm was applied to the experimental echo data. To perform parameter estimation, RF data were separated into three dimensional regions (five times the spatial resolution in each dimension).

ii. Weighting filter method for detecting steatosis area

Polar plot-based visualization was applied to three samples of each steatosis progress (healthy, mild fatty and serious fatty livers).

The visualization used a two-dimensional (2D) histogram within Cartesian coordinates. Bin width was 0.05 for each direction. The 2D histogram counts were normalized by the total ROI number of each sample.

For easy visualization of the fatty liver structure area, the superimposed image required a suppression filter which masked the healthy liver structure area. The filter was developed using three healthy liver samples. The “healthy liver structure parameter” was defined in the polar plot area where the 2D histograms had the top 90% frequency. Finally, the superimposed image was composed with ROIs which were located outside the healthy liver structure parameter.

iii. Echo signal acquisition

The echo datasets were acquired experimentally from excised healthy (0 % of hepatocytes contain lipid droplets), moderately fatty (10 to 20 %), and severely fatty (~70 %) rat livers using a 15-MHz single-element transducer (Olympus NDT V328). All animal protocols were approved by the Animal Experiment Committee of Chiba University.

RF echo signal data were acquired from the rat livers immediately after they were excised. One liver lobe from a total of five lobes was placed in a water tank that was filled with degassed water during the measurements.

[1]k.tamura@hama-med.ac.jp

3. Results and Discussion

i. Double Nakagami parameter estimation

Figure 1. is a 2D histogram of the estimation results. The color range shows the probability density of the estimated parameter distribution. Mild and serious fatty liver samples (**Fig. 1**(a) and (b)) are distributed on the outer part of the mean healthy liver plot (**Fig. 1**(c)).

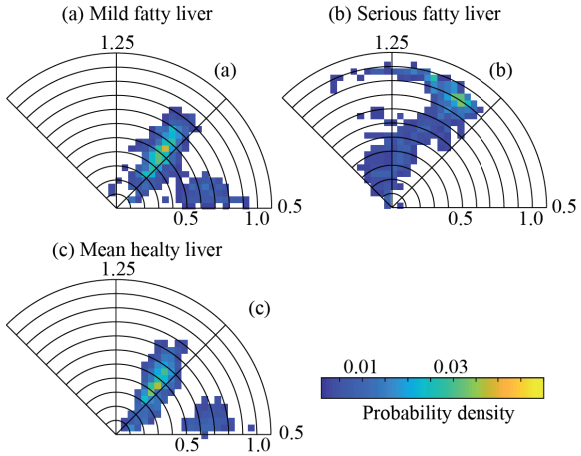

Fig. 1 Estimated DN-PDF parameter distribution. Rotation direction and radial direction are μ_F and the lipid droplets echo intensity (α times ω_F), respectively. (a) and (b) are the estimation results for the mild and serious fatty live samples, respectively. Plot color illustrates the probability of the estimation result distribution.

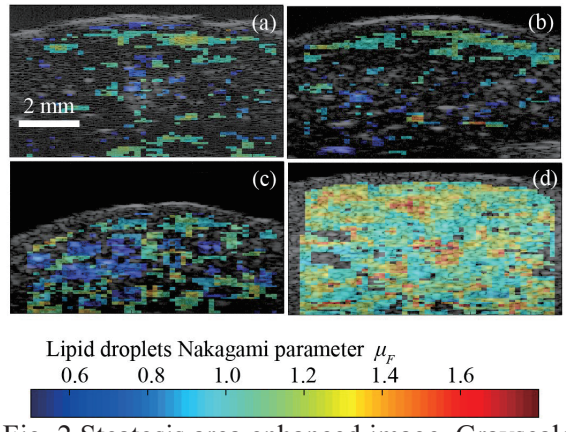

Fig. 2 Steatosis area enhanced image. Grayscale images are log compressed echo images. Superimposed color images illustrate the corresponding estimated μ_F parameters which were enhanced steatosis area. (a), (b), (c) and (d) are representative images of healthy (0 % of hepatocyte has lipid droplets), mild (10 %), mild fatty liver (20 %) and serious fatty liver (100 %), respectively

ii. Weighting filter method

Figure 2. displays the weighted Nakagami parameter images. Uncolored areas are estimated to have the characteristics of healthy liver tissue because the parameter is located inside the mean healthy liver distribution (**Fig. 1** (c)). Comparing each of the steatosis stage images (i.e., Fig. 1 (a)–(d)) shows that the colored area increases with the progression of steatosis. Nevertheless, a difference exists in the colored areas in **Fig. 2** (b) and (c), despite the fact that both are moderately fatty liver images. This is because the difference in the number density of lipid droplets was directly reflected in the analysis results. In addition, comparing **Fig. 2** (c) and (d), Almost the whole region is colored in both results because the lipid droplets were distributed through the whole liver. The Nakagami parameter of lipid droplets was significantly high in the severe fatty liver samples. This indicates that the number density of lipid droplets is larger in the liver shown in **Fig. 2** (d) than in the liver shown in **Fig. 2** (c).

4. Conclusion

The weight filter suppressed overestimation of healthy liver tissues and allowed a quantitative evaluation of the number of lipid droplets with high sensitivity from an early stage in the fatty liver.

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