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Ultrasound window-modulated compounding Nakagami imaging: Resolution improvement and computational acceleration for liver characterization

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ABSTRACT

Ultrasound Nakagami imaging is an attractive method for visualizing changes in envelope statistics. Window-modulated compounding (WMC) Nakagami imaging was reported to improve image smoothness. The sliding window technique is typically used for constructing ultrasound parametric and Nakagami images. Using a large window overlap ratio may improve the WMC Nakagami image resolution but reduces computational efficiency. Therefore, the objectives of this study include: (i) exploring the effects of the window overlap ratio on the resolution and smoothness of WMC Nakagami images; (ii) proposing a fast algorithm that is based on the convolution operator (FACO) to accelerate WMC Nakagami imaging. Computer simulations and preliminary clinical tests on liver fibrosis samples ($n = 48$) were performed to validate the FACO-based WMC Nakagami imaging. The results demonstrated that the width of the autocorrelation function and the parameter distribution of the WMC Nakagami image reduce with the increase in the window overlap ratio. One-pixel shifting (i.e., sliding the window on the image data in steps of one pixel for parametric imaging) as the maximum overlap ratio significantly improves the WMC Nakagami image quality. Concurrently, the proposed FACO method combined with a computational platform that optimizes the matrix computation can accelerate WMC Nakagami imaging, allowing the detection of liver fibrosis-induced changes in envelope statistics. FACO-accelerated WMC Nakagami imaging is a new-generation Nakagami imaging technique with an improved image quality and fast computation.

1. Introduction

The statistical distribution of ultrasonic backscattered envelopes depends on the properties of microstructures in tissues [1]. Ultrasound Nakagami imaging is a recent and attractive Nakagami statistical model-based parametric mapping technique for visualizing changes in envelope statistics. Systematic studies reported that ultrasound Nakagami imaging can provide additional information for improving tissue characterization in several conditions, such as in liver fibrosis detection [2,3], breast tumor classification [4,5], radiotherapy evaluation [6,7], cataract (a clouding of the lens in the eye) detection [8], skin characterization [9], blood clot characterization [10], vascular flow analysis [11,12], thermal ablation monitoring [13,14], and characterizing the structural anisotropy in the myocardium [15].

The sliding window technique is typically used for constructing an ultrasound parametric image [12–17]. Ultrasound Nakagami imaging adopts this technique, and images are constructed using a window that slides on the envelope image obtained from the demodulation of beamformed radiofrequency (RF) signals and estimates the local Nakagami parameters for imaging [8,18]. The resolution of a parametric image is determined by the window size. Using a small window endows a parametric image with a favorable resolution but simultaneously results in the unstable estimation of ultrasound statistical parameters because of limited data points. A

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large window sacrifices the image resolution, but it improves parameter estimation and image smoothness. Determining an appropriate window size for constructing an ultrasound statistical parametric image is a trade-off between image resolution and parameter estimation. For ensuring reliable tissue characterization through appropriate parameter estimation, most studies used windows larger than at least one spatial resolution of the B-scan to construct the Nakagami image [6,8,18,19]. To improve the resolution and smoothness of the Nakagami image, the small-window Nakagami imaging technique based on the kernel density function was further investigated [20]. Subsequently, window-modulated compounding (WMC) Nakagami imaging was proposed for improving image smoothness without affecting the resolution [21].

Further enhancement of the resolution and computational efficiency of ultrasound WMC Nakagami imaging is the focus of this study. In the WMC Nakagami imaging algorithm, two parameters may affect the WMC Nakagami image resolution, the window size and the window overlap ratio used for sliding the window on the envelope image. The WMC Nakagami image is constructed through summing and averaging the Nakagami images formed by sliding windows of varying window side lengths ranging from 1 to N times the transducer pulse length in one pulse-length step (the parameter N was set at 7 to reduce the estimation error by <5%) [21]. Thus, the window size in the algorithm is fixed. However, the window overlap ratio possibly affects the resolution of the WMC Nakagami image. A low window overlap ratio results in a low line density of the WMC Nakagami image. The decreased line density decreases the spatial resolution of an image [22], and therefore providing sufficient spatial information to describe the region of interest (ROI) is difficult. A high window overlap ratio results in a high line density, possibly improving the WMC Nakagami image resolution; the computational efficiency and speed, however, may reduce because a large amount of data must be processed. Current relevant literature does not address these fundamental questions, which are crucial in ultrasound parametric imaging. In this study, certain unanswered questions regarding the WMC Nakagami imaging were explored, including (i) what is the effect of the window overlap ratio on the resolution and smoothness of the WMC Nakagami image? (ii) how can the fast WMC Nakagami imaging be implemented if large window overlap ratios are used? and (iii) how does the fast WMC Nakagami imaging perform in clinical tissue characterization?

In the following sections, the theoretical background and the rationale behind designing a fast algorithm based on the convolution operator (FACO) for WMC Nakagami imaging are introduced. Computer simulations and clinical measurements on liver fibrosis *in vivo* were conducted for validations. The results demonstrated that the maximum window overlap ratio (based on one-pixel shifting) significantly improves the image resolution and smoothness. Compared with the conventional algorithm, the proposed FACO-based algorithm largely accelerates the computation of WMC Nakagami imaging for liver fibrosis detection.

2. Theoretical background

2.1. Nakagami distribution

In general, the statistical distributions of the backscattered signals of the tissues are of three types [10,23,24]: (i) Rayleigh distribution, caused by a large number of randomly distributed scatterers in the resolution cell of the ultrasound transducer, (ii) pre-Rayleigh distribution, caused by randomly varying scattering cross-sections of the scatterers in the resolution cell with a comparatively high degree of variance, and (iii) post-Rayleigh distribution, caused by periodically located scatterers in addition to randomly distributed scatterers in a resolution cell. The different backscattered statistics from tissues can be described according to the Nakagami statistical distribution [1,25,26]. The probability density function $f(r)$ of the envelope R under the Nakagami distribution is given by [25,26]

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

where $\Gamma(\cdot)$ and $U(\cdot)$ are the gamma and unit step functions, respectively. Let $E(\cdot)$ denote the statistical mean. The scaling parameter Ω and the Nakagami parameter m associated with the Nakagami distribution can be respectively obtained using

$$\Omega = E(R^2) \tag{2}$$

and

$$m = \frac{[E(R^2)]^2}{E[R^4] - [E(R^2)]^2}. \tag{3}$$

The Nakagami parameter is the shape parameter that determines the Nakagami statistical distribution. As the Nakagami parameter varies from 0 to 1, the corresponding envelope statistics change from a pre-Rayleigh to a Rayleigh distribution; a Nakagami parameter >1 means that the backscattered statistics conform to a post-Rayleigh distribution. Hence, the Nakagami parameter can be used for detecting the arrangement of scatterers in the tissue for tissue characterization [10,23].

2.2. Nakagami imaging

An ultrasound Nakagami image is essentially a Nakagami parametric map comprising local Nakagami parameters. The Nakagami imaging algorithm was cited in several studies [2,3,10,18]. First, the raw beamformed RF signals (i.e., the scan lines of an image) are demodulated to obtain the envelope image without log-compression $\widehat{R}(x,y)$, as follows:

$$\widehat{R}(x,y) = \begin{bmatrix} r_{(1,1)} & r_{(1,2)} & \cdot & \cdot & r_{(1,x)} \\ r_{(2,1)} & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ r_{(y,1)} & \cdot & \cdot & \cdot & r_{(x,y)} \end{bmatrix}. \tag{4}$$

Subsequently, a window measuring $l \times k$ in size within the uncompressed envelope image is used for obtaining the local backscattered envelope R_w:

$$R_w = \begin{bmatrix} r_{(i,j)} & r_{(i,j+1)} & \cdot & \cdot & r_{(i,j+k)} \\ r_{(i+1,j)} & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ r_{(i+l,j)} & \cdot & \cdot & \cdot & r_{(i+l,j+k)} \end{bmatrix}, \tag{5}$$

where i and j are the location corresponding to the upper left corner of the window. R_w is used for estimating the local Nakagami parameter m_w using Eq. (6) [25], which is assigned as the new pixel located at the center of the window:

$$m_w = \frac{[E(R_w^2)]^2}{E[R_w^4] - [E(R_w^2)]^2}. \tag{6}$$

Notably, R_w^2 and R_w^4 are the second and fourth powers of the Hadamard product of R_w. In general, the nth power of the Hadamard product of R_w is denoted as