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Window-modulated compounding Nakagami imaging for ultrasound tissue characterization

Po-Hsiang Tsui [a,b,*], Hsiang-Yang Ma [a,c], Zhuhuang Zhou [d], Ming-Chih Ho [e], Yu-Hsin Lee [e]

[a] Department of Medical Imaging and Radiological Sciences, College of Medicine, Chang Gung University, Taoyuan, Taiwan
[b] Institute for Radiological Research, Chang Gung University and Chang Gung Memorial Hospital, Taoyuan, Taiwan
[c] Graduate Institute of Clinical Medical Sciences, College of Medicine, Chang Gung University, Taoyuan, Taiwan
[d] Biomedical Engineering Center, College of Life Science and Bioengineering, Beijing University of Technology, Beijing, China
[e] Department of Surgery, National Taiwan University Hospital and College of Medicine, National Taiwan University, Taipei, Taiwan

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ABSTRACT

Ultrasound Nakagami parametric imaging is a useful tool for tissue characterization. Previous literature has suggested using a square with side lengths corresponding to 3 times the transducer pulse length as the minimum window for constructing the Nakagami image. This criterion does not produce sufficiently smooth images for the Nakagami image to characterize homogeneous tissues. To improve image smoothness, we proposed window-modulated compounding (WMC) Nakagami imaging based on summing and averaging the Nakagami images formed using sliding windows with varying window side lengths from 1 to N times the transducer pulse length in 1 pulse length step. Simulations (the number densities of scatterers: 2–16 scatterers/mm^2) and experiments on fully developed speckle phantoms (the scatterer diameters: 20–106 μm) were conducted to suggest an appropriate number of frames N and to evaluate the image smoothness and resolution by analyzing the full width at half maximum (FWHM) of the parameter distribution and the widths of the image autocorrelation function (ACF), respectively. In vivo ultrasound measurements on rat livers without and with cirrhosis were performed to validate the practical performance of the WMC Nakagami image in tissue characterization. The simulation results showed that using a range of N from 7 to 10 as the number of frames for image compounding reduces the estimation error to less than 5%. Based on this criterion, the Nakagami parameter obtained from the WMC Nakagami image increased from 0.45 to 0.95 after increasing the number densities of scatterers from 2 to 16 scatterers/mm^2. The FWHM of the parameter distribution (bins = 40) was 13.5 ± 1.4 for the Nakagami image and 9.1 ± 1.43 for the WMC Nakagami image, respectively (p-value < .05). The widths of the ACF for the Nakagami and WMC Nakagami images were 454 ± 5.36 and 458 ± 4.33, respectively (p-value > .05). In the phantom experiments, we also found that the FWHM of the parameter distribution for the WMC Nakagami image was smaller than that of the conventional Nakagami image (p-value < .05), and there was no significant difference of the ACF width between the Nakagami and WMC Nakagami images (p-value > .05). In the animal experiments, the Nakagami parameters obtained from the WMC Nakagami image for normal and cirrhotic rat livers were 0.62 ± 0.08 and 0.92 ± 0.07, respectively (p-value < .05). The results demonstrated that the WMC technique significantly improved the image smoothness of Nakagami imaging without resolution degradation, giving Nakagami model-based imaging the ability to visualize scatterer properties with enhanced image quality.

1. Introduction

The ultrasound B-mode image is a crucial tool for clinical diagnosis. B-mode intensity relies on several factors, such as signal and image processing, system settings, and user operations [1–3], and thus the B-scan only provides a qualitative description of the morphology, without quantifying tissue properties. To complement the conventional B-scan for tissue characterization, many quantitative ultrasound (QUS) methods and functional ultrasound imaging techniques were explored and developed, such as backscatter [4–6], attenuation [7–9], sound speed [10,11], spectrum [12–15], and elastography [16–18]. The statistical analysis of the ultrasound

* Corresponding author at: Department of Medical Imaging and Radiological Sciences, College of Medicine, Chang Gung University, 259 Wen-Hwa 1st Road, Kwei-Shan, Tao-Yuan 333, Taiwan. Tel.: +886 3 2118800; fax: +886 3 2118700.
E-mail address: tsuiph@mail.cgu.edu.tw (P.-H. Tsui).

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0041-624X/

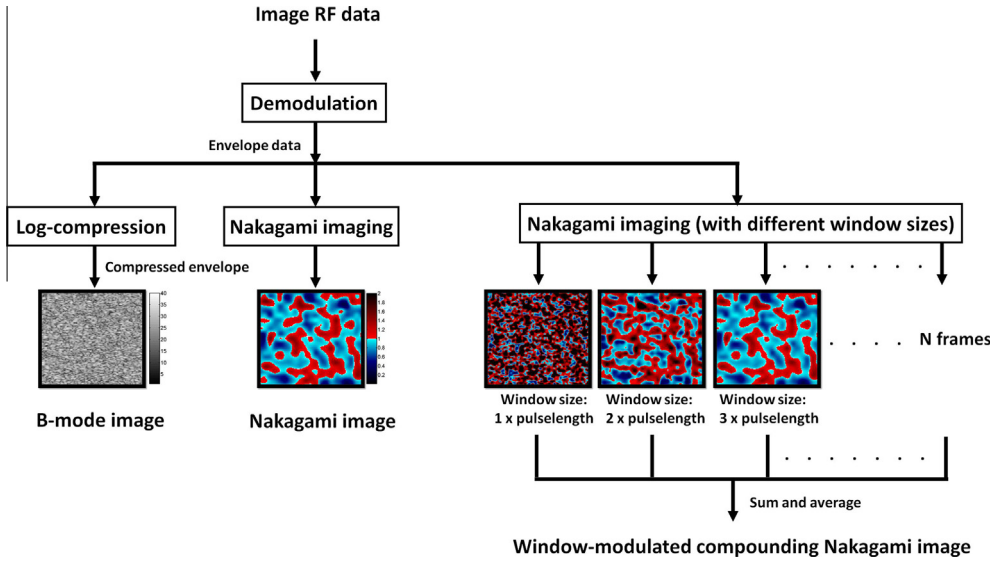

Fig. 1. Block diagram for the algorithm of WMC Nakagami imaging. The WMC Nakagami image is obtained from summing and averaging the Nakagami images formed using sliding windows with varying window side lengths from 1 to *N* times the transducer pulse length in 1 pulse length step.

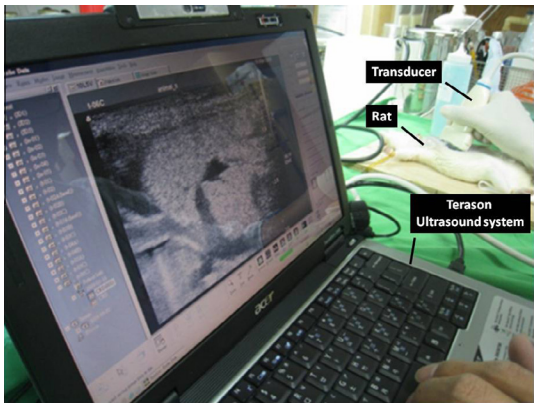

Fig. 2. Experimental arrangement for in vivo ultrasound measurements on rat livers.

backscattered signals is also an important approach used to characterize tissues. Studies have shown that the raw ultrasound radio frequency (RF) signals backscattered from tissues contain valuable information associated with the shape, size, density, and other properties of scatterers in a tissue [19–21]. Based on the randomness of ultrasonic backscattering, mathematical statistical distributions can be used to model the probability density function (pdf) of the backscattered echoes to complement the B-mode image for evaluating scatterer properties in tissues.

The Rayleigh distribution was the first model used to describe the statistics of the ultrasonic backscattered signals. The pdf of the backscattered envelope follows the Rayleigh distribution when the resolution cell of the ultrasonic transducer contains numerous randomly distributed scatterers [22,23]. Scatterers in most biological tissues have numerous possible arrangements. If the resolution cell contains scatterers that have randomly varied scattering cross-sections with a comparatively high degree of variance, the envelope statistics are pre-Rayleigh distributions. If the resolution cell contains periodically located scatterers in addition to randomly distributed scatterers, the envelope statistics are post-Rayleigh distributions. This is why non-Rayleigh statistical models were developed to encompass various backscattering conditions in medical ultrasounds [23–26].

The Nakagami model initially proposed to describe the statistics of radar echoes [27] has been applied to the statistical analysis of backscattered signals [28–31] and attracted researcher attention. Compared to other non-Rayleigh distributions, the Nakagami distribution has less computational complexity and describe all of the scattering conditions in medical ultrasound, including pre-Rayleigh, Rayleigh, and post-Rayleigh distributions. The Nakagami parameter has been shown to have the ability to distinguish various scatterer properties [32–34]. Nakagami compounding distributions have also been developed to better fit the statistical distribution of backscattered envelopes [35–39].

Ultrasound Nakagami imaging based on the Nakagami parametric map is a new development for visualizing the scatterer properties in clinical applications. Various research groups have recently demonstrated that the Nakagami image provides information on scatterer arrangements and concentrations to complement the B-scan for tissue characterization [40–44]. The sliding window technique is a frequently used method for constructing ultrasound parametric images. The choice of the window size is a trade-off between the image resolution and the stability of the estimator (i.e., the smoothness of the parametric image) [45]. To obtain an enhanced image resolution without affecting the stability of the parameter estimation, previous studies have suggested using a square window with a side length equal to 3 times the pulse length of the incident ultrasound for Nakagami image construction [40,41].

Image smoothness is also a critical consideration, particularly for using Nakagami imaging to characterize homogeneous tissues. For this reason, the smoothness of the Nakagami image needs to be improved. Using the sliding window with the suggested size, it is difficult to provide a smooth estimate of the parameter for Nakagami imaging. Previous results have indicated that the Nakagami image of a homogeneous medium simultaneously contains pre-Rayleigh and post-Rayleigh regions [40,41]. On one hand, the number densities of scatterers in a homogeneous medium may differ locally to result in local differences in backscattered statistics. On the other hand, this is also because of the lack of smoothness of the Nakagami image produces larger variations between local Nakagami parameters. As stated earlier, the determination of the window size is a result of the compromise between the resolution and the smoothness. Using a single sliding window with a specific size to construct the Nakagami image, it is nearly impossible to