STATISTICS OF ENVELOPE OF HIGH FREQUENCY ULTRASOUND SIGNAL BACKSCATTERED IN HUMAN DERMIS

HANNA PIOTRZKOWSKA, JERZY LITNIEWSKI, ELŻBIETA SZYMAŃSKA*, MARCIN LEWANDOWSKI, ANDRZEJ NOWICKI

Institute of Fundamental Technological Research, Department of Ultrasound
Pawińskiego 5b, 02-106 Warsaw, Poland
hpiotrzk@ippt.gov.pl
*CSK MSWiA Hospital, Dermatology Clinic
Wołoska 137, 02-570 Warsaw, Poland

The scattering of ultrasonic waves depends on the size, shape, acoustical properties and concentration of scatterers in tissue. In these study K distribution of the ultrasound backscatter envelope was used to assess the structural properties of the skin tissue. The custom-designed high frequency ultrasonic scanner was applied to obtain RF B-scans of the skin in vivo at the frequency of 20 ÷ 30MHz.

The results are encouraging. The K distribution models the envelope statistics very well. The parameters of the K-distribution, namely, the effective number of scatterers may be useful for the skin characterization.

INTRODUCTIONS

High frequency ultrasounds have been successfully applied in dermatology. However, conventional B-scan images of skin do not fully exploit the information contained in backscattered echoes. The additional information useful for the tissues characterization using ultrasounds can be obtained from the analysis of statistical fluctuations of the envelopes of backscattered signals received by the transducer.

The ultrasonic echo-signal is formed from the summation of partial echoes received by transducer from the scatterers located in tissue. The interference of reflected waves from randomly located scatterers results in speckles formation. When the number of partial echoes, and so scatterers involved in signal formation, is large, speckles intensity (envelope) is Rayleigh distributed. The Rayleigh distribution is not applicable when scatterers number is low. In this case, K distribution models the envelope statistics well [1,2]. We intend to apply scattered signals statistics to assess the spatial density and homogeneity of scatterers in the

skin and in this way to characterize the skin condition or to enhance medical diagnostic of skin lesions.

1. MATERIALS AND METHODS

1.1 MODEL FOR SCATTERING

When the tissues is interrogated with ultrasounds, the backscattered signal received by the transducer results from the backscattering on the individual scatterers contained in the resolution cell. The resolution cell is defined by the pulse length and the area of the beam cross-section. The echo signal *s(t)* from the resolution cell can be expressed as:

$$s(t) = Re\left\{A^* e^{j\omega t}\right\}, \tag{1}$$

where $Re\{.\}$ denotes the real part of the expression, ω is the transmitted frequency and A^* is a complex amplitude of the echo signal, described as:

$$A^* = A_{re} + jA_{im} \tag{2}$$

Assuming that there are N scatterers in the resolution cell, the quantity A^* results from summation of backscattered echoes from all scatterers:

$$A^* = \sum_{i=1}^{N} a^*_i \tag{3}$$

where a^*_i is the complex echo amplitude from the individual scatterer, expressed as:

$$a^* = a_{re} + ja_{im} = a_i e^{j\theta_i} \tag{4}$$

a_i depends on the shape, size and acoustical properties of i^{th} scatterer and θ_i is the phase of the signal backscattered from the individual scatterer and it depends on the scatterer's position.

The details of scattering by individual scatterers are unknown, thus the a_i's are modeled as random variables. Also the locations of the scatterers are unknown and θ_i's are modeled as random variables too. Thus the resulting amplitude A is also the random quantity that can be described using probability density function (PDF).

1.2 STATISTICS OF THE ECHO-ENVELOPE

Several authors [4,6], shown that the statistics of envelope of signal backscattered by a medium consisted of a large number of randomly distributed scatterers follows Rayleigh distribution. The Rayleigh distribution leads to a signal-to-noise-ratio (SNR) equaled to 1.913. SNR is defined as:

$$\mathrm{SNR} = \frac{\langle A \rangle}{\left[\langle A^2 \rangle - \langle A \rangle^2\right]^{1/2}}, \tag{5}$$

where $\langle . \rangle$ indicates the averaging operator. Any departure of SNR from the value of 1.913 can be regarded as the departure from the Rayleigh distribution.

If the number of scatterers in the resolution cell is low, or their properties are not uniformly distributed the statistics of envelope can be described in terms of K-distribution

[4,6]. Studies on the healthy skin tissues showed that K distribution was able to model the envelope PDF well. The K distribution is given by:

$$p(A) = 2\left(\frac{A}{2}\right)^{M} \frac{b^{M+1}}{\Gamma(M)} K_{M-1}(bA) \qquad A \geq 0;\ \ M, b > 0 \tag{6}$$

where

$$b = \sqrt{\frac{4M}{\langle A^2 \rangle}} \tag{7}$$

Here A is the envelope of the echo signal, $\Gamma(.)$ is the gamma function, $K_{M-1}(.)$ is the modified Bessel function of the second kind of order $(M-1)$ and b is the scaling parameter. M is called the effective number of scatterers and is expressed as:

$$M = N(1+v) \qquad\qquad v > -1 \tag{8}$$

N is the actual number of scatterers and the factor v describes the degree of homogeneity of scatterers in the resolution cell.

The M parameter can be used to distinguish between regions differing in special density of scatterer or between regions of varying scatterer's cross-section. Values of M parameter could be applied for the distinguishing between regions of normal and pathological tissue. In this approach estimation of the M parameter was obtained from the forth normalized moments r_4 of the probability density function, given in equation (6).

The normalized even moment r_4 of K distribution is given by:

$$r_4 = \frac{\langle A^4 \rangle}{\langle A^2 \rangle^2} = 2\left(1 + \frac{1}{M}\right) \tag{9}$$

M parameter can be obtained from this moment as:

$$M = \frac{2}{r_4 - 2} = \frac{2}{\frac{\langle A^4 \rangle}{\langle A^2 \rangle^2} - 2} \tag{10}$$

The experimental date (RF-echoes) obtained from the skin were processed to calculate M parameter. To this end the histogram of RF signals envelopes were determined and compared with K and Rayleigh distribution.

The goodness of the fit of K and Rayleigh distribution to the empirical histograms was evaluated using the mean square error (MSE) . The small value of MSE indicates the good fit of the distribution to the empirical data.

1.3 ATTENUATION COMPENSATION

Prior to the statistical evaluation of the received RF signals it is necessary to compensate the signal for the Time Gain Control (TGC) and for the attenuation in the tissue.

The attenuation coefficient $\alpha(f)$ of the skin was determined using the spectral difference technique based on the comparison of the power spectra of the signals backscattered at different depth in the tissue. We used the following relation to determine $\alpha(f)$:

$$\alpha(f) = -\frac{1}{4(x_2 - x_1)} ln \frac{S_2(f)}{S_1(f)} \tag{11}$$

where $S_2(f), S_1(f)$ are the power spectra of ultrasound pulses scattered in tissues, received from two tissue areas separated by the $(x_2 - x_1)$ distance.

It is important to compensate for the effects of focusing when using the spectral difference technique to estimate the attenuation coefficient from the backscattered signals emitted from the focused sources. Otherwise, in regions in front of the focus the attenuation is underestimated and in regions beyond the focus is overestimated. The depth of the focus depends on the frequency and is shorter for the high frequency waves and longer for the low frequency waves. Thus when the acoustic pulse is approaching the focus the amplitude of the pulse high frequency components increases faster than the amplitude of the lower frequencies and consequently the shifting up of the pulse spectrum occurs. For the diverging beam the opposite effect takes place. In our study we compensated the effect of diffraction or focusing using amplitude spectrum of echoes obtained from a rigid plane reflector located in water at the various axial distances from the transducer.

The pressure amplitude variation of the selected frequency components for the ultrasonic pulse passing through the focus are clearly visible in Fig.1a. For each spectral component the correction curve that compensated to the amplitude changes induced by focusing was calculated (see Fig. 1b). The attenuation coefficient was then computed using the corrected power spectra.

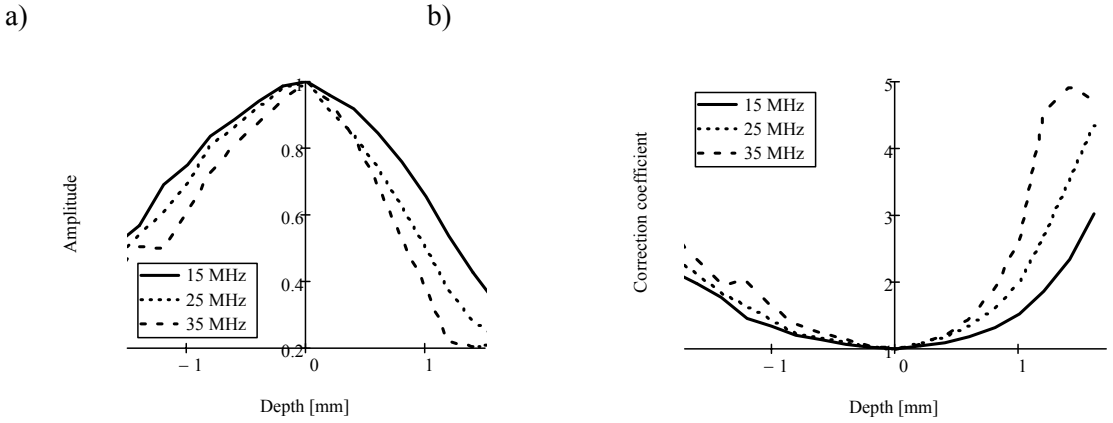

Fig.1. The amplitude of the selected frequency components of the emitted pulse spectrum measured at different depth(a), and corresponding correction curves (b). 0-depth indicates focal plane position

The following algorithm for the compensation of attenuation was used. First, the spectrum of attenuated signal (FA) was calculated. Next, the synthesis of a new signal ($F(.)$) on the basis of spectral components of the backscattered signal was performed. During the synthesis, the amplitudes of spectral components were increasing with the increasing value of the depth co-ordinate corresponding to the penetration depth and the value of frequency-dependant attenuation coefficient α. This process is described by the formula:

$$F(t_i) = \sum_{k=1}^{G} FA_k exp(\alpha \cdot f_k \cdot v \cdot t_i) \cdot exp(-j \cdot 2 \cdot \pi \cdot f_k \cdot t_i) \quad (12)$$

where k stands for the index of the spectral component, f_k denotes frequency, FA_k is a complex spectrum of backscattered signal, v denotes phase velocity of the longitudinal acoustic wave in the skin and α is the frequency-dependant attenuation coefficient, $t_i = i \cdot \delta t$ stands for time, where δt is a time step given by the signal sampling rate. The summation is carried over the whole range of frequencies of backscattered signal (G). The real part of $F(.)$ is the desired backscattered signal compensated for attenuation.

Fig. 2 shows RF line before the TGC and attenuation compensations (a), and after the TGC and attenuation compensations (b).

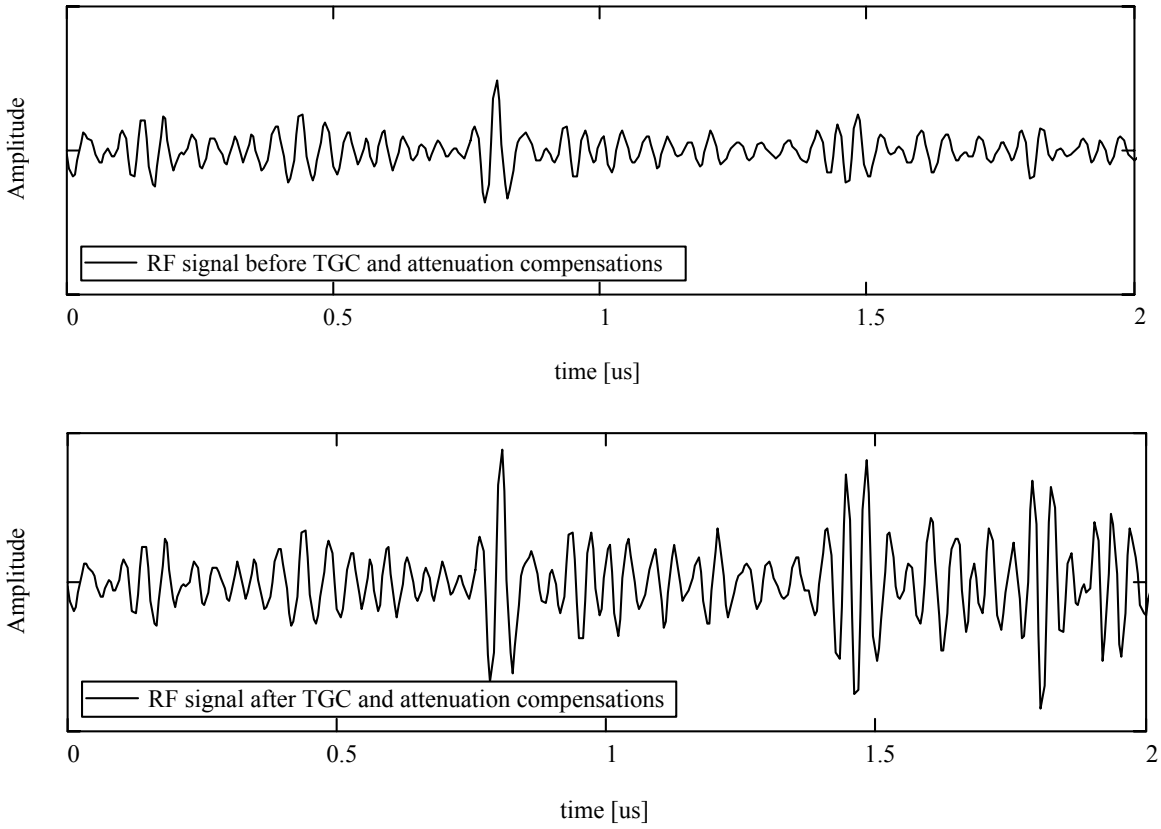

Fig.2. RF signal before (a) and after (b) the TGC and attenuation compensations

After applying the compensation procedures the Hilbert transform was used to obtain signal envelope. Fig.3. shows signal after the TGC and attenuation compensation and its envelope.

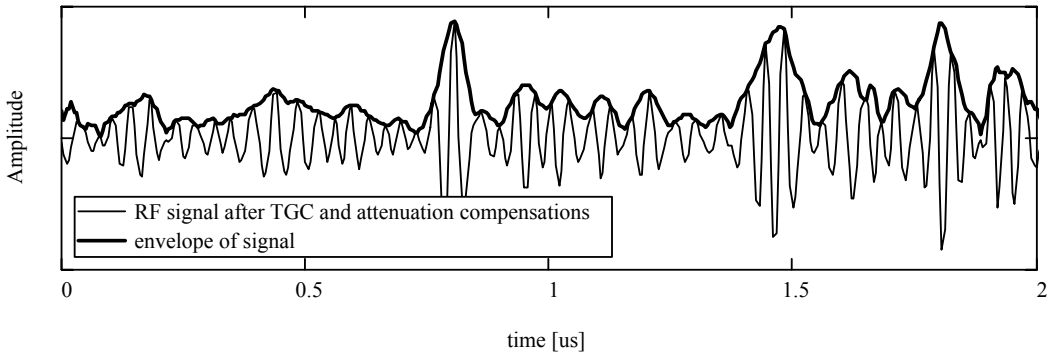

Fig.3. RF signal after the TGC and attenuation compensations and its envelope

1.4 DATA ACQUISITION

The skin scanner was used for the data from the skin acquisition. The scanner was developed in our laboratory. It performed a sector scan with the image frame rate up to 10 Hz. The transmitted signal and scattered echoes were sampled at 200 MHz frequency with 12 bits resolution. In this study we have used a 20 μm thick spherical transducer (with 3 mm diameter, 8.6 mm focal length) made of the modified PZT 37 deposited on the PZT substratum using the thick-film technology (Ferroperm, Denmark). The received sequences were envelope detected and displayed. Simultaneously, the RF data were stored separately.

The skin consists of thin layer of epidermis (thickness 0.15 mm) and thicker layer of dermis (thickness 0.5-3.5mm). Region beneath the dermis consists of subcutaneous fat, which is sometimes considered as the third layer of the skin and referred to as the hypodermis.

In this study, the measurements were performed in the dermis at a nape of a neck and at the dorsal side of the forearm. Because skin conditions depends on age the study was restricted only to the young adults. Four healthy volunteers (age about 28) were participated in this study.

2. RESULTS

This study presents the first results concerning the determination of the effective number of scatterers of the human skin.

To verify that K distribution can be used to model scattering statistical parameters of the human dermis, the histograms of experimental data were calculate and compared with the K and Rayleigh distributions. Fig. 4 shows that the histogram of echo-envelope signal of the dermis are well described by K distribution, whereas the Rayleigh distribution does not successfully fit the experimental data.

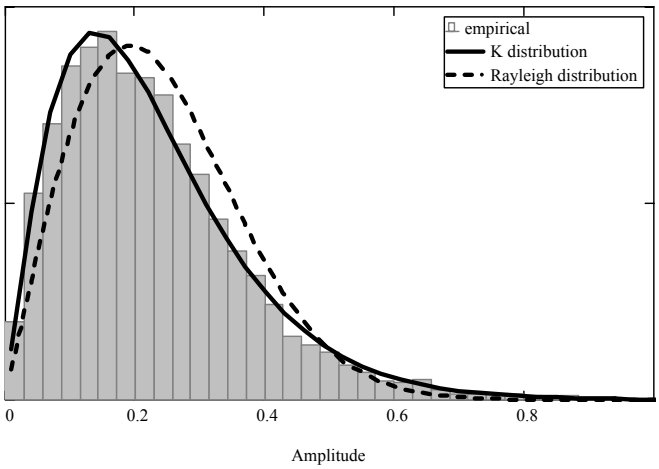

Fig.4. Theoretical Rayleigh and K distribution and histogram of empirical data obtained at the nape of neck

Tab.1. MSE coefficient calculated for the histograms of the signal envelopes measured from the skin backscatter and theoretical K and Rayleigh distributions

	nape of a neck					dorsal side of forearm				
	I case	II case	III case	VI case	MEAN	I case	II case	III case	IV case	MEAN
K	0.014	0.011	0.013	0.009	**0.011**	0.011	0.013	0.011	0.008	**0.010**
Rayleigh	0.087	0.085	0.09	0.084	**0.086**	0.076	0.081	0.087	0.089	**0.083**

The MSE calculated for the K distribution and empirical data was eight times lower than the MSE obtained for the Rayleigh distribution and the experimental data (see Table 1.)

Fig. 5a and Fig.6a show PDFs K distribution and histogram of empirical data obtained from the in vivo measurements performed in human skin at the nape of a neck (Fig.5b) and at the dorsal side of the forearm (Fig.5b).

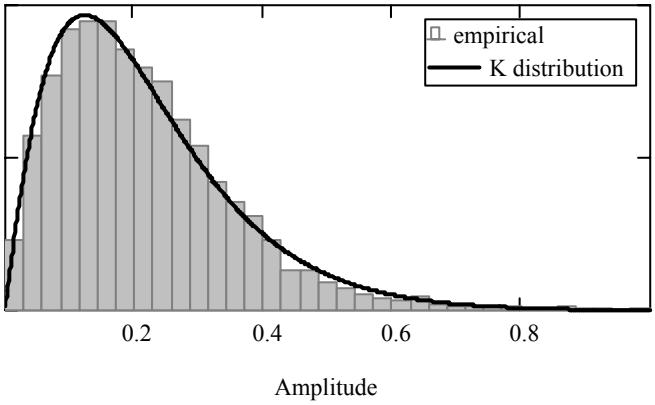

Fig.4a. The comparison of K distribution and empirical data histogram (nape of a neck)

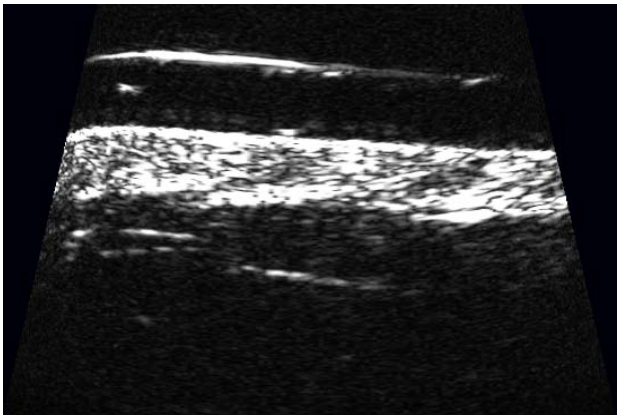

Fig.4b. B-scan image obtained from the skin at the nape of the neck. The data used in calculations were collected from the dermis (the bright area of the image)

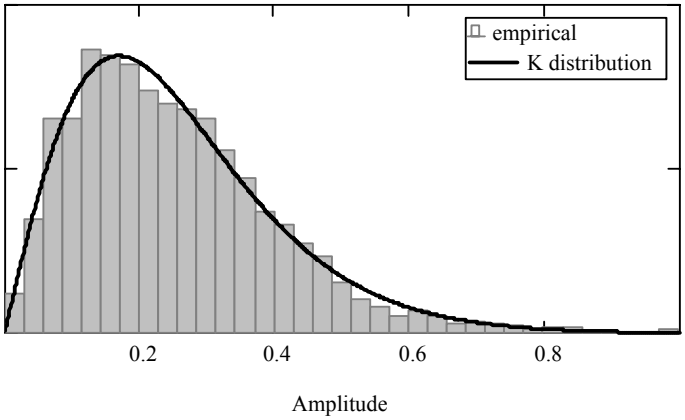

Fig.5a. The comparison of K distribution and empirical data histogram (dorsal side of the forearm)

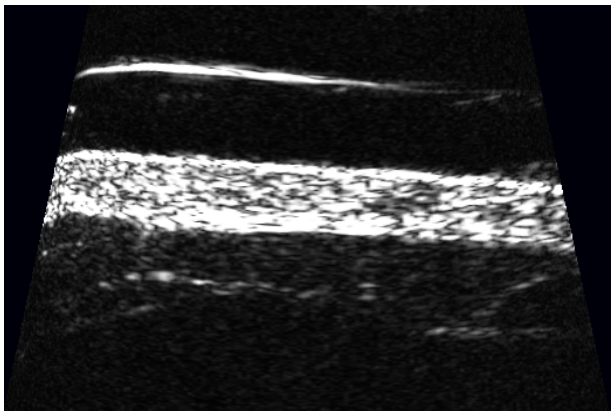

Fig.5b. B-scan image obtained from the skin at the dorsal side of the forearm

To study M parameter and to calculate its mean value the envelopes from eight sets of the RF B-scans, (4 nape of neck and 4 dorsal side of forearm) were used.

Tab.2. M and SNR coefficients calculated for experimental data obtained in vivo from the skin

	nape of a neck					dorsal side of forearm				
	I case	II case	III case	VI case	MEAN	I case	II case	III case	IV case	MEAN
SNR	1.548	1.592	1.556	1.569	**1.566**	1.709	1.648	1.457	1.583	**1.598**
M	1.811	2.50	1.988	2.195	**2.123**	4.353	3.211	1.542	2.341	**2.862**

The mean value of parameter M obtained for dermis of neck was equal 2.123 and ranged from 1.811 to 2.5. Parameters M calculated for dermis of forearm (except one case) were higher. The M varied between 1.542 and 4.53 and the averaged M calculated using results of the four cases was equal to 2.862. This difference may results from differences in anatomical structure of skin in various regions of human body and encourages us to further analysis of ultrasound data to determine e.g. effective scatterer number density.

The SNRs also were calculated. The mean values of SNRs were found to be equal to 1.566 and 1.598 for dermis of neck and dermis of forearm respectively. Reduction in SNR below value 1.913 demonstrated the need of application another kind of statistics than the Rayleigh one.

The good performance of K distribution to describe experimental date suggest that effective number of scatterers and spatial density of scatters is a high significant parameter to characterize changes in structure in human dermis.

3. CONCLUSION

The presented results are interesting and promising. We have found that the RF B-scans of skin obtained with our high frequency scanner can be used to characterize the tissue by evaluating its statistical parameters. The K distribution seems to be a good model to describe the envelope statistics of signals from the human dermis. Determined values of the effective number of scatterers are similar to those published in other studies that were analyzing the statistical prosperities of dermis [2,4,5].

The parameter M can be used to determine the effective scatterers number density and potentially it can be apply to the assessment of the tissues structural properties.

In future work we plan to concentrate on the capability of K distribution parameters to differentiate between skin lesions and normal skin area.

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