Tissue Characterization on Ultrasound Harmonic Signals using Nakagami Statistics

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Abstract

Quantitative ultrasound (QUS) imaging provides a way to characterize biological tissue. The QUS estimates can be obtained from the envelope statistics. Previous studies are mainly based on the whole backscattered signals analysis. However, the ultrasound propagation is a nonlinear process and the harmonic signals can therefore reveal the nonlinear nature of a biological medium. The present study investigates the statistics of harmonic signal envelopes to relate the distribution parameters to the nonlinear coefficients. The main results demonstrate that the distributions exhibit a different behavior for fundamental and harmonic signals and that media with different nonlinearities can be distinguished, when using Nakagami statistics on the harmonic signal envelopes.

1. Introduction

Quantitative ultrasound (QUS) imaging aims to characterize and distinguish biological tissues, based on tissue properties like scatterer size, shape, number density and acoustic impedance. QUS methods can be divided into two groups: quantification of the backscattered radio-frequency (RF) spectrum [1] and quantification of echo signal envelope statistics [2]. In the first group, frequency-dependent backscattered information is used to quantify tissue properties. In the second group, quantification is performed by modeling the distribution of signal envelope statistics.

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Our study mainly investigates into the second group. To model the envelope distribution, a specific distribution model is chosen. The QUS parameters are the fit parameters of the observed signal envelop distribution. Previous studies have used different models, such as Gaussian, Rayleigh, Nakagami and homodyned-K distribution models [3], [4]. Among these models, Nakagami model has been praised by its analytical simplicity. This model is defined by two parameters: \( \mu \) is related to the scatterer density and \( \omega \) is a measurement of the scattered energy. Previous studies demonstrate that QUS using the envelop statistics has the ability to quantify tumors [5].

However, these studies are mainly based on the analysis of the whole backscattered signals. Considering that the ultrasound propagation is a nonlinear process and the harmonic signals can therefore reveal the nonlinear nature of a biological medium [6]. The present study investigates into the statistics of harmonic signal envelopes to relate the distribution parameters to the nonlinear coefficients.

2. Methods

2.1. Nakagami model

The Nakagami statistical model was chosen to analyze the backscattered second-harmonic signal envelopes. The probability density function (pdf) \( f \) of the ultrasonic backscattered envelope \( x \) under the Nakagami statistical model is described as:

\[
f(x) = \frac{2\mu^\mu}{\Gamma(\mu)\omega^\mu} x^{2\mu-1} \exp\left(-\frac{\mu}{\omega} x^2\right)
\]

(1)

where \( \Gamma(\cdot) \) is the gamma function. Then, the scaling parameter \( \omega \) and the Nakagami parameter \( \mu \) can be obtained from

\[
\omega = E(x^2)
\]

(2)

\[
\mu = \frac{E(x^2)^2}{E[x^2 - E(x^2)]^2}
\]

(3)

The Nakagami parameter \( \mu \) reflects the shape of the envelope pdf. The envelop statistics change from a pre-Rayleigh to a Rayleigh, and then a post-Rayleigh distribution when \( \mu \) is less than, equal to and larger than 1, respectively. From the physical point of view, \( \mu \) is related to the scatterer density and \( \omega \) is a measurement of the scattered energy.

2.2. Simulation

The CREANUIS simulator was used to simulate ultrasound images [7]. The transmitted frequency was 10MHz. The probe pitch and kerf was 214 \( \mu \)m and 12.5 \( \mu \)m, respectively. The focus was 20 mm. In the region of interest (ROI), different concentrations (2-30 scatterers/ resolution cell) and different nonlinear coefficients (\( \beta \)=3.5-50) were used. Fig. 1 is the schematic diagram of the simulation. For each concentration and each nonlinear coefficient, 50 images with randomly distributed scatterers were simulated. Each simulated image was filtered around the fundamental band or second-harmonic band, using a 3-order Butterworth filter. These filtered image envelopes were used to estimate the Nakagami parameter \( \mu \) and the scaling parameter \( \omega \), using a maximum-likelihood estimator. Therefore, for each concentration and each nonlinear coefficient, 50 values of \( \mu \) and 50 values of \( \omega \) were obtained. The average and the variance of the two parameters were calculated.
Fig. 1 Schematic diagram of the simulation

Fig. 2 Nakagami parameters (left) and the scaling parameters (right) versus number of scatterers per resolution cell for different $E$, obtained from the fundamental filtered images.

Fig. 3 Nakagami parameters (left) and the scaling parameters (right) versus number of scatterers per resolution cell for different $E$, obtained from the second-harmonic filtered images.

Fig. 4 Nakagami parameters (left) and the scaling parameters (right) versus nonlinear coefficient $E$ for different scatterers concentration, obtained from the second-harmonic filtered images.

3. Results and discussions

Fig. 2 shows the Nakagami parameters and the scaling parameters versus scatterers concentration for different $\beta$, obtained from the fundamental filtered images. Fig. 3 presents the same type of curves, but obtained from the second-harmonic filtered images. Fig. 2 shows $\mu$ increases with increasing concentration and saturates at a concentration of about 14 scatterers/ resolution cell, $\omega$ increases monotonously with increasing concentration. However, the curves corresponding to different $\beta$ coincide with each other. Fig. 3 shows the same relation for $\mu$ versus concentration, and for $\omega$ versus concentration. The important difference of Fig. 3 from Fig. 2 is that the curves are separated for different $\beta$. Fig. 4 represents the statistical results of second-harmonic filtered images in a
different way: the Nakagami parameters and the scaling parameters versus nonlinear coefficient for different scatterers concentration were drawn. It can be observed from Fig. 4 that for each concentration, $\mu$ decreases and $\omega$ increases with increasing $\beta$.

These figures demonstrate that the distributions exhibit a different behavior for fundamental and harmonic signals and that media with different nonlinearities can be distinguished, when using Nakagami statistics on the harmonic signal envelopes. The different behavior of second-harmonic envelop statistics can be explained by the fact that the medium is inhomogeneous (see Fig. 1), and with higher nonlinear parameter in the ROI, although the average envelop signal become higher, the variance of signal envelop become even higher (see Eq. 3), resulting in a reduced Nakagami parameter.

In this simulation, the attenuation was not considered. In realistic situation, the attenuation can influence the spectrum of the backscattered signals and therefore influence the statistical results of the filtered images. Experiments with attenuation will be further tested in future work.

4. Conclusion

This paper investigates the statistics of harmonic signal envelopes in quantitative ultrasound imaging, using Nakagami statistics on the harmonic signal envelopes. The simulation results show that the distributions exhibit a different behavior for fundamental and harmonic signals and that media with different nonlinearities can be distinguished.

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