

The Empirical Mode Decomposition and the Discrete Wavelet Transform for Detection of Human Cataract in Ultrasound Signals

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Abstract. This paper presents a new approach for human cataract automatic detection based on ultrasound signal processing. Two signal decomposition techniques, empirical mode decomposition and discrete wavelet transform are used in the presented method. Performance comparison of these two decomposition methods when applied to this specific ultrasound signal is given. Described method includes ultrasonic signal decomposition to enhance signal specific features and increase signal to noise ratio with the following decision rules based on adaptive thresholding. The resulting detection performance of the proposed method using empirical mode decomposition was better to compare to discrete wavelet transform and resulted in 70% correctly identified “healthy subject” cases and 82%, 97% and 100% correctly identified “cataract cases” in the incipience, immature and mature cataract subject groups, respectively. Discussion is given on the reasons of different results and the differences between the two used signal decomposition techniques.

Key words: biomedical signal processing, empirical mode decomposition, discrete wavelet transform, ultrasound, human cataract, clinical decision support.

1. Introduction

A new nonlinear signal decomposition technique, called Empirical mode decomposition, has recently been introduced by N. Huang (Huang *et al.*, 1998). This method is used for adaptive representing non-stationary signals as narrow band components, called intrinsic mode functions (IMF). The IMFs are extracted from signal using empirical mode decomposition technique (EMD). The technique was already successfully applied in a number of applications (Echavaria *et al.*, 2001; Chau-Huei *et al.*, 2002), but it, however, is still lacking of theoretical background. The EMD technique actually is an empirical algorithm and its properties and performance can be established and compared to the other methods by comparing results when applying methods on the specific class of the signals. In

this paper EMD technique is compared to discrete wavelet transform (DWT), being well established and well known signal decomposition technique.

Empirical mode decomposition technique as well as discrete wavelet transform are used as a part of the method for human cataract automatical detection. The method analyzes ultrasonic echo signal from human eye determining representative parameters, that are used for signal classification into “cataract” or “healthy” groups. The results of the method is also important from medical point of view.

The lens of human eye is a transparent tissue due to the highly organized arrangement of structural proteins, called crystallins. If this arrangement becomes disrupted, the lens may lose its transparency and develop the opacities known as cataract.

Normal lens is acoustically homogenous and clear. It’s characteristics change according to the density of cataract that is due to changes in tissue density and structure (Tabandeh *et al.*, 1998).

When examining the patient it is very important to describe the cataract quantitatively, but it is complicated using only optic methods (biomicroscopy).

Ultrasonic measurement of thickness of the lens is widely used in ophthalmology for calculation of power of intraocular lenses (IOC). Though this method is not enough informative for the evaluation of internal structure of the eye lens. Ultrasound is attenuated as the result of absorption and scattering as it goes through the lens.

There are a few published studies in changes of ultrasound attenuation characteristics of human lens according to the stage of cataract and investigation the possibility to quantitative description for an early detection of cataract (Sugata *et al.*, 1992; Paunksnis *et al.*, 2001).

The ultrasonographic findings in cataract lenses such as increase of attenuation coefficient and attenuation frequency dependency in higher grade cataract lenses, also changes in thickness of lens capsule and internal reflectivity in lens nucleus suggest the use of these findings for cataract detection.

In the present article we present an automatical method for determination of the ultrasonic signal parameters related to the thickness of the lens capsule and internal reflectivity of the lens nucleus. The method is based on the signal decomposition for application related signal features enhancement, fiducial points detection using adaptive thresholding and decision parameters calculation. The performances of this method is compared for the cases when EMD and DWT techniques are used for signal decomposition. Differences between these two techniques are discussed in terms of properties and performance results.

Outline. This article has the following structure. In Section 2 we provide a description of the implemented method with a short theoretical background of the empirical mode decomposition and discrete wavelet decomposition methods, being the main components of the proposed cataract detection method. The method itself is described in Subsection 2.3. Subsections 2.4, 2.5 describes the database of the ultrasonic signals used for performance estimation of the method and the method of clinical examination. Results and discussion are given in Sections 3 and 4, respectively.

2. Materials and Methods

This section consists of three parts. Parts 2.1 and 2.2 provide mathematical background of empirical mode decomposition (EMD) and discrete wavelet transform respectively used as a part of the presented method, while the proposed method itself is described in the Subsection 2.3.

2.1. Empirical Mode Decomposition

Empirical mode decomposition is a novel method for non-linear and non-stationary data analysis (Huang *et al.*, 1998; Magrin-Chagnolleau and Baraniuk, 1999). This method decomposes the original time series into “monocomponent functions” called intrinsic mode functions, suitable for defining meaningful instantaneous frequency calculation using the Hilbert transform (Huang *et al.*, 1998). An intrinsic mode function (IMF) is, by definition, a function that satisfies two conditions:

- the function should be symmetric in time, and the number of extrema and zero crossings must be equal, or at most differ by one;
- the mean value of the envelope, defined by the local maxima and envelope defined by a local minima must be zero at any function point.

This means that the IMF is obtained by locally eliminating the superposition of different frequency and amplitude waves, and eliminating signal asymmetries with respect to the zero level. This is done by using the EMD technique, which decomposes the signal into IMFs with an iterative procedure consisting of extrema identification and “sifting” steps, explained below.

Let the original signal $s(t)$ be the input to the sifting process. The signal $s_{i,k}(t)$ defines a component of the sifting process, which for the first iteration is $s_{1,1}(t) = s(t)$. The sifting process consists of the following steps:

1. First, local minima and maxima are extracted from $s_{i,k}(t)$.
2. Lower and upper envelopes are created by interpolation of $s_{i,k}(t)$ between local maxima and minima.
3. The mean value $m_{i,k}(t)$ of the resulting upper and lower envelopes is calculated for each signal point.
4. The resulting $m_{i,k}(t)$ is subtracted from the signal $s_{i,k}(t)$ so that the next component of the sifting process is defined by:

$$s_{i,k+1}(t) = s_{i,k}(t) - m_{i,k}(t). \quad (1)$$

5. The component $s_{i,k+1}(t)$ is checked against the IMF criteria and, if not met, the sifting process (1–4 steps) is repeated with $k = k + 1$.
6. The above steps are repeated until the resulting signal meets IMF criteria and, consequently is IMF $c_i(t)$. To speed up the procedure, a second condition for the

signal to be IMF is relaxed when the standard deviation SD , computed from two consecutive sifting is less than 0.2–0.3:

$$SD = \sum_{t=0}^T \left[\frac{|s_{i,k-1}(t) - s_{i,k}(t)|^2}{s_{i,k-1}^2(t)} \right] < 0.3. \quad (2)$$

The next sifting process starts after subtraction of the extracted IMF $c_i(t)$ from signal $s_{i,k}(t)$, and the resulting signal $r_i(t)$ is input to the successive sifting process:

$$r_i(t) = s_{i,k}(t) - c_i(t), \quad (3)$$

$$s_{i+1,k}(t) = r_i(t), \quad (4)$$

where $k = 1$.

The sifting process is repeated until all, or the required number of IMFs, are extracted from the signal. In the first case the sifting process is terminated when the residual $r_N(t)$ of the sifting process has less than 3 extrema.

The original signal $s(t)$ can be expressed as a sum of extracted IMFs $c_i(t)$ and the residual of the sifting process $r_N(t)$:

$$s(t) = \sum_{i=1}^N c_i(t) + r_N(t). \quad (5)$$

Physically, the empirical mode decomposition process can be understood as a step-by-step extraction of the *locally* highest frequency oscillation of the signal progressively forming low-pass intrinsic mode components (Fig. 1).

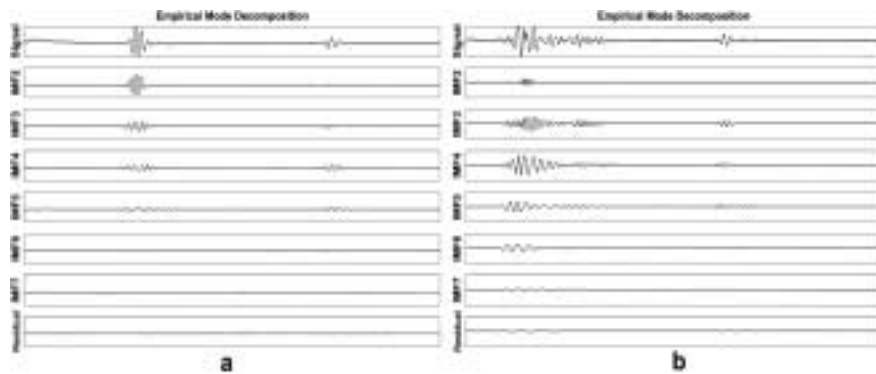


Fig. 1. Intrinsic mode components obtained from ultrasound signals from healthy (a) and cataract (b) eyes.

2.2. Discrete Wavelet Transform

Discrete wavelet transform (DWT) is well established method having solid theoretical background and equipped with efficient fast implementation algorithms (Strang and Nguyen, 1996). The Wavelet transform provides an efficient time-scale representation for functions which have similar character to the functions in the wavelet basis. For signal decomposition on the time-scale plane we have used the orthogonal DWT, which represents the signal $s(n)$ by:

$$s(n) = \sum_{j=1}^K \sum_{k=-\infty}^{\infty} w_j(k) \psi(2^j n - k), \quad (6)$$

where the function $\psi(n)$ represents a discrete analysis wavelet and the coefficients $w_j(k)$ represent the signal at level j . In the presented method the Coiflet5 wavelets were used for decomposition since they have a shape similar to analyzed signals. In the present method, the DWT is performed by the use of low-pass filters for the “approximate” signal and high-pass filters for the “detailed” signal followed by down sampling (Mallat’s pyramid algorithm (Mallat, 1989)).

Physically discrete wavelet transform can be understood as band-pass octave filter bank which decomposes a signal into scales (levels) each of which contains signal components with progressively lower frequency contents (Fig. 2). With this approach, the time resolution becomes arbitrarily good at high frequencies, while the frequency resolution becomes arbitrarily good at low frequency. The main differences between EMD and WT decomposition are:

- WT scales frequency contents is always fixed and depends on sampling frequency and decomposition level (scale), while IMF may have variable frequency contents depending of *local* signal properties.
- Performance of WT depends on choice of wavelet, its similarity to analyzed signal, while EMD have no basic functions and is dependant on the signal itself.

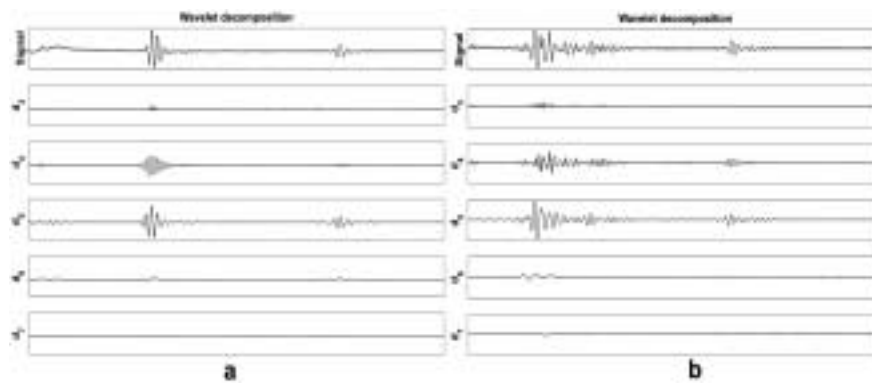


Fig. 2. Wavelet transform scales (levels) obtained from ultrasound signals from healthy (a) and cataract (b) eyes.

2.3. Algorithm of the Method

The present method for detection of human cataract in ultrasonic eye signals consists of the main steps given in Fig. 3. Main tasks solved in the method are related to detection of the fiducial points in the echo signals received from anterior and posterior interfaces of lens, parameter calculation from time intervals defined by these fiducial points and, finally decision making based on calculated parameters. Empirical mode decomposition or discrete wavelet transform for extraction of signal – specific time frequency features is the first step of the method. Time and frequency interval specific on each task is then extracted. Fiducial points are calculated based on theoretical assumptions and properties of the signal, using adaptive thresholds. Two decision parameters are then calculated and are used for signal classification as “healthy” or “cataract”.

2.3.1. Detection of the Fiducial Points in Signals from Anterior Lens Interface

In this stage onset and offset time of the echo signal reflection from anterior lens interface are determined. It was found that this reflection is well described by higher frequency components and should be the highest amplitude signal component located in the first part of the recorded signal. In order to enhance this component and to reduce high frequency noise only 2–5 intrinsic mode functions $c_i(t)$ from EMD (see Fig. 1) were used forming enhanced signal $s_A(t)$:

$$s_A(t) = \sum_{i=2}^5 c_i(t). \quad (7)$$

Based on the same assumptions only 3–5 levels from DWT were used for enhanced signal formation in wavelet case:

$$s_A(t) = \sum_{i=3}^5 d_i(t). \quad (8)$$

Threshold L_1 for fiducial points detection was then defined as

$$L_1 = 0.04 \cdot \max \{s_A(t)\}, \quad t = 1 \dots T/2, \quad (9)$$

where T denotes length of the recorded echo signal. An envelope $s_{H1}(t)$ of the signal $s_A(t)$ is then calculated based on modulus of the Hilbert transform:

$$s_{H1}(t) = |H's_A(t)|, \quad t = 1 \dots T/2, \quad (10)$$

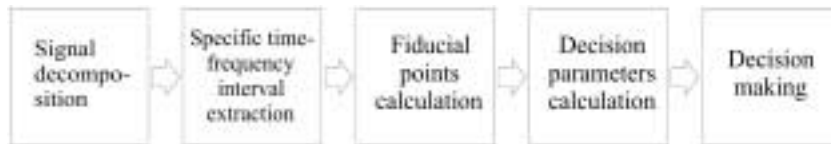


Fig. 3. General algorithm of the method.

where $H^1 s_A(t)$ denotes Hilbert transform of the signal s_A filtered with 30 point ($0.12\mu s$) median filter in order to smooth noise related dips. Onset T_1 and offset T_2 time points of the echo signal reflection from anterior lens interface are then determined as the first s_{H1} points below threshold L_1 to the left and to the right from the signal maxima, respectively. Detected points for the different clinical cases are shown in the Fig. 4, 6 and 7.

2.3.2. Detection of the Onset Point in Signals from Posterior Lens Interface

In this stage onset point of the posterior lens interface is found using similar steps as described above. It was found that this reflection is well described by lower frequency components and should be found in the end part of the recorded signal. To enhance signal to noise ratio in the reflection signal s_P is formed using lower frequency IMF (see Fig. 1) components:

$$s_P(t) = \sum_{i=3}^5 c_i(t). \quad (11)$$

In DWT case 4–6 levels were used for enhanced signal formation since in these levels reflection from posterior lens interface is strongest (see Fig. 2):

$$s_P(t) = \sum_{i=4}^6 d_i(t). \quad (12)$$

Threshold L_2 for fiducial point detection is then defined as

$$L_2 = \frac{1}{1.9} (2\bar{s}_P(t) + 0.4 \max \{s_P(t)\}), \quad t = T_{\max} + \Delta_1 \dots T_{\max} + \Delta_2, \quad (13)$$

where $\bar{s}_P(t)$ denotes mean value of the $s_P(t)$ in the specified time interval; T_{\max} denotes maximum position in signal $s_A(t)$, Δ_1 and Δ_2 correspond to $2.8\mu s$ and $8.5\mu s$ and are based on anatomical properties of the human lens. Two terms in equation 13 are used

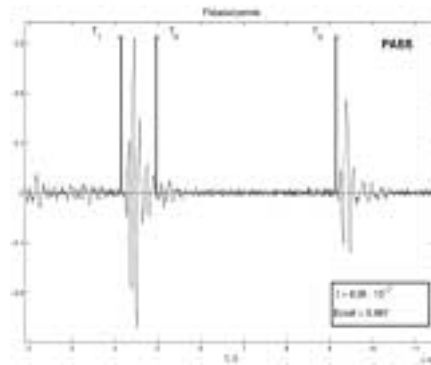


Fig. 4. Calculated fiducial points from healthy subject.

in order to correctly estimate reflection threshold both in “cataract” and “healthy” subject signal cases. In the first case reflection from posterior lens interface usually has low amplitude and is drawn in the small background reflections. In this case the first term in Eq. 13 has high influence to L_2 value. In the “healthy” subject cases reflection from posterior lens interface is usually high and well above the background reflections. In such case the second term in Eq. 13 has the main influence to L_2 value.

An envelope of the signal $s_{H2}(t)$ is then calculated in a similar way shown in Eq. 10:

$$s_{H2}(t) = |H' s_P(t)|, \quad t = T_{\max} + \Delta_1 \dots T_{\max} + \Delta_2. \quad (14)$$

After the last $s_P(t)$ peak above the threshold L_2 is found and the onset time point T_3 of the echo signal reflection from posterior lens interface are determined as the first s_{H2} point below threshold to the left from the peak. Detected points for the different clinical cases are shown in the Fig. 4, 6 and 7.

2.3.3. Decision Parameters Calculation

Two parameters are calculated based on the fiducial points calculated in Subsections 2.3.1 and 2.3.2. First parameter τ is defined as a reflection length of echo signal part from anterior lens interface:

$$\tau = T_2 - T_1. \quad (15)$$

It is assumed that in the signals from cataract subjects τ should be longer compared to signals from healthy subjects because of changed thickness and elasticity of the lens.

The second parameter $Ecoef$ is defined by

$$Ecoef = \sqrt{\sum_{t=T_2}^{T_3} s_{R_N}^2(t)}, \quad (16)$$

where $s_{R_N}(t)$ is defined by

$$s_{R_N}(t) = \frac{\sum_{i=4}^7 c_i(t)}{\max\{\sum_{i=4}^7 c_i(t)\}} \quad (17)$$

in EMD case and by

$$s_{R_N}(t) = \frac{\sum_{i=5}^7 d_i(t)}{\max\{\sum_{i=5}^7 c_i(t)\}}, \quad (18)$$

in DWT case and T_2 and T_3 are fiducial points defined in Subsections 2.3.1 and 2.3.2.

This parameter reflects energy of the normalized lower frequency components from the echo signal part corresponding inside of the lens nucleus. It is assumed the $Ecoef$ will be higher in signals from cataract subjects because of the reflections from inhomogeneities in the pathological nucleus. This parameter also improves results when the method fails to correctly detect fiducial points.

2.4. Database

A database consisting of ultrasonic echo signals from 203 eyes (142 subjects) were used for evaluation of the present method. The examination was performed in Eye Clinic of Kaunas University of Medicine. According to the cataract severity subjects were sorted into three groups and the control group of subjects without cataract was examined as well.

- Senile cataract:
 - early cataract stadium – incipience cataract group (61 eyes),
 - immature cataract group (56 eyes),
 - mature cataract group (20 eyes).
- Control group of patients without cataract (66 eyes).

Age of the subjects in the control group was from 19 to 35 years and from 59 to 89 years in the senile cataract group.

2.5. The Method of Clinical Examination

A-scan examination has been performed by *MentorTM* A/B ultrasonic imaging system (Advent, Norwell, MA, USA) using 7 MHz A-mode probe. Radio frequency (RF) echo signals from lens were digitized by *TEKTRONIX TDS 220* oscilloscope (Tektronix Inc., Beaverton, OR, USA) at the sampling rate 250 MHz and 8 bit amplitude resolution, 100 MHz bandwidth for analog signal. In order to get reliable results quality of echosignals was controlled by imaging system, synchronization was organized between oscilloscope and imaging system, and operator accessed the echosignals for use in automatic cataract detection algorithm. The imaging system identifies perpendicularity of ultrasonic beam to eye structures by analyzing the amplitude of the echoes in four reference locations, i.e., the cornea, the two interfaces of the lens, and the posterior pole of eye. When the amplitude of all four reference echoes are greater than certain level the imaging system performs lengthwise measurements of eye structures and signalize that event with sound. This sound is used to trigger echosignal acquisition in oscilloscope. After completion of lengthwise measurements imaging system locks echosignal waveform and measurements readings in freezing display, while oscilloscope acquires echosignal from the eye in the direction of visual axis. Segments of those echosignal corresponding to lens are shown in Figs. 4, 6, 7. Signal averaging was not used, but five signals were acquired from each lens.

A contact method is used through the open eye after blocking the blink reflex. The height and angle of probe was adjusted as close to the visual axis as possible. The probe was applied to the cornea. Subject was asked to look at the red light LED (light emitting diode) in the tip of ultrasonic probe, because of needed alignment of acoustic axis with visual axis of eye. This position aids last-minute adjustments in alignment and helps to detect when the exact point of contact is achieved. A contact method is used through open eye after blocking the blink reflex. The high and angle of probe was adjusted as close to visual axis of eye as possible. It is, however, not easy exactly to capture the visual axis due to unrest of the eye.

Table 1
Cataract detection results

Clinical case	Correctly detected, EMD	Correctly detected, DWT
<i>Healthy</i>	70%	70%
<i>Incipience cataract</i>	82%	74%
<i>Immature cataract</i>	97%	95%
<i>Mature cataract</i>	100%	100%

3. Results

EMD and DWT modifications of the presented method was applied to the described database of ultrasonic eye signals for objective separation of “healthy” and “cataract” subjects. Criterion values for decision parameters τ and E_{coef} were set to $1.22\mu s$ and 1.83 for EMD and to $1.18\mu s$ and 1.37 for DWT signal decomposition cases, respectively. These values were chosen as a compromise between specificity and sensitivity of the method. Subject was classified as “healthy” and passed the test if both decision parameters had values below the specified criterion value. Detection results are shown in Table 1.

Results show that prediction was lower for the less expressed cataract cases, while was very high in mature and immature cataract cases. It is seen that with the chosen decision criteria values method correctly identified 100% of mature cataract cases and 95%–97% of immature cataract cases. The method, however failed to detect 18% of incipience cataract cases when EMD decomposition method was used and failed even in 26% of the cases when DWT was used. Specificity of the method was 70% in both decomposition cases.

In the most of the good quality signal cases method was able to correctly detect fiducial points in the echo signals and at least the chosen τ decision parameter was different for the investigated clinical cases. The mean of τ parameter was clearly different as it is

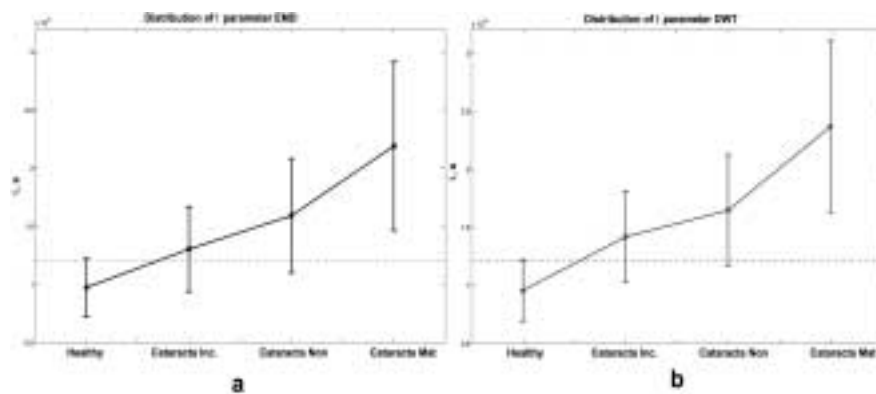


Fig. 5. Distribution of τ decision parameter for a) EMD and b) DWT. Mean values and standard deviations for investigated clinical cases are shown. Dotted line shows decision criterion value.

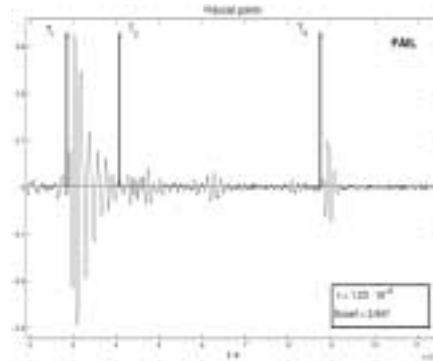


Fig. 6. Calculated fiducial points. Incipience cataract case.

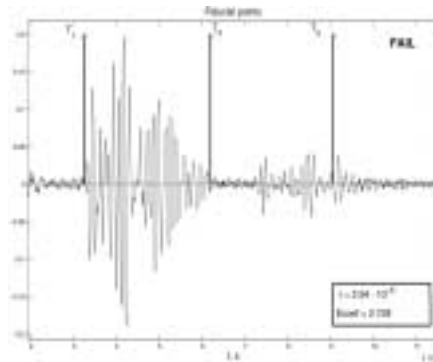


Fig. 7. Calculated fiducial points. Mature cataract case.

seen in Fig. 5. Standard deviation, however, showed quite large variance in each group investigated. Differences between “healthy” subject and “cataract” cases were found to be significant ($p < 0.02$ for incipience and $p < 0.01$ for immature and mature cataract groups).

Individual examples of good quality echo signals showed similar behavior as well. Fig. 4 represent signal from healthy subject and $T_2 - T_1$ interval is $0.836\mu\text{s}$ which is well below of the criterion value. The second decision parameter value does not exceed the threshold as well. Visually this is seen from low “noise” level in the signal $T_2 - T_3$ interval.

The longer $T_2 - T_1$ interval is usually observed in incipience cataract cases (see Fig. 6). As it is seen from the given example τ value is $1.23\mu\text{s}$ above the threshold value. The second parameter value is 3.947 and in this case exceeds significantly decision criterion value. This can be predicted investigating $T_2 - T_3$ signal interval which is quite “noisy”. This is even more expressed when only lower frequency signal components are used (See Section 2.3). The same but even more expressed could be observed in immature and mature cataract cases, as it is seen in given example (Fig. 7).

4. Discussion and Conclusions

Cataract is very frequent disease of human eye and its diagnosis is not difficult. The opacities of the lens are seen with the slit lamp. But there is no any objective examination method in order to determine the degree of the intensity of cataract. Ultrasound examination is largely influenced by the presence of high-molecular-weight compounds and in cataract lenses increased protein aggregation contributes to the hardening of the lens and differences of the ultrasound radiofrequency signals.

The introduced method provided acceptably high cataract detection results on a database of 203 ultrasonic signals. Specificity of the method, however, was not very high. Both specificity and sensitivity of the method, however, could be significantly improved by using more precise measurement technique, including more accurate probe positioning and signal averaging. Results of the proposed method in its current form could be used by doctor and support the final decision for the tactics of the cataract surgery. Method could be also applied for automatical calculation of anatomical properties of the lens, e.g., thickness of the lens capsule or nucleus length.

In the introduced method we proposed to use either EMD or DWT signal decomposition techniques and adaptive thresholding for an automatical estimation of echosignal parameters related to the thickness of the lens capsule and internal reflectivity of the lens nucleus.

The signal decomposition was used for the extraction of the specific time-frequency intervals from the signal. Both EMD and DWT with adaptive thresholding provided acceptable results in terms of sensitivity and specificity. Results, however, in all cases were better when EMD technique for signal decomposition was used. This method were able to separate better overlapped reflections from eye structures and more enhance signal specific features to compare to DWT.

Fig. 8 shows an incipience cataract case when using EMD cataract was correctly detected while using DWT method failed. Arrows denotes subtle differences between

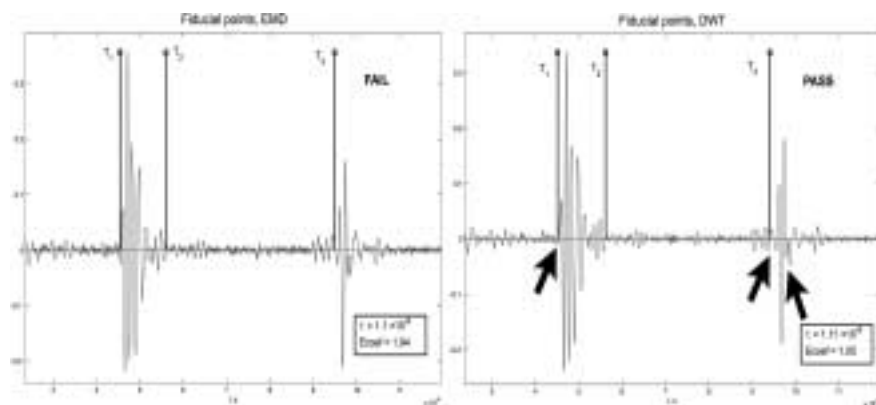


Fig. 8. DWT and EMD method comparison. Incipience cataract case. d3–d6 levels for DWT and IMF2–IMF6 summed. Fiducial points, differences and result are shown.

EMD and DWT decomposed and summed signals. In this case these small differences lead to the failure of the method when DWT was used for signal decomposition.

Conclusion can be made that EMD method is better for analysis of ultrasonic echo signal contents since in a number of cases extracted IMF coincided with reflections allowing better separate different signal components. In DWT case reflections were not so well distinguished because of limited match of wavelet basic and frequency grid to analyzed signal.

In this investigation a few more wavelets were used for decomposition, such “Symlets” and “Daubechies”. Results using these wavelets were 2–5% worse than in the presented case which shows that choice of the wavelet as close as possible to analyzed signal is important factor. To choose wavelet which would fit to all analyzed biomedical signal cases is, however, almost impossible task. Empirical mode decomposition has no such shortcoming since this method has no basic functions and is fully adaptive to the signal itself. This method, however, also have serious drawbacks. The first is the lack of well-established theoretical basis. Second is the lack of fast algorithms. In DWT case signal decomposition time depends on signal length and number of levels extracted while in EMD case decomposition time also depends on complexity of the signal. In the presented method EMD decomposition took up to 50 times longer to compare to DWT. This mean that in its present form the EMD method is suit able only for off-line analysis, since it is time consuming and requires significant computational power. The development of a hardware-based EMD calculation equipment may, however, remove this drawback and widen its application area (Kizhner *et al.*, 2004).

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Empirinio modų išskyrimo ir diskretinės vilnelių transformacijos metodų taikymas žmogaus kataraktos detekcijai ultragarsiniuose signaluose

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Straipsnyje pristatoma nauja metodika, skirta kataraktos automatiniam atpažinimui, ir pagrįsta ultragarsinių signalų skaitmeniniu apdorojimu. Pristatoma metodika naudoja modernų empirinio modų išskyrimo metodą specifinių signalo savybių išryškiniui bei signalo ir triukšmo santykio pagerinimui, o taip pat sprendimo priėmimo taisyklės, naudojant ir signalui adaptyvių slenksčių skaičiavimą. Pateikiama metodika teisingai klasifikavo 70% sveikų žmonių signalų (iš 66 signalo), bei 82% (iš 61), 97% (iš 56), 100% (iš 20) įvairaus laipsnio kataraktos atvejų. Ši metodika taip pat buvo realizuota naudojant diskretinę vilnelių transformaciją palyginimui. Šiuo atveju buvo gauti blogesni rezultatai, dėl riboto vilnelių transformacijos adaptyvumo. Gautas tikslumas įgalina naudoti automatinį kataraktos požymių atpažinimo metodą klinikinėje praktikoje, kaip „antrąją nuomonę“.