Novel spectral approach for pulse waves contour analysis

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Abstract— **This paper considers novel techniques for pulse wave contour analysis. Classical morphological pulse wave analysis by using stiffness index and reflection index does not provide the required accuracy of diagnosis for patients with severe arterial stiffness due to indistinguishable dicrotic peak of pulse wave. We proposed a novel approach for pulse wave contour analysis based on spectral analysis of replicated single pulse waveform. The newly developed spectral harmonic index was defined as the amplitude ratio of the first two harmonics of the amplitude spectrum. Comparative analysis of sensitivity and specificity for various indices for a set of 45 volunteers of different age and arterial stiffness was carried out. It was found that the proposed spectral harmonic index has the highest values of sensitivity (89%) and specificity (86%) compared to the existent indices defined in the time domain.**

Keywords— **digital pulse wave, contour analysis, spectral transform, arterial stiffness.**

I. Introduction

Early diagnosis of human cardiovascular pathologies may use methods based on estimation of arterial stiffness for the purpose of prognostic evaluation of atherosclerosis, coronary heart disease and other serious cardiac diseases [1]. Modern clinical approaches and instruments for noninvasive diagnosis of blood vessels includes noninvasive pulse wave recording (most common by using photoplethysmography technique) with further application of advanced signal processing methods [2]. Estimation of arterial stiffness could be realized by contour analysis of the pulse waveform [3].

The shape of pulse waves, propagating along blood vessels, is mainly formed by the interaction between the left ventricle of the heart and large vessels of the systemic circulation, and reflects the composition of forward and reflected pulse waves [4]. The aim of this work is to develop new approach as well as analysis of existing methods for pulse wave contour analysis in order to determine the most effective noninvasive tool.

II. Theory

The composition of the digital pulse waveform is given schematically in Fig. 1; where ➤ is the forward pulse wave; ≫ is the reflected pulse wave; and ● is the femoral bifurcation of the aorta; A_1 – amplitude of the forward wave, A_2 – amplitude of the reflected wave (amplitude of dicrotic peak); Δ – the time of the pulse wave reflection.

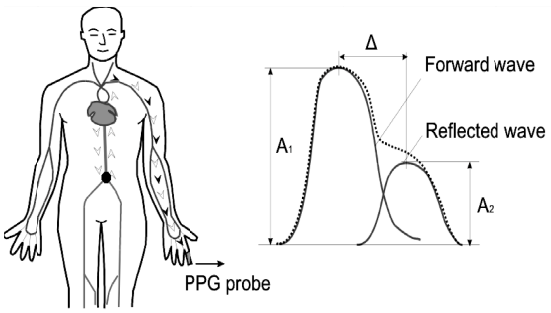

Fig. 1. The composition of digital pulse waveform

The forward pulse wave is formed by the systolic blood volume, which transferred directly from the left ventricle to the arteries of the upper extremities during the systole. The reflected pulse wave arises mainly from pressure waves transmitted along the aorta to small arteries in the lower extremities, where they are then reflected back along the ascending aorta and then travels to the finger arterioles [3, 4].

The intensity of the reflection (amplitude of the reflected wave A_2) is determined by the tone of the small muscle arteries. The time of the pulse wave reflection (Δ) depends primarily on the arterial stiffness and pulse wave velocity in the following segment of the arterial bed: *aorta – large arteries – femoral bifurcation of the aorta.*

The pulse wave velocity depends on the elasticity of blood vessels, their geometry and blood density and is determined by the Moens-Korteweg equation [4]:

$$v = \sqrt{\frac{Eh}{2\rho r}}$$

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where: v – pulse wave velocity; E – the Young's modulus of the arterial wall; h – the arterial wall thickness; ρ – blood density; r – the arterial radius.

The basic hemodynamic parameters that affect the pulse wave velocity, and hence, the pulse waveform is arterial stiffness, which in turn, is an effective and reliable prognostic marker of atherosclerosis and endothelial dysfunction [5]. Thus it is undeniably very important to create novel approach for pulse wave contour analysis in order to estimate the arterial stiffness by using simple, reliable, noninvasive and inexpensive diagnostic methods based on recording and digital processing of arterial pulse waves.

III. Materials and Methods

Currently in clinical practice for the contour analysis of digital pulse waves the reflection index (RI) and the stiffness index (SI) are widely used. These indices are defined as follows:

$$RI = \frac{A_2}{A_1} \cdot 100\%, \quad SI = \frac{L}{\Delta}$$

where: L is the subject's height expressed in meters.

The time of the pulse wave reflection Δ estimates arterial stiffness and also depends on the length of corresponding arterial bed. The variation of arterial path length with a patient's height could be addressed by means of a stiffness index defined as height divided by the time of the pulse wave reflection. The reflection index RI is determined by the intensity of pulse wave reflections and depends on the tone of small muscular arteries and impedance mismatches in arterial system [1, 3].

However using traditional indices for contour analysis of the pulse wave for patients with severe arterial stiffness is associated with a number of obstacles and difficulties, the main of which is the complication of detecting the reflected wave maximum (so called dicrotic peak) and the further definition of its amplitude and temporal position [6]. Below you may see the visual confirmation of this well-known phenomenon.

As an alternative index for the pulse wave contour analysis we could propose to use the form factor of pulse wave defined as follows [8]:

$$FF = \frac{\sigma_{x''} / \sigma_{x'}}{\sigma_{x'} / \sigma_x}$$

where: FF is the form factor; $\sigma_{x''}$ is the standard deviation of the second derivative of the considered pulse waveform; $\sigma_{x'}$ is the standard deviation of the first derivative of the considered pulse waveform; σ_x is a standard deviation of the considered pulse waveform.

The transition from the time domain to the frequency domain by using the spectral Fourier transform allows to obtain a clearer assessment of the pulse wave morphological characteristics. Given the fact that in practice the pulse wave signal processing is realized by software, the transition to the frequency domain is implemented by means of discrete Fourier transforms. In this case the expression for the amplitude spectrum of the pulse wave could be determined as follows:

$$X(k) = \sum_{n=0}^{N-1} x(n) \cdot e^{-j\frac{2\pi}{N}nk}$$

where: $x(n)$ is a sample of the pulse wave in time domain; n is sample's number in the time domain; k is sample's number in the frequency domain; N is a total number of samples in the considered sequence of pulse waves; $X(k)$ is a sample of the pulse wave in the frequency domain.

To obtain novel index for pulse wave morphology assessment we perform Fast Fourier Transform for the sequence formed by consecutive replication of a single pulse waveform with removed dc component. For accurate extraction of single pulse waveform from raw biosignal sequence the adaptive detector of pule wave beats was used [7]. This detector is characterized by small errors in detecting maximums and onsets of pulse waves, contaminated by various types of artifacts and noise of different origin and intensity.

Analysis of the obtained spectral characteristics for different types of pulse waveforms has shown significant differences in the structure of the amplitude spectrum. For numerical evaluation of these spectral differences we suggest the use of spectral harmonic index (SHI) defined as the amplitude ratio of the first harmonic (As_1) to the second harmonic (As_2):

$$SHI = \frac{As_1}{As_2}$$

For practical studies of different approaches to the pulse wave contour analysis it is necessary to collect clinical pulse wave recordings from people with various conditions of arterial vessels. The pulse wave signals were recorded by using certified photoplethysmography device ELDAR ("New Devices Ltd", Samara, Russian Federation) with the probe located at the cuticle of forefinger of the right hand, sampling rate of 100 Hz, ADC resolution of 10 bits, bandwidth of 0,05 – 15 Hz.

Three groups of volunteers, consisting of 75 people aged from 20 to 70 years were examined. The 1st group (Group A) consisted of 30 young healthy people aged 20 to 35 years; the 2nd group (Group B) consisted of 25 people at

ages from 40 to 55 years with typical age-related changes in arterial stiffness, but without significant cardiac diseases; and the 3rd group (Group C) consisted of 20 elderly people with different cardiovascular diseases aged 60 to 75 years. Informed consent was obtained from all participants. The Ethical Committee of the Regional Hospital at Samara has approved the clinical study.

The study was conducted in a regional clinical hospital in a quiet room at 22^0 C. Pulse wave recording for all subjects was performed in the period from 8 a.m. to 10 a.m. on an empty stomach after a 10 minute rest in the supine position. All drugs were canceled 12 hours before the study. To assess differences between mean values in compared groups we used the non-parametric Mann-Whitney U test. All experimental data are presented as M ± SD (M is the mean value of the arterial index and SD is the standard deviation), the differences were considered significant at $p < 0{,}02$.

IV. Results

Fig. 2 shows typical pulse waveforms in the time domain for each of the three groups, the amplitude of the pulse wave is given in arbitrary units. Typical waveforms from each group demonstrate obvious morphological features of the pulse wave signal and emphasize distinctions among the considered groups. Figure 3 illustrates the amplitude spectrum of the corresponding replicated pulse waveforms from Figure 2.

With developing severe functional changes in the arterial system (see Fig. 3), the bimodal shape of pulse wave disappears, and the dicrotic peak becomes indistinguishable, which leads to significant difficulties in using classic indices for pulse wave contour analysis.

Table 1. Arterial indices for three observed groups

Group	Arterial indices M ± SD			
	SHI, units	*FF, units*	*SI, m/s*	*RI, %*
Group A	1.05±0,16	1.91±0,22	7.5±0,65	54±11
Group B	1.48±0,36	1.51±0,31	9.8±1,15	61±15
Group C	2.25±0,34	1.25±0,19	n/a	n/a

The values of different arterial indices for three observed groups are listed in Table 1 (n/a means non applicable).

Table 2 contains the results of quantifying the statistical reliability of different indices for arterial stiffness assessment; we have calculated Specificity (S^+) for two groups of healthy people (*Groups A* and *B*) and Sensitivity (S^-) for the group of people with cardiovascular diseases (*Group C*) [9].

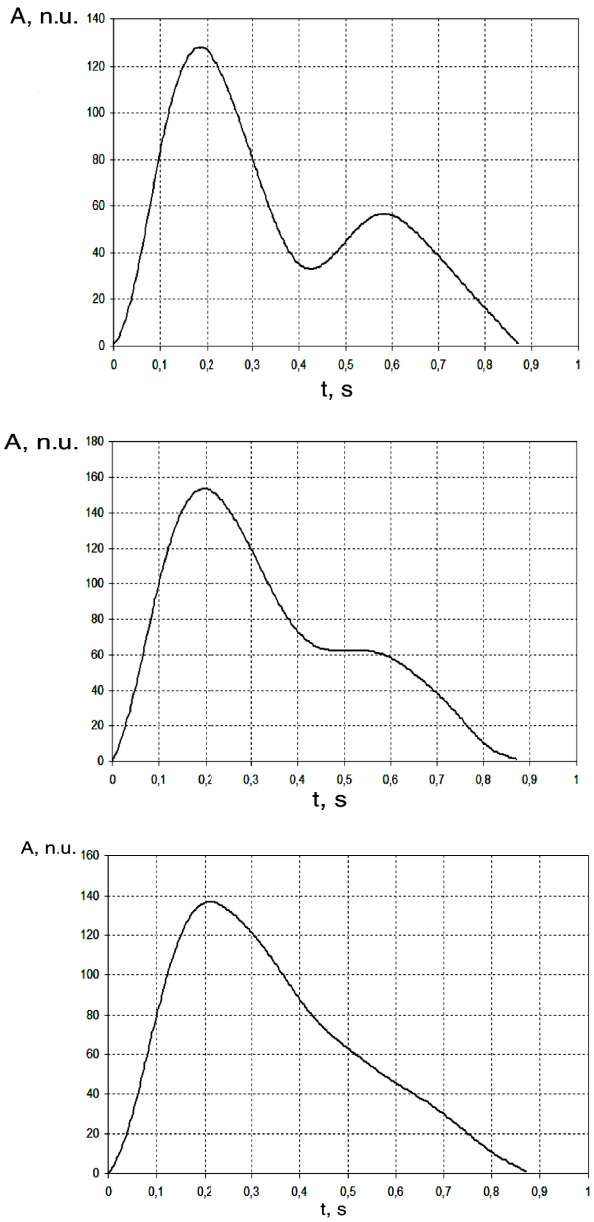

Fig. 2. Typical pulse waveforms: top trace is from group A; middle trace is from group B; bottom trace is from group C

We were unable to obtain any reliable results of calculating *SI* and *RI* for the participants from *group C* due to inevitable issue with dicrotic peak detection, at the same time there were no problems with defining arterial indices for that group by using proposed spectral approach or calculating form factor of single pulse waveform. Obtained results also suggest that there are substantial and significant differences ($p < 0{,}02$) in the values of

form factor *FF* and the *SHI* defined for people with different functional state of the arterial system.

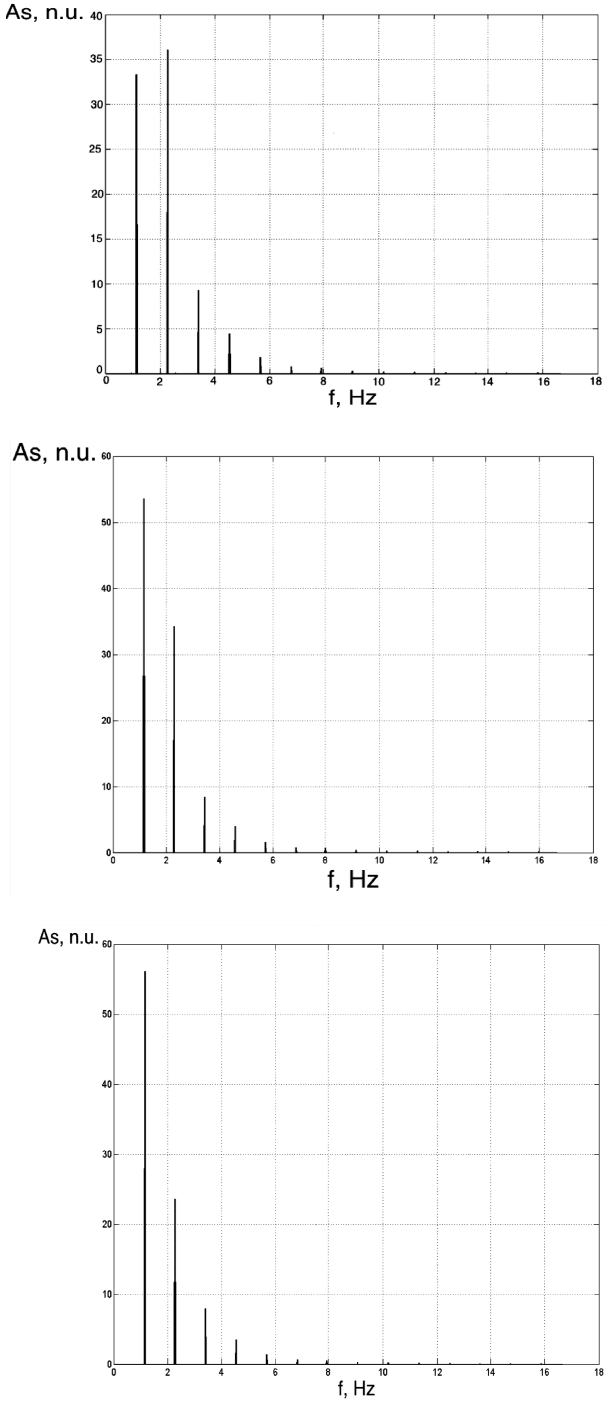

Fig. 3. The amplitude spectrum for replicated pulse waveform from Fig. 2; top trace is from group A; middle trace is from group B; bottom trace is from group C

Table 2. The sensitivity and specificity for different indices of pulse wave contour analysis

Group	Sensitivity S^+, %				Specificity S^-, %			
	SHI	*FF*	*SI*	*RI*	*SHI*	*FF*	*SI*	*RI*
Group A	–	–	–	–	**86**	82	78	72
Group B	–	–	–	–	**85**	81	78	74
Group C	**88**	80	n/a	n/a	–	–	–	–

V. Conclusion

The results of our study indicate that using spectral analysis for sequence of replicated pulse waveform is a powerful method for noninvasive arterial vessels diagnostics, which characterized by higher values of sensitivity and specificity compared to classic contour analysis implemented in the time domain. Spectral analysis of replicated pulse waveform could be an effective basis for creating novel diagnostic algorithms for assessment of arterial stiffness based on the pulse wave contour analysis.

The clear advantage of using the proposed spectral approach in comparison with classic time domain methods is that there is no need for accurate detection of the pulse wave's dicrotic peak that is crucial in case of assessment arterial stiffness for elderly people with severe cardiac diseases and almost indistinguishable dicrotic peak. The disadvantage of the suggested technique may include the need for correct extraction of the single pulse wave, which in practice may be difficult due to present baseline wander and movement artifacts, heavily distorting the shape of the pulse waveform.

Conflict of Interest

The authors declare that they have no conflict of interest.

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