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Ultrasound Quantitative Evaluation of Human Eye Cataract

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Abstract. A technique to improve an eye cataract early detection and quantitative evaluation of maturity using ultrasound was investigated. A broadband coherent signal, backscattered from an eye lens tissue, was digitized, recorded and processed. A new parameter – lens quality was proposed for the human eye cataract quantitative evaluation. Lens quality reflects two phenomena of ultrasound interaction with lens tissue – attenuation and scattering. Digital technique for echo-signal energy and time frequency analysis was applied, ultrasound waves scattering strength and spectral slope was calculated.

Experimental statistical investigations performed with signals divided into five groups – mature cataract, immature form of cataract, incipience cataract phase, healthy lenses and human eye phantom. Investigations have showed that value of specific quality in the test groups vary in the wide range from 1 to 60. This feature allows theoretically differentiate eye lenses cataract in different classes with defined boundaries. Presented results show that we with high reliability can differentiate lenses into three groups: healthy lenses ($Q_L > 50$), lenses with incipient or immature cataract ($Q_L = 2 - 20$) and lenses with mature cataract ($Q_L < 1$).

The investigated method can be used for an eye lens classification and for early cataract detection This technique was used at the Department of Ophthalmology, Institute for Biomedical Research, Kaunas University of Medicine.

Key words: ultrasound, attenuation, spectral slope, scattering, eye cataract, classification, digital spectral analysis.

1. Introduction

Cataract is one of the well known disease disabling eye condition. The appearance of a cataract seems to be a result of biochemical changes in the lens, but the nature and mechanism of these changes is still under investigation. For diagnosis and therapeutic purposes it is very important to determine cataract type, identify disease stages especially in its early development. Ultrasound technique offers a powerful noninvasive instrument for tissue characterization and allows better understanding of tissue structure and morphological changes.

Frequency-domain analysis of ultrasonic signals offers new improvements in medical imaging, tissue segmentation, however their full potential for conveying relevant information is not fully realized. Fundamental advantage for quantitative tissue evaluation suggest radiofrequency signal mode. It allows to record echo-signal with more information about the ultrasound waves interaction with various tissue microstructures. Amplitude, phase and frequency attenuation characteristics reflect tissue structure, tissue density homogeneity and morphology. It is useful to interpret segments of tissue in terms of deterministic and stochastic structures. Many deterministic structures produce "prickle pattern" of periodic spectral peaks. Stochastic structures contain numerous amounts of small scatteters with randomly distributed positions. Normal human lens structure has deterministic spectrum of signal from anterior and posterior lens interfaces and nucleus with primary acoustically homogenous and clear formation. Interfaces characterize increased reflection of ultrasound waves. Cataract nucleus is characterized by growing microscatteters and stochastic structure. The lens size exceeds the width of ultrasound beam. Under certain conditions ultrasound scattering strength and attenuation can be used to estimate physical properties of tissue constituents (Lizi *et al.*, 2003).

It is widely known that ultrasound attenuation coefficient depends on cataract development stage. Attenuation in lenses with cataract is larger than in healthy lenses. However quantitatively this difference is not very significant. For example, (Paunksnis, 2003) shows that ultrasound mean attenuation coefficient in lenses with type I and type II diabetic cataract vary in the range (4.8–9.4) dB/MHz cm (about 1.9 times). Sugata (1992) found that ultrasound attenuation coefficient in groups senile (mild), diabetic and nuclear cataract vary from 1.3 to 2.3 dB/MHz cm, that is less than 1.8 times. Considering the fact that measurements have significant variance (Paunksnis, 2003), distance between different groups of classification is relatively small and group boundary often is fuzzy.

The main purpose of this work is to propose a new human eye lens quality evaluation parameter obtained by tissue ultrasound quantitative analyses. In comparison to well known parameter – ultrasound attenuation lens the quality coefficient additionally estimates echo-signal energy characteristics and therefore is more sensitive for tissue structure and morphological changes. It can be used for an eye cataract detection and classification. Potentially, lens quality allows to improve diagnostics and reduce requirements, for radio frequency (RF) signal acquiring data quality.

2. Materials and Methods

Model of the ultrasonic signal interaction with soft tissue has been used. Expressed in the frequency domain, power density spectrum of received echo signal can be written as

$$G(f,z) = |C(f,z)|^2 \cdot |T(f)|^2 \cdot |H(f,z)|^2 \quad (1)$$

where $C(f,z)$ – Fourier transform of scatteters, $T(f)$ – transfer function of ultrasound transducer, $H(f,z)$ – transfer function of amplitude attenuation in tissue, f – ultrasound frequency, $z = c_0 t$ – distance from the transducer, c_0 – velocity of sound, t – time.

Ultrasound attenuation was determined by widely used simple phonological tissue attenuation model. Expressed in the frequency domain, module of amplitude attenuation transfer function for a ultrasound plane wave propagation through tissue is:

$$|H(f,z)| = e^{-\alpha_1 z - \alpha_2 z} = e^{-\alpha_1 z - \beta f z}, \quad (2)$$

where α_1 – frequency independent coefficient of attenuation, $\alpha_2 = \beta f$ – frequency dependent term of attenuation, β – ultrasound attenuation coefficient Np/MHz · cm.

Three methods were analyzed: spectral differences, zero crossing and time domain technique. Spectral difference method appeared to be the most suitable for RF digitized signals, obtained using standard ultrasonography equipment with A mode probe. Typical view of eye lens signal is shown in Fig. 1.

The power spectra difference logarithm can be written using Eq. (1), (2):

$$D(f) = 2\ln\frac{|C(f,z_1)|}{|C(f,z_2)|} - 2\alpha_1 z_1 - 2\beta f z_1 + 2\alpha_1 z_2 + 2\beta f z_2 = W(f) + 2\alpha_1 d + 2\beta f d, \quad (3)$$

where $d = z_2 - z_1$ – lens width; z_1, z_2 – coordinates of anterior and posterior lens nucleus interfaces (Fig. 1); $W(f)$ – noise, received from randomly distributed tissue scatteters. As function $C(f,z)(1)$ estimates Fourier transform of a white process, $W(f)$ has a zero mean value. Power spectra difference (3) may be considered as straight line function of frequency and depth.

Ultrasound spectral slope $\gamma = \beta d$[dB/MHz] will be used for further calculations. The advantage of this parameter is that measurements become simple. There is no requirement to know in advance sound velocity in lens and measure width d. Sound velocity depends on tissue density, which is unknown. Moreover, width of human lens vary in a relatively small range, significantly less than spectral slope or scattering strength in normal and cataract lens.

Difference of logarithmic power spectra of ultrasound echo-signals

$$D_{ex}(f) = 10\lg\frac{S_1(f)}{S_2(f)} = 10\lg S_1(f) - 10\lg S_2(f), \quad (4)$$

where S_1, S_2 – power spectra density of echo-signal from anterior and posterior nucleus interfaces. The spectral slope is calculated as a slope of straight line, fitting experimental

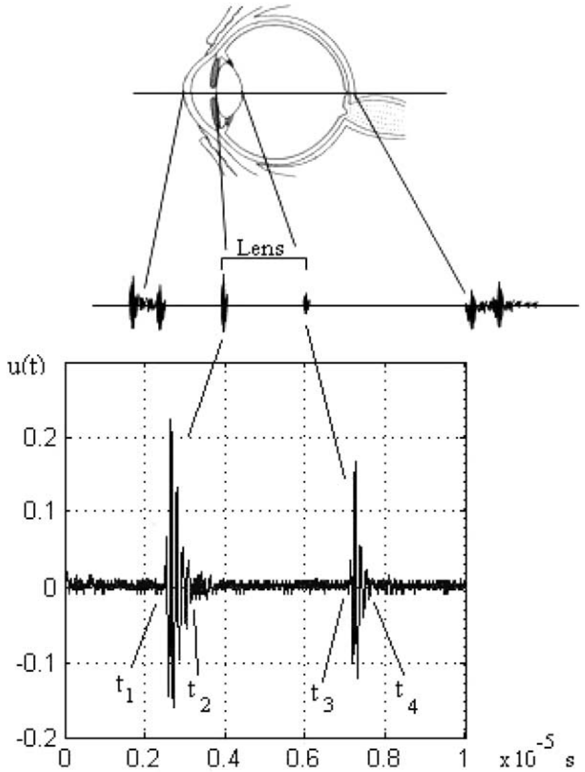


Fig. 1. Illustration of eye structure and RF echo signals from anterior and posterior lens interfaces, where $d = 0.5c_0(t_4 - t_1)$ – width of lens, $d_n = 0.5c_0(t_3 - t_2)$ – width of lens nucleus.

data $D_{ex}(f)$, obtained from (4). The difference of logarithmic power spectra is found by the following expression:

$$D_{ex}(f) = \gamma_{SL} f + D_0, \tag{5}$$

where γ_{SL} is average spectral slope, D_0 the spectral intercept. For radiofrequency echo-signals γ_{SL} and D_0 is estimated by the least squares method:

$$\gamma_{SL} = \frac{\frac{1}{n}\sum_{i=1}^{n} f_i D_i - \overline{f} \cdot \overline{D_i}}{B_x}, \quad \overline{f} = \frac{1}{n}\sum_{i=1}^{n} f_i, \quad \overline{D} = \frac{1}{n}\sum_{i=1}^{n} D_i,$$
$$D_0 = \overline{D_i} - \gamma_{SL} \cdot \overline{f}, \quad B_x = \frac{1}{n}\sum_{i=1}^{n} f_i^2 - \overline{f}^2, \tag{6}$$

where n is the number of sample points in user-defined frequency interval, $\overline{D}$ the average difference of logarithmic power spectra, $\overline{f}$ the average frequency.

A cataract disease first degrades lens nuclear, making it opaque, changing structure, originating microscatetters and causes increase in scattering strength. Therefore, is proposed to introduce lens nuclear scattering strength as an eventual parameter for the lens classification.

Scattering strength may be measured as mean energy of radiofrequency signal, reflected from eye lens tissue. Amplitude of echo-signals from anterior and posterior interfaces of lens typically is higher than amplitude of signal from lens nuclear. To avoid measurements error due to influence of unit gain adjusting, the relative mean energy of scattering signal from lens nuclear was calculated according the following expression:

$$P_S = \frac{P_L}{P_\Sigma} = \frac{\frac{1}{t_3-t_2}\int_{t_2}^{t_3} u^2(t)dt}{\frac{1}{t_4-t_1}\int_{t_1}^{t_4} u^2(t)dt} \cong \frac{\frac{1}{N_n}\sum_{i=1}^{N_n} u_i^2}{\frac{1}{N_l}\sum_{i=1}^{N_l} u_i^2}, \tag{7}$$

where P_L – energy of echosignal from eye lens nucleus; P_Σ – total energy of signal from eye lens, including nucleus, anterior and posterior interfaces; u – instant amplitude; t_2, t_3 – time moments, indicating nucleus region; t_1, t_4 – time moments, indicating lens region (Fig. 1); N_n, N_l – number of discreate samples in nucleus and whole lens.

Finally, quality of eye lens, expressed in terms of parameters, characterizing interaction of ultrasound waves with tissue can be written as

$$Q = (\gamma_{SL} P_S)^{-1}, \tag{8}$$

where γ_{SL} – ultrasound waves spectral average slope in dB/MHz, P_S – relative energy of ultrasound signal, backscattered from an eye lens. Spectral slope in Np/MHz may be converted to dB/MHz by multiplying with 8.686. A specific quality of lens is obtained as

$$Q_L = \frac{Q}{Q_M}, \tag{9}$$

where Q_M – the minimal value of quality. According to (9), minimal specific quality $Q_L \approx 1$ has lens with highly matured cataract. The value of Q_L shows the degree of lens disease (degree of cataract). The higher value of Q_L is measured in healthy lens. The specific quality of lens is proposed as a parameter for simplest evaluation of cataract.

3. Experimental Methods

Database of diagnostic signals (228 cases) was collected in the Eye Clinic of Kaunas University of Medicine. Patients were investigated with ultrasonic echoscope “Mentor A/B”, 7 MHz probe was used. RF signals along the axis of a lens were captured with constant time window 10 μs (Fig. 1), digitized by A/D converter (sampling rate 250 MHz, 8 bit accuracy) and saved in a PC. Signals were sorted into 5 groups: 10 signals obtained from eye phantom (group ETL), 54 signals from healthy lenses (SVK), 68 signals from lenses incipient cataract (INC), 72 signals from lenses with immature cataract (NON) and 24 signals from lenses with mature cataract (MAT).

A special program was developed using MATLAB software. Echo-signals from anterior and posterior interfaces of lens nucleus were selected semi manually with time window length of approximately 1 μ s. The starting and ending points of selected sliding rectangular time window were coincident with zero-crossing time moments. Echo signal relative scattering energy P_S, spectral slope γ_{SL} and lens quality were calculated using expressions (7, 8, 9). Statistical parameters – mean value and standard deviation (SD) of these parameters were calculated using all RF signals from each group.

Logarithmic signal power spectral density and spectral difference are shown in Fig. 2. It can be shown that high frequency components of echo signal from posterior interfaces are more attenuated. Reliability of measured parameters evaluated according to the obtained variance. In any case the minimal SD was sought. Influence of frequency analysis resolution and frequency bandwidth (5–9, 3–14 and 1–25 MHz) to accuracy of calculation was initially investigated. Results show (Fig. 3) that frequency bandwidth of 1–25 MHz allows obtain the minimal SD of estimated attenuation slope. Signal spectral analysis were performed with 30 kHz frequency resolution by using optimal 8192 point FFT.

The quality of some (about 8 %) RF signal recordings were insufficient, spectral slope value became negative and therefore these signals were rejected. Results of mean spectral slope calculation before and after data rejection are presented in Fig. 4. In all groups SD decreased more than 1.5 times.

Interesting results were obtained by analyzing relationship between spectral slope, relative energy of scattering signal and the proposed parameter – quality of lens. Results of calculations in all investigated groups are presented in Figs. 5, 6, 7. It was found that correlation exists between echo-signal scattering strength and spectral distortion in the same segment of tissue (Fig. 7). Higher attenuation coefficient value corresponds to higher energy of scattering signal. This phenomena may be explained as follow: micro structural stochastic formations appear in cataractous lenses, having different density and acoustic impedance than surrounding tissue. Increase of nuclear opacity grade causes both attenuation and scattering of ultrasound waves. Tissue of normal lenses homogeneous,

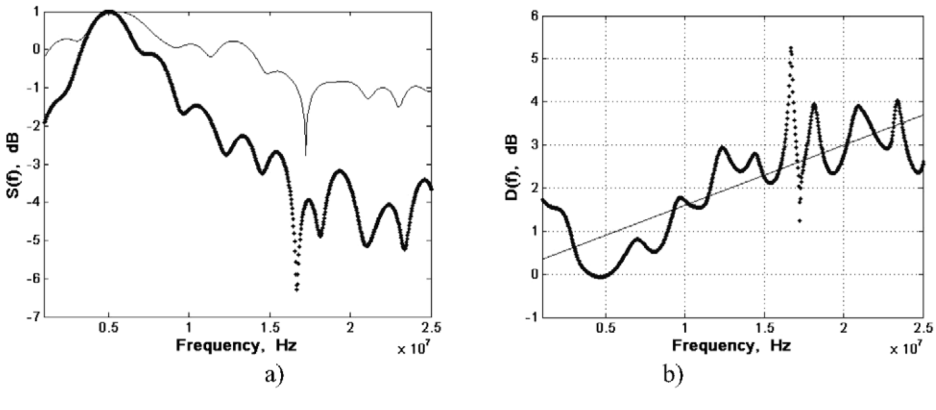


Fig. 2. Example of normalized logarithmic power spectral density of echo signal from anterior (upper line) and posterior (below line) interfaces of lens (a); estimation spectral slope of spectra differences by the regression line fitted within the fixed frequency band width (b).

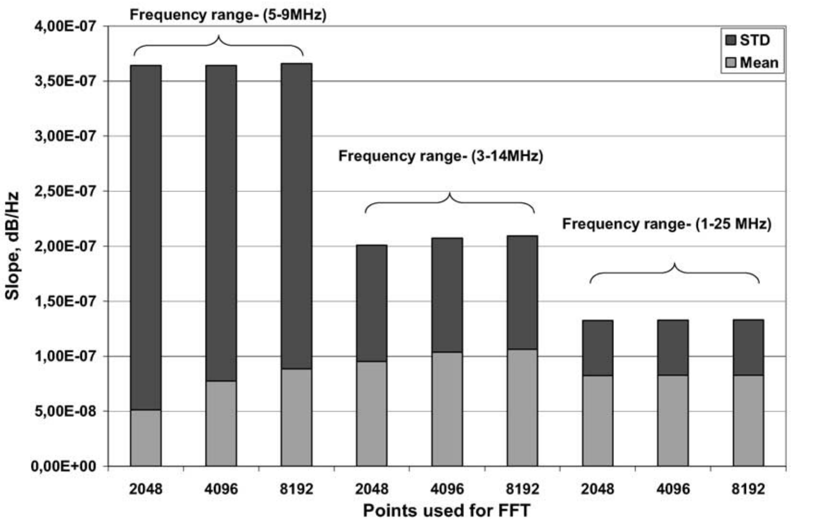
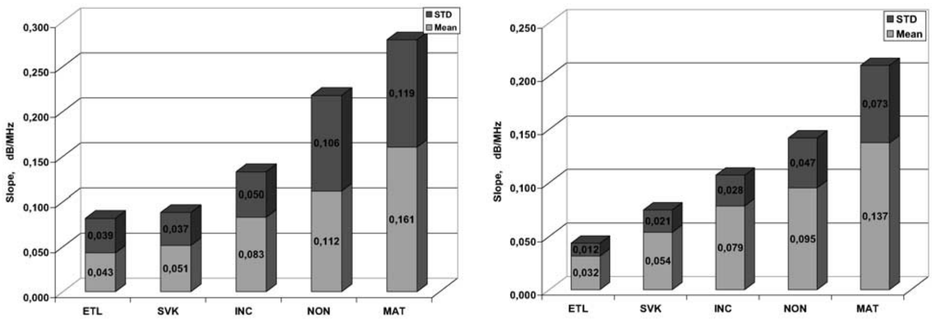


Fig. 3. The results of mean spectral slope calculations in INC control group using different frequency bandwidths – (5–9 MHz), (3–14 MHz), (1–25 MHz). Various number of points (2048, 4096, 8192) for FFT spectral analysis were used.



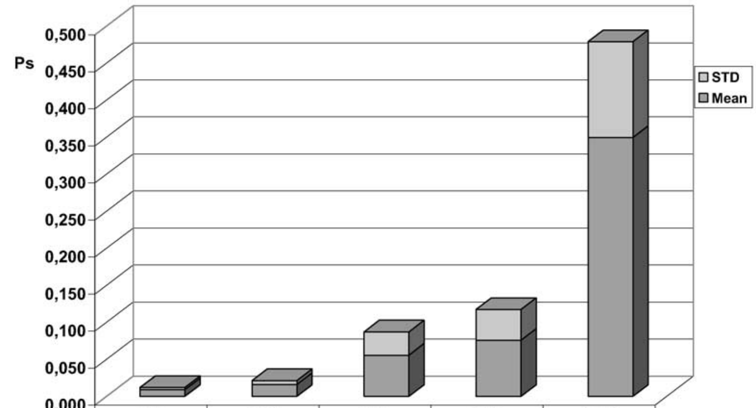
a) b)

Fig. 4. The results of the mean spectral slope and STD calculation in the control groups before (a) and after (b) the rejection of erroneous measurement values.

acoustically clear and have no scatteters, so it is reasonable that echo-signal energy and attenuation are small.

The lowest mean spectral slope 0.052 ± 0.021 dB/MHz was found in healthy lenses group. Spectral slope in phantom is 0.032 ± 0.012 dB/MHz. Significantly higher spectral slope 0.137 ± 0.073 dB/MHz was found in matured cataract group.

The lens quality coefficients in all groups were calculated as well. Distribution of the lens quality coefficients in all groups is presented in Fig. 6. The dependence of eye lens quality coefficient on signal energy in all control groups was found (Fig. 8). Results of the main parameters quantitative evaluation for lens disease classification are presented



	ETL	SVK	INC	NON	MAT
STD	0,003	0,005	0,031	0,042	0,129
Mean	0,009	0,016	0,056	0,076	0,350

Fig. 5. Distribution of mean values of relative energy P_S in different groups

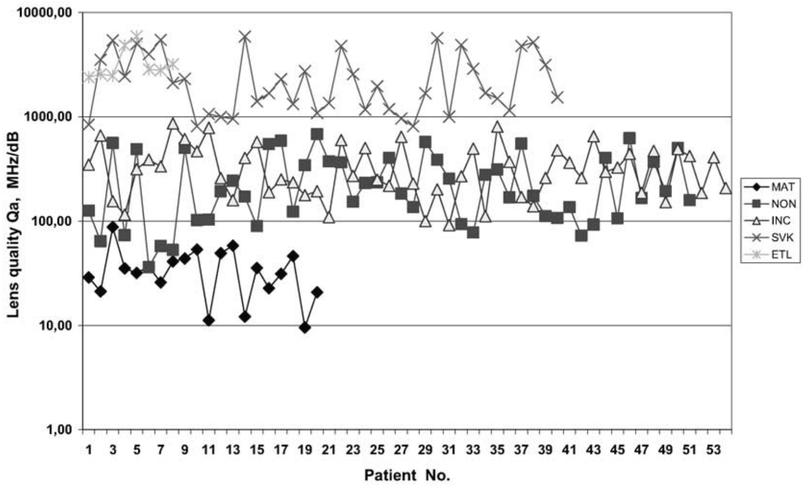


Fig. 6. Distribution of eye lens quality coefficient in control groups.

in Table 1. Specific quality of lens Q_L was calculated according to (9) considering that quality of lenses with mature cataract $Q = 50$.

4. Discussion

A new parameter – lens quality for a human eye cataract quantitative evaluation was studied in this paper. Lens quality reflects two phenomena of ultrasound waves interaction with lens tissue – attenuation and scattering. Echo-signal energy and time frequency analysis technique was applied to calculate ultrasound wave scattering strength and ul-

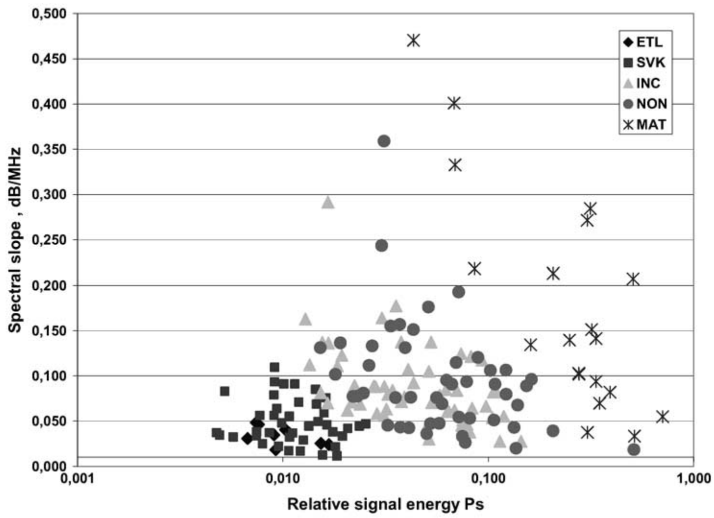


Fig. 7. Distribution of eye lens spectral slope coefficients from relative signal energy in control groups.

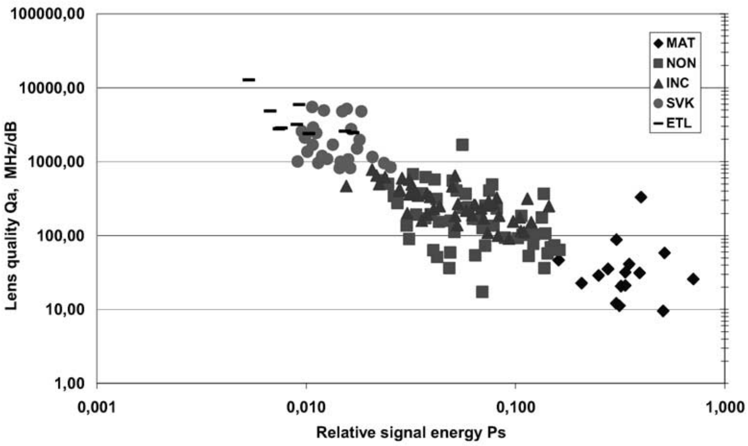


Fig. 8. Dependence of eye lens quality coefficient from relative signal energy in control groups.

Table 1

Results of main parameters for cataract classification

Test group	Amount of signals	γ_{SL} dB/MHz	P_S	Q, MHz/dB	Q_L $(Q = 50)$
ETL	10	0.032±0.012	0.009±0.003	3372±1287	67±26
SVK	54	0.054±0.021	0.016±0.005	> 2454±1610	> 49±32
INC	68	0.079±0.028	0.056±0.031	345±195	6.9±3.9
NON	72	0.095±0.047	0.076±0.056	270±180	5.4±3.6
MAT	24	0.137±0.073	0.350±0.129	< 35±18	< 0.7±0.36

trasound spectral slope. Experimental investigation performed in five groups showed that lens quality evaluation coefficient varies in wide range in dependence to test group and the stage of lens disease. The investigated method can be used for an eye lens quality classification.

Experimental investigation shows, that new parameter – lens quality evaluation coefficient varies in a wide range depending to test group and stage of lens disease. For example, if spectral slope varies in a range of five times, relative energy – 30 times, quality coefficient varies in a range more than 50 times. This incredible feature allows to classify theoretically cataract to some groups with defined boundaries. Results, presented in table, show the possibility to classify lenses with high reliability into three groups: healthy lenses group ($Q_L > 50$), lenses with incipient or immature cataract ($Q_L = 2 - 20$) and lenses with mature cataract ($Q_L < 1$). The great distance between these groups show reliability of classification using lens quality parameter. Sure enough, human eye phantom has maximum quality $Q_L = 67$.

The investigated method can be used for classification eye lenses with different stages of cataract. With high confidence we may conclude, that increase of quality coefficient value coincide with the lower disease stage of the lens.

5. Conclusions

1. The investigated method can be used for quantitative evaluation of cataract maturity.
2. The high quality signals are necessary to improve accuracy of diagnostic signals analysis: the high amplitude, minimal noise, clearly defining reflected signals from lens interfaces.
3. According to the estimated results we found possibility to create an automatic classificator for evaluation of cataract maturity.
4. The additional investigations are necessary for classification of lenses into incipience and immature cataract groups.

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Ultrgarsinis kokybinis akies kataraktos subrendimo įvertinimo metodas

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Šiame darbe pagrįsta metodika, skirta kataraktos subrendimo stadijos nustatymui, pateikiami šios metodikos tyrimo rezultatai. Kauno Medicinos universiteto Biomedicininių tyrimų instituto Oftalmologijos laboratorijoje buvo atliekamas ultragarsinis pacientų tyrimas, diagnostiniai signalai nuo akies lęšiuko buvo diskretizuojami, išsaugojami ir vėliau analizuojami panaudojant skaitmeninių signalų apdorojimo metodus. Kataraktos kokybiniam įvertinimui pasiūlytas naujas diagnostinis parametras – lęšiuko kokybės koeficientas QL. Šis koeficientas apibūdina du ultragarso sąveikos su akies lęšiuku audinio aspektus – signalo slopinimą ir išsibarstymą. Atlikus diagnostinių signalų energijos įvertinimą ir dažninę analizę buvo nustatytas signalų energijos absorbcijos ir spektro slopinimo pobūdis.

Eksperimentiniai tyrimai atlikti signalams, suskirstytiems į penkias kontrolines grupes: signalai nuo akies fantomo (1), signalai gauti tiriant sveikus žmones (2), signalai gauti tiriant pacientus, segančius katarakta pradinėje stadijoje (3), nesubrendusioje stadijoje (4) ir subrendusioje stadijoje (5). Tyrimo rezultatai parodė, kad skirtingose kontrolinėse grupėse lęšiuko kokybės koeficientas kinta plačiose ribose – nuo 1 iki 60. Ši kokybės koeficiento savybė leidžia klasifikuoti lęšiukus į skirtingas grupes, įvertinant kataraktos subrendimo stadiją. Su dideliu patikimumu galima diferencijuoti lęšiukus į tris grupes: sveikųjų grupę ($QL > 50$), lęšiukų grupę su silpnais kataraktos požymiais ($QL = 2 - 20$) ir subrendusios kataraktos grupę ($QL = 1$). Darbe pateikiamas metodas neleidžia patikimai klasifikuoti lęšiukų į nesubrendusios kataraktos ir pradinės kataraktos stadijos grupes. Šiuo atveju reikalingi papildomi klasifikaciniai parametrai. Sukurta metodika gali būti panaudota klinikinėje praktikoje kaip „antroji nuomonė“ kataraktos subrendimo įvertinimui.