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Nakagami shape parameter 2D image for visualization of internal biological tissue heat denatured by radiofrequency ablation

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1. Introduction

Radiofrequency (RF) ablation (RFA) is one of the most workable option for radically curing hepatocellular carcinoma. Metastatic liver cancer is also treated with RFA. In RFA, malignant tumor tissue is cauterized by RF current flowing from an ablation antenna inserted into a cancerous liver. While RFA procedure is operated, the cauterization target area is monitored with ultrasound B-mode image. A day after RFA procedure is finished, it is necessary to evaluate based mainly on a computed tomography image whether the whole region of diseased tissue is completely cauterized. If not, RF procedure needs to be carried out again. Besides, the incomplete cauterization can lead to a catastrophic complication, neoplastic seeding. Tumor cell seeding results from being disseminated by the ablation antenna plucked out from the tumor tissue cauterized incompletely. According to a study to evaluate the risk of RFA procedure, the rate of tumor seeding after RFA for hepatocellular carcinoma is 0.9%.[1)] Hence, incorrect evaluation of RFA treatment is a crucial issue.

It was reported that the Nakgami shape parameter m obtained from statistical analysis of ultrasonic scattered echoes varies with a change in scatterer density of the medium.[2,3)] The m value increases with increasing the scatterer concentration in the medium. The scatterer concentration in the biological tissue is presumed to vary dramatically when the biological tissue is thermally denatured with RF current; thus, the thermal denaturalization of the biological tissue can be detected with a change in m value. In this study, we present our study results that the region of tissue denatured due to heat could be visualized with two-dimensional (2D) m value maps.

2. Experimental setup

In this study, two healthy porcine liver specimens were cauterized by RF current using an RFA system (Japan Lifeline ARFA-GEN200). In order to make difference in degree of tissue thermal denaturization, one (specimen A) was ablated with the energy at P = 15 W, and the other (specimen B) was ablated with the higher energy at P = 20 W of the two specimens. The reference temperatures at five points were measured with five thermocouple temperature sensor probes inserted into the tissue. Ultrasound echoes scattered from the tissue specimens were measured at intervals of 30 seconds by an ultrasonic measurement system (Microsonic RSYS0016) with a linear array transducer (Hitachi UST-5412). The 2D Nakagami parametric image was processed by conducting statistical analysis of ultrasonic scattered echoes with custom-made software written in MATLAB R2021a. The experimental setup is shown in **Fig. 1**. After the RFA treatment was finished, the tissue specimens were cut into two to confirm the appearance of heat denaturation inside the tissues.

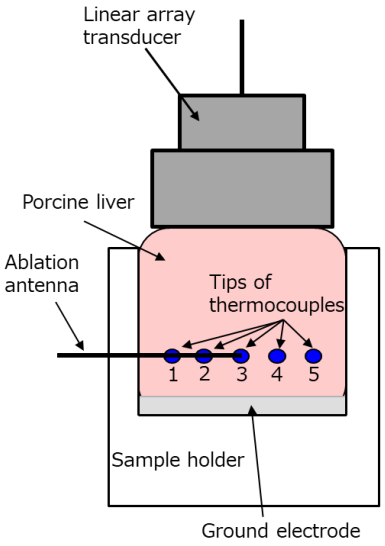

Fig. 1. Experimental setup.

3. Analysis and discussion

In the convolution layer of processing 2D m value map, the histograms of envelopes of the analytic ultrasonic signals obtained with the Hilbert transformation were created in each region of interest (ROI) by a sliding window overlapped with an overlapping ratio of 50% between ROIs. The Nakagami shape parameter m for each ROI was

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estimated by fitting the Nakagami distribution function to the histograms of the envelope. The Nakagami distribution function with the shape parameter m is given by

$$f_N(r) = \frac{2m^m r^{2m-1}}{\Gamma(m)\Omega^m} \exp\left(-\frac{m}{\Omega} r^2\right) U(r), \quad (1)$$

where $\Gamma(\cdot)$ and $U(\cdot)$ are the gamma function and unit step function, respectively, r is the amplitude of the ultrasound backscatter envelope, and Ω is a scaling parameter. Meanwhile, in order to evaluate the goodness of fitting of the Nakagami distribution function to the histograms, the normalized mean squared error (NMSE) was calculated as

$$\mathrm{NMSE} = \frac{\sum_{i=1}^{M} \{h(r_i) - f_N(r_i)\}^2}{\sum_{i=1}^{M} h(r_i)^2}, \quad (2)$$

where M and $h(r_i)$ are the number of bins and the height of bin at each amplitude of envelopes of ultrasound scattered echoes. In the pooling layer, the weighted average (WAVG) of m was calculated with 1 - NMSE as the weight (w) by

$$\mathrm{WAVG} = \frac{\sum_{j=1}^{ns} w_j \cdot m_j}{\sum_{j=1}^{ns} w_j}, \quad (3)$$

where ns is the sample size. In the calculation of WAVG for m, the sliding window with an overlap ratio of 50% was operated. Then the 2D m value images indicating WAVG of m were generated in the output layer.

Figures 2a and **2b** show the gray-scale B-mode images, the parula-scale m value maps indicating WAVG of m, and the photographs of the cross sections of specimen A and B, respectively. The location of the tip of the ablation antenna is enclosed by the *dotted orange line* in the B-mode image. The areas enclosed by the *dotted red line* and the *dotted blue line* in the B-mode image obtained from specimen A indicate the area on the porcine liver tissue and the area on the sample holder. In the process of generating the 2D m value map for specimen A, WAVG of m was calculated on the area enclosed with the *dotted red line* in Fig. 2a. In the 2D parula-scale images indicating WAVG of m for specimen A, the slight increase in the m value brightness was observed. In contrast, the m value brightness rapidly increased after being heated with RF current at 90 s in the 2D parula-scale images obtained from specimen B. The rapid elevation in the m value brightness implies a scatterer density increase in the tissue. In the photographs of the cross sections of specimens A and B, the degree of thermal denaturation of the tissue heated with the energy at P = 15 W is low, while that of the tissue cauterized with the energy at P = 20 W is quite high due to thermocoagulation. The steep increase in the m value brightness on the parula-scale m value maps for specimen B indicates the increase of scatterer density inside the liver tissue due to the thermocoagulation.

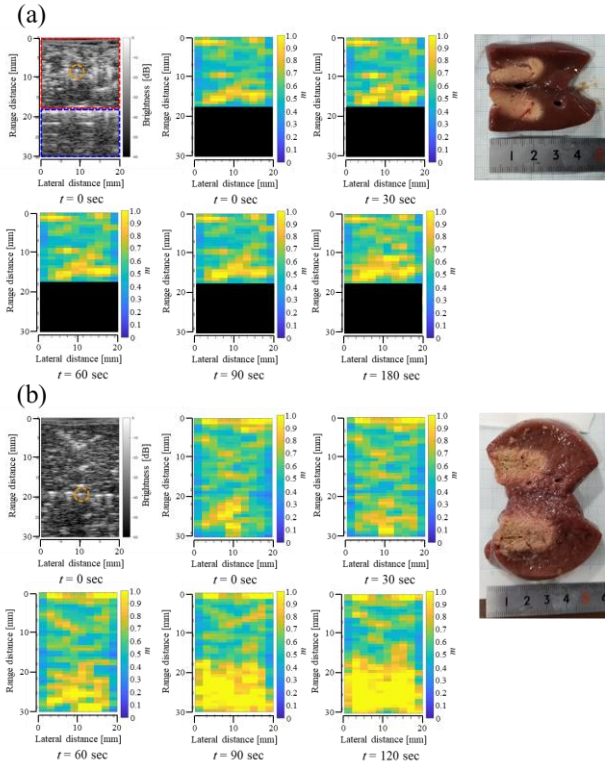

Fig. 2. B-mode image, m value maps, and photograph of cross section of tissue for (a) specimen A and (b) specimen B.

4. Conclusion

In this study, we showed that thermocoagulation of porcine liver tissue induced by RFA could be clearly visualized on 2D parula-scale images indicating WAVG of m. The result proposes that the acoustic method is useful for diagnosing treatment effect of RFA for hepatocellular carcinoma and metastatic liver cancer.

References

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