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Статистичний алгоритм для швидкої оцінки частоти серцебиття й локалізації серцевих тонів у фонокардіограмах, записаних за допомогою електронних стетоскопів

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A statistical algorithm for fast estimation of heart rate and localization of cardiac sounds in phonocardiograms recorded by electronic stethoscopes

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Представлено пілотну версію алгоритму для швидкого визначення тривалостей систолічної й діастолічної фаз серцевого циклу на базі статистичної обробки цифрової фонокардіограми. Розроблена методика включає локалізацію серцевих тонів у записі за допомогою квантильної дихотомії та модовий аналіз обчислених часових інтервалів між сусідніми знайденими піками. Після цього будується діаграма розсіювання в термінах часових інтервалів до і після кожного піку. Стабільність серцевого ритму визначається щільністю кластеру, який утворюється поблизу перетину двох модальних значень, нанесених уздовж осей. При домінуванні в сигналі кардіологічної компоненти запропонований підхід дозволяє досить надійно визначати моменти появи першого й другого серцевих тонів практично на кожному з циклів роботи серця. Це відкриває можливість для аналізу варіації тривалостей окремих фаз серцевих скорочень з плином часу. Завдяки роботі безпосередньо в часовій області й низьким обчислювальним затратам алгоритми цього класу придатні для застосування в портативних діагностичних системах з обмеженими процесорними потужностями.

Ключові слова: фонокардіографія, серцеві тони, цифрова фонограма, квантиль, мода.

A draft version of the algorithm for fast determination of duration of the systolic and diastolic phases of the cardiac cycle based on a statistical analysis of a digital phonocardiogram is presented. The developed technique includes localization of the cardiac tones in the record by a quantile dichotomy and modal analysis of the calculated time intervals between the adjacent detected peaks. Next, the scatter plot is constructed in terms of time intervals before and after each peak. The stability of the cardiac rhythm is determined by the density of the cluster occurring near the cross-section of two modal values plotted along the axes. At dominance of a cardiac component in the signal, the discussed approach allows quite reliable determination of the moments of the emergence of the first and second cardiac sounds tones practically on each of the cardiac cycles. This opens the possibility to analyze the variation in the duration of separate phases of heart contractions over time. Due to the work directly in the time domain and low computational costs, the algorithms of this class are suitable for application in portable diagnostic systems with limited processor power.

Key Words: phonocardiography, cardiac sounds, digital sound record, quantile, mode.

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Introduction

The key role of the heart in ensuring the vital functions of the human body determines the unfailing interest in its studying. It is well known that the operation of this organ is accompanied by various biophysical phenomena. This makes the heart a unique manifold object of investigation far from fully revealing its secrets. Indeed, one can consider it as a hydraulic pump, an electromagnetic generator, a source of vibroacoustic signals, and so on.

Finally, the heart is a classic example of the essentially nonlinear dynamic system demonstrating the full range of possible regimes from almost exact periodicity to chaos.

The great variety of physical effects emerging at cardiac activity lead to the creation of several objective instrumental methods of medical diagnosis of the heart. In particular, the electro- and phonocardiography related to the interpretation of the collateral electric and acoustic phenomena should be noted in this context.

There is now a demand for the creation of portable and easy-to-use medical tools for telemedicine diagnosis and self-diagnosis of the cardiovascular system. Expensive stationery echocardiographs are absolutely unsuitable for this purpose. Therefore, one should focus on passive non-invasive techniques that are not associated with the potentially negative effect of ultrasound on the patient's body. A preliminary analysis shows that the phonocardiographic examination method may be even more suitable than the electrocardiographic one for the mentioned segment of the medical equipment market [1, 2]. This inevitably puts forward the necessity for developing fast, simple, reliable, and clear ways to present data on the characteristics of cardiac activity. Based on this, in this study, we would focus on current issues of digital phonocardiograms processing with a focus on methods that require minimal computing power.

Features of Cardiac Sounds

It is known that the work of the heart is of cyclic nature. It consists of the sequential repetition of similar phases that correspond to the contraction and relaxation of the myocardium, the opening, and the closing of the heart valves. Determination of cardiac rhythm, quantitative parameters of individual phases, their regularity, and duration are a valuable part of cardiovascular diagnostics.

The cardiac sounds are the short pulses (tones) generated at the opening and closing of the tricuspid pulmonary, mitral, and aortic valves. They distinguish four cardiac sounds, S1 ,..., S4, still, only S1 and S2 can be usually heard. Their appearances coincide with the start and the end of the myocardium contraction phase, the systole. The emergence of S3 and/or S4 sounds, along with valve murmurs, are evidence of cardiac pathologies [2, 3].

Note that the electrocardiographic examination does not provide exact localization of the moments of operation of valves. The reason is that the emergence of the measured electric signal is related to the myocardium repolarization-depolarization being the processes of fundamentally different origins.

A Statistical Approach to Analysis of Phonocardiograms

Despite their cyclic nature, cardiac contractions are rarely strictly periodic. Such aperiodicity inevitably leads to the widening of the efficient band of cyclic frequencies of the cardiac signal. This results in the dramatic decrease of resolution of the spectral techniques when used for determining actual heart rate, including the cyclostationarity approach. On the other hand, the adaptive methods like the Empirical Modal Decomposition or Empirical Wavelet Transform are insufficiently reliable when separating the intrinsic signal modes related to cardiac activity [4].

The above difficulties require withdrawal from the use of spectral-frequency decomposition of the signal, traditional for various branches of acoustics. In these conditions, attention should be paid to the approaches which allow the analysis of the sampled phonocardiograms in the time domain. These include, in particular, the quantile analysis of statistics proposed in the 1940s by Maurice Kendall [5]. Currently, this young branch of mathematical statistics is actively developing. This results in the successful application of quantile-based techniques to process data in various fields of knowledge, from econometrics to psychophysiology.

The digital phonocardiogram is the recorded acoustic response of the cardiac activity sampled for the discrete sequence of instant values of the signal amplitudes. Within mathematical statistics, it is considered as the statistical population. The essence of the chosen approach is the statistical dichotomy of the series of amplitudes absolute values with a cut-off of the given portion of its terms having the relative length $0<p<1$ (where unity means the whole sequence). Call the number x_p the p-quantile of a probability distribution if the values of the p-th part of the statistical population are less or equal to x_p. In these terms, the median is the most common kind of a quantile with the level of 0.5 since it divides the population into two parts of equal lengths.

The utility of a quantile dichotomy is manifested in much better separating sharp bursts in the numerical sequences than the analysis based on average values. For example, the median is a more reliable measure of the typical term than the Root Mean Square. It was already mentioned that the cardiac sounds have a pronounced impulse character and form short peaks on the phonogram. Therefore, cutting off the part of the sequence by a quantile close to unity provides the efficient localization of the instants associated with the components S1, S2, etc. To apply this procedure, calculate the normalized signal energy by a standard Hilbert Transform. Then localize the peak values by a quantile with the level *p*. Practice shows that at a sufficiently high Signal-to-Noise Ratio, the acceptable range of *p* makes mostly from 0.8 to 0.95.

The next step is a modal analysis of the sequence of peak-to-peak intervals. This procedure allows the separation of the characteristic values supposed to correspond to systolic (from S1 to S2) and diastolic (from S2 to the next S1) intervals. Such recognition is practically possible since the duration of the systole is always shorter. Finally, the obtained values are grouped in the scatter plot, which is built in the coordinates of S1-S2 and S2-S1 intervals.

Application of the Method

Now proceed to an example of using the method. The considered record of cardiac sounds is obtained from a healthy male by electronic stethoscope paired with a smartphone. The signal was recorded with delayed breathing to improve the phonogram quality. The resulting Signal-to-Noise Ratio in a frequency range from 50 Hz to 400 Hz was not worse than 12 dB.

A fragment of the time dependence of normalized energy of the chosen cardiac signal is shown in fig. 1. A horizontal line in the plot corresponds to the quantile with a level *p*=0.9. Study the properties of the localized high-energy maximums shown with the markers.

The main problem of phonocardiography is the practical impossibility of signal recording without impulse vibrational interference from traffic, vibration noise from the friction of the sensor against the skin, etc. Therefore, some "parasitic" peaks may occur in the set detected using quantile localization. Moreover, some cardiac sounds might be omitted since the strength of individual heartbeats can vary significantly. Let us illustrate this point with fig. 2 depicting the evolution of time intervals between the adjacent detected peaks. Note that most of them separate into two subsets with quite regular properties. However, several false maxima are found that are not related to cardiac activity. Nevertheless, the applied basic statistical algorithm assessed the characteristic values of the systolic and diastolic intervals and the limits of their variation during the recording. Analysis of the frequency distribution of the calculated peak-to-peak intervals yields two vivid modal maximums of 0.3 sec and 0.425 sec.

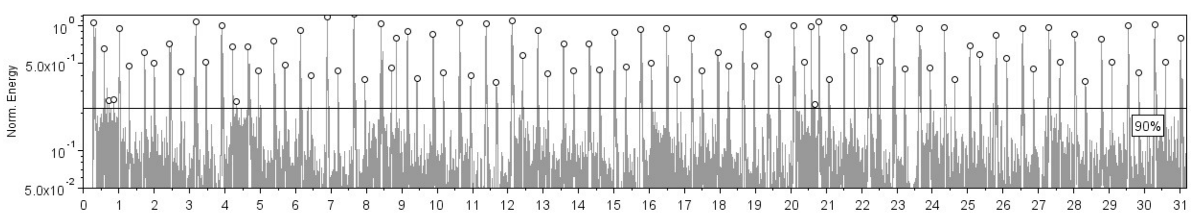

Fig. 1 Time dependence of normalized energy of a cardiac signal with a quantile localization of maximums.

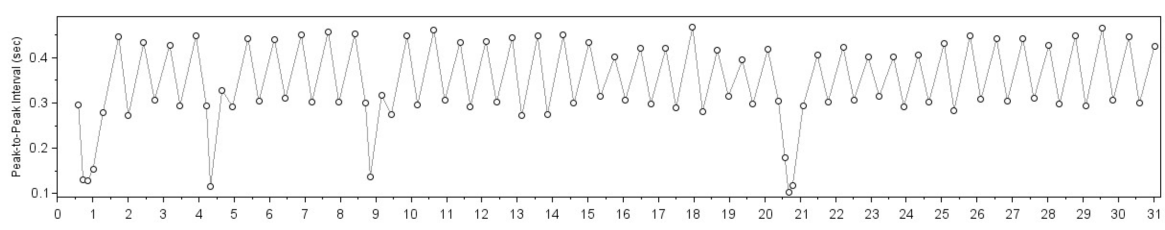

Fig. 2 Evolution of the intervals between the adjacent detected peaks over the record time.

Plot all localized energy maximums on the scatter diagram (fig. 3). Here, the shorter peak-to-peak intervals are set along the abscissa axis, and the longer ones are along the ordinate axis. One may consider them as durations of the systole and diastole, respectively. Two dashed straight lines stand for detected modes. As expected, the vast majority of the peaks form a dense cluster at the intersection of the modal values. Such behavior proves the absence of evident pathologies for the examined heart. The sum of the systolic and diastolic intervals gives the period of the cardiac cycle. It may be readily converted to a usual cardiac rate calculated in beats per minute.

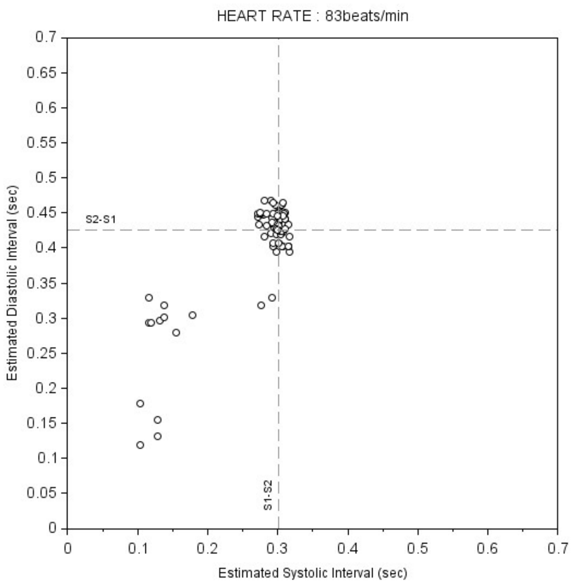

Fig. 3 The scatter diagram for peak-to-peak intervals

Conclusion

1. An algorithm for the statistical analysis of phonocardiograms in the time domain is developed and implemented. The proposed approach is based on the quantile localization of signal energy maximums related to the emergence of cardiac tones and subsequent modal analysis of time intervals between adjacent detected peaks.
2. The effectiveness of the method is illustrated by a particular example. For the case of dominance of a cardiac component in the record, it is possible to determine the typical values of the systolic and diastolic intervals and their variation with time.

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