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METHOD OF EXTRACTING SIGNIFICANT COMPONENTS FOR ASSESSING THE VARIABILITY OF THE PULSE WAVE FORM

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Abstract

The generally accepted approach to pulse wave analysis is based on the assessment of its shape features within each cardio interval. In this case, a set of indices (cardiac efficiency index, reflection index, stiffness index) is calculated, which are determined by the reference points of the waveform. The authors propose an alternative method based on harmonic analysis of the resampled signal for each of the cardio intervals and has a number of advantages in studying the variability of the pulse waveform separately from the variability of its rhythm. The results of a pilot series of experiments using the new method indicate its promise in solving the problems of restoring the central pulse from distal measurements.

Keywords: Pulse wave, harmonic analysis, rheography, central pulse, pulse waveform variability.

Introduction

Analysis of signals characterizing physiological activity is one of the important and permanently relevant tasks of biophysics. The complexity of the quantitative description of pulse signals of a living organism is largely determined by their variability in time, dependence on the point and method of measurement, as well as individual characteristics. The generally accepted approach to the analysis of the pulse wave (PV) shape within one cardio interval is based on the assessment of the features of its shape. In this case, a set of indices is calculated (cardiac efficiency index, reflection index, stiffness index), which are determined by the reference points of the wave shape (maxima of the most pronounced peaks, points of maximum velocity and acceleration). It has been confirmed that the tone and elastic properties of the vessels significantly affect the specified characteristics of the pulse wave - thus, in work a change in the amplitude-temporal parameters of the pulse wave due to the attenuation of the dicrotic tooth of the photoplethysmogram with age was recorded. Approaches based on the analysis of the second derivative are also being developed, based on the relationship between the characteristics of the pulse wave acceleration signal and the main indicators of the cardiovascular system, such as the stiffness or dispensability of the arteries. Note that in the conditions of practical calculation of indices by reference points, automated detection of the necessary events on the pulse gram is unreliable and, at a minimum, requires adaptive preprocessing methods. The specific pulse wave form (PWF) depends on a large number of external factors, such as the signal pickup location, the type of recording device, the measurement time, and the impact of the environment [9]. For this reason, the analysis of the shape variability is currently mainly limited to assessing the error of the selected characteristics on the average cardio interval [10, 11], and their dynamics during one implementation are not considered. Since the value of the cardio interval is also variable, when analyzing the PWF, the question arises of the correct segmentation of the signal into individual fragments, the components of which do not depend on the number of readings of a specific cardio interval. In the works [12–14], an algorithm for dividing a pulse gram into cardio intervals and a method for analyzing functionally significant elements for each of them are proposed. The resulting series represent the dependence of elements on the cardio interval number, in which periodic components are identified using spectral analysis. In medical practice, an assessment of the condition of the aorta and large arteries is of key importance for the early diagnosis and treatment of cardiovascular disorders such as heart attacks, diabetes, and renal complications. It has been shown that the shape of blood pressure fluctuations at the central level (central pulse) is a stronger predictor of complications compared to similar measurements at the periphery (distal pulse) [15–19]. Since noninvasive recording of the central pulse is relatively complex and of little use for screening and self-diagnosis, methods for reconstructing the central pulse wave from the distal pulse are being developed. A notable achievement in this area was the radial applanation tonometry method, implemented in the Sphygmo Cor device (At Cor Medical, West Ryde, NSW, Australia). For mathematical processing of the signal, an approach based on the generalized transfer function (GTF) was used, establishing a connection between the peripheral pulse signal as input data and the central pulse as a result of transformation. Despite the fact that this method is recognized as the "gold standard" of noninvasive central arterial pressure measurement and is considered validated in relation to the invasive measurement method, questions about the clinical significance of the transfer function remain open. Since the pulse wave propagates from the center to the periphery and the distal pulse signal is a transformed signal of the central pulse, the problem of reconstructing the central pulse from the distal one is, in principle, solvable. However, the practical solution of this problem is complicated by the fact that the pulse wave signal changes shape on the way from the center to the periphery due to dispersion and nonlinearity of the propagation medium, effects of spatial inhomogeneity (wave reflection), as well as modulation of the properties of the propagation medium (elasticity of the walls of blood vessels) by various systemic and local factors. In such conditions, an additional assessment of the relationship between the central pulse signal and the measurement results at distal points is necessary.

In this paper, a method for such an assessment is proposed based on a specially developed method for analyzing the pulse wave shape, which meets the following requirements:

1) is operational under conditions of significant variability in the pulse wave shape over time (does not depend on the presence or position of local peaks);

2) does not discard a priori some of the information, as is done by any methods that quantify the features of the PDF (for example, the presence of more than one secondary peak is ignored when processing by the traditional method);

3) automatically highlights the most significant features of the PDF;

4) allows for quantitative comparison of PV signals of different shapes, as well as with different durations of the cardio interval.

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Sections 1, 2, 3 of the article describe in detail the proposed method, demonstrate its performance on surrogate data, and present the results of a "pilot" experiment, which indicate the feasibility of restoring the central pulse.

The measurements were carried out on a group of 16 healthy volunteers aged 20–35 years after 20 minutes in a calm state. Rheographic signals were synchronously recorded from three points on the surface of human skin: Rc (the projection area of the aorta, located at the second intercostal space at the left edge of the sternum), Rw (left wrist, radial artery), Rf (left index finger, micro vessels) (Fig. 1, a). To minimize interference from respiratory activity, the recording was made during the volunteer's breath-holding during inhalation for 30 s. A typical view of the recorded signals before their pre-processing is shown in Fig. 1, b. Pre-processing of the data included filtering frequencies above 25 Hz using standard methods, trend removal, and segmentation of the pulse wave sequence into separate fragments corresponding to cardio intervals. This segmentation was performed according to the time coordinates of the maxima of the first derivative

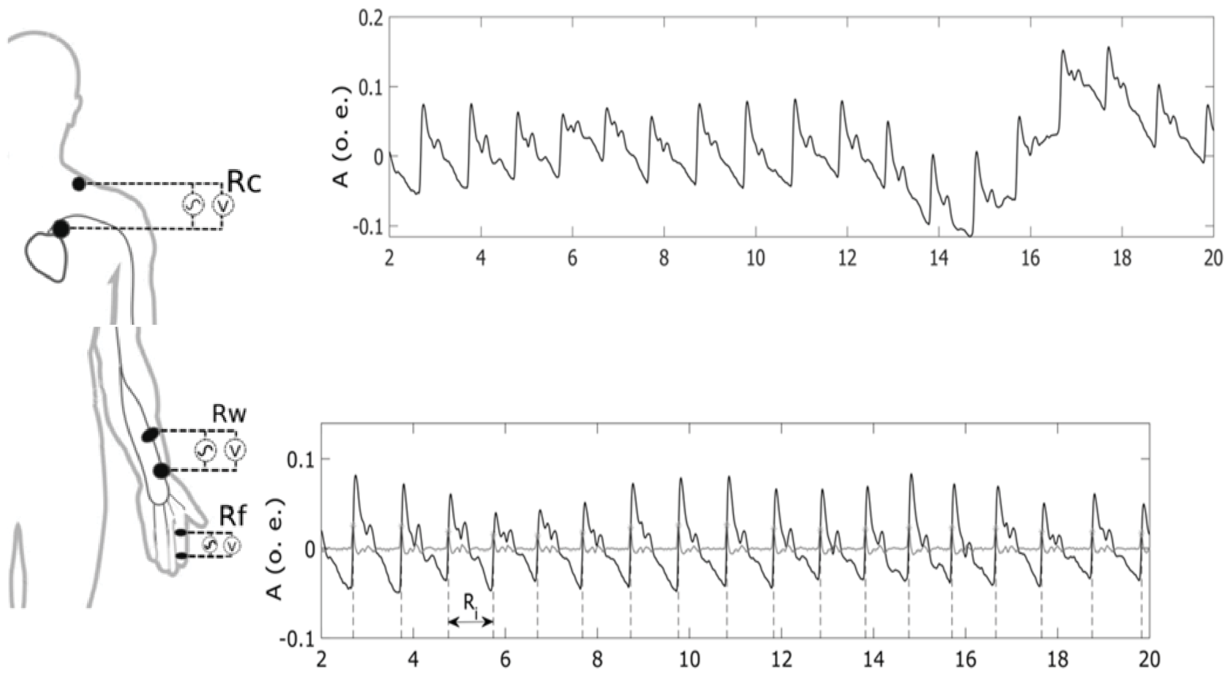

Fig. 1. To the experimental technique description: (*a*) diagram of the used rheographic leads; (*b*) a typical view of the recorded

signals before preprocessing (top panel) and stage of segmentation into cardio intervals (bottom panel) During the analysis, rheographic signals were divided into single pulses by the time coordinates of the maxima of the first derivatives (inflection points), and the linear trend was subtracted for each pulse burst.

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Method of extracting significant components of pulse waves

The described method was developed to solve the problems of analyzing the variability of the pulse wave shape regardless of the rhythm variability and the value of the cardio interval. A distinctive feature of the method is that the classic instrument of spectral analysis - Fourier series expansion by harmonic functions - is used not for frequency analysis, but to describe the features of the pulse wave shape regardless of its frequency-time characteristics. As indicated above, the initial data are presented as a set of individual fragments, each of which corresponds to one cardio interval (from the beginning of one to the beginning of the next). The first step is to resample each cardio interval by the same, predetermined number of samples M. Thus, information about the current cardiority, including its variability, is deliberately removed from the signal. Next, the variability of the shape of individual waveforms is quantitatively measured by calculating the amplitudes and phases of the harmonics of each waveform as a representative of a strictly periodic sequence. The latter is important, since the original pulse wave signal, due to the variability of the cardiac rhythm (and other factors), belongs to the class of random signals and for it, as for the whole, the amplitude and phase Fourier spectra (only the power spectrum) are not determined.

Results

The method described above was applied to process the data of the "pilot" series of experiments aimed at quantitatively calculating the relationship between the central and distal pulses. This was done by assessing the stability of the pulse wave harmonics recorded at different sites in the vascular bed, as shown in Fig. 1.

At the first stage, the number of significant harmonics was determined for each site in the vascular bed, a shows the power spectrum for pulse waves averaged over cardiointervals from three recording sites. Note that the harmonic composition is noticeably wider for peripheral pulse waves than for aortic ones. It can be seen that the spectrum of the central pulse, which is shown by the solid line, quickly decreases as the harmonic number increases. Significant components for the periphery are determined by seven significant harmonics. For the central pulse, their number does not exceed 5. It is worth emphasizing that with the selected number of samples for single fragments of the PV (64 samples), one or two harmonics can be considered significant differences in the spectrum. Note that the wrist signal in this case has the most complex structure in comparison with the central wave and the finger microcirculation wave, which is expressed in an increased number of significant components.

Conclusions

A method for analyzing the variability of the pulse wave shape has been proposed, implemented, and tested. It is based on the harmonic analysis of the resampled signal for each of the cardio intervals and is aimed at studying the variability of the pulse wave shape separately from the variability of its rhythm.

The study conducted using the developed method revealed significant differences in the stability of the pulse wave shape recorded in different areas of the vascular bed, which is expressed in different degrees of variability of their main components. It is important that the central pulse has a smaller number of significant harmonics compared to the distal one, and is more stable in the

first four harmonics containing the main signal power. The obtained quantitative data on the stability of the harmonics of the central pulse
wave can be used in the course of further development of the transfer function method in the task of restoring the shape of the central pulse based on distal measurements.
Comparison of the radial artery pulse with the microcirculatory pulse recorded on the phalanx of the finger showed a different nature of variability depending on individual characteristics. It should be emphasized here that the individual characteristics of the contribution of various regulatory mechanisms to the shape do not allow one of these two recording methods to be classified as the most stable. In comparison with widely used methods such as wavelet analysis or empirical mode decomposition, the proposed method is more narrowly specialized in accordance with the task for which it was developed - comparison of the degree of variability of the shape of several different signals. Considering the low computational costs and simple processing scheme, we assume that the proposed method can be used as a numerical analysis method for assessing the variability of the pulse wave signal shape regardless of the method of its registration.

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