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Mathematical Heart Sound Model Construction Criteria

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Abstract*: The article analyzes the capacities of phonocardiography, a diagnostic method based on the registration and analysis of heart sounds. The authors recognize a considerable contribution made by subjective assessments reasoned by the individual peculiarities of physicians' hearing and the existence of a method objectification problem. The article substantiates the need for developing a method to synthesize the fragments of physiological and pathological phonocardiograms (PCGs) as a source of reference signals used for comparison purposes when making diagnoses in clinical and educational settings. The authors made an attempt to objectively assess reference PCGs from the 3M Library and their own findings obtained in the course of a medical and biological experiment. They demonstrated the high individuality of systolic sounds and the high repeatability of diastolic sounds even within the limits of one and the same phonocardiogram and obtained high-resolution spectral, amplitude-and-frequency and time-and-frequency characteristics. No fundamental differences between the signals obtained via a measurement condenser microphone and piezoceramic contact sensors were revealed.

***Index Terms*: Phonocardiogram, heart sounds, spectral analysis, frequency characteristics, time characteristics, piezoceramic microphone.**

I. INTRODUCTION

Introduced in the late 1950s, the phonocardiography method based on the registration and further analysis of physiological and pathological heart sounds has not gained widespread use yet. Some authors believe that the reason is the impossibility to assess the state of the cardiac conduction system, which can be performed via electrocardiography, whereas experienced physicians effectively differentiate acoustic phenomena associated with different pathological conditions during auscultation [1], [2]. The acoustic assessment of heart sounds and murmurs is subjective, which is associated with personal physiological and age-related hearing features [3]. For instance, less than 2% of the population is characterized by absolute pitch that allows identifying and re-creating a given audio tone without the benefit of an external reference tone. Most likely, it is connected with inherited abilities [4]. Another infrequent ability in the community is musical memory that allows recognizing complex acoustic images and matching them with the previously heard ones [5]. However, auscultation analyses definitely require both of these inherited abilities to hear and recognize sounds, even if they are not of an absolute quality. It is highly unlikely that the absolute majority of practicing physicians are people with high levels of the sense of pitch and musical memory. Physicians who are engaged in cardiology and pulmonology claim that they quite often hold mutual consultations to determine the type and nature of pathological sounds registered via auscultation. The analysis of phonocardiograms (PCGs) obtained with electronic stethoscopes has not gained widespread use in diagnostic practice, since they introduce specific errors in the flow of sounds and do not always allow making an objective evaluation even by means of signal visualization [6]. Therefore, there is the problem of objectifying diagnostic decisions based on auscultation findings regardless of physicians' personal abilities. However, making such decisions requires a set of reference signals that would be near-perfect in terms of their primary parameters. Choosing such signals during clinical examinations, e.g., to train students and residents, is definitely a challenging task that can take a lot of time: usually hospitalized patients have several comorbidities. In this context, the second problem emerges: generation of signals with pre-set parameters close to canonic physiological and pathological heart sounds. The authors did not find a solution to this problem in the existing literature. This article analyzes the parameters of phonocardiograms obtained from different sources. The findings will allow determining criteria being necessary to synthesize clinically valid signals imitating both physiological PCGs and primary pathological forms. Eventually, they will allow developing a PCG generator to create signals that can be used for education and as reference sounds for expert evaluation.

II. MATERIALS AND METHODS

Before developing criteria to synthesize PCG signals, it was necessary to carry out several different studies to determine the physical parameters of native verified signals from generally accepted libraries that were recommended by reputable organizations as reference. A library of cardiologic sounds and murmurs created by the 3M Company, a manufacturer of electronic stethoscopes, was chosen as such a source [7].

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Further signal verification was performed with the help of records obtained by means of a wearable PCG monitor developed by the authors [8]. Recorded PCGs passed the signal processing stage and, along with the reference recordings, were subjected to extensive analysis in order to determine relevant characteristics and parameters. PCGs were recorded in clinical settings in adult patients aged 18-47 who provided informed consent. During the PCG registration procedure, the patients were in the lying position; the recording was started after a 5-7-minute adaptation period. Signals registered by the device sensors were submitted to the precision "charge-to-voltage" transformer, then an electron filter singled out oscillations within the operating band of 16-180 kHz (Figure 1). These oscillations were submitted to the input of the automatic voltage control system and further on, to the analogue-to-digital converter. The signals were converted into the byte format with no loss in quality and saved as byte streams with a sampling frequency of 1-10 kHz.

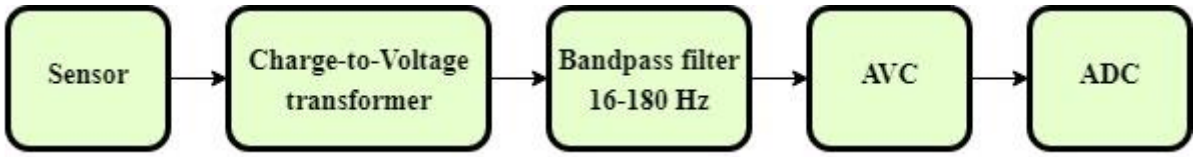

Fig. 1: PCG monitor

An identical procedure was used to single out, process and analyze systolic PCG cycles for reference signals and records obtained in the course of a medical and biological experiment. Initially, the Audacity audio editor, version 2.3.1 (https://www.audacityteam.org), was used to visually rank records by the quality of the registered signals. PCG sections with the minimum level of noise and disturbance were singled out and saved as individual files. Every PCG section was manually divided into separate systolic cycles. The borders of each cycle were determined via a verified procedure described in [8]. Every singled-out systolic cycle was also saved as an individual WAVE file, which guaranteed the absence of distortions caused by the editor. In total, 42 systolic cycles from the library [7] and 417 systolic cycles from the authors' own research findings were singled out and analyzed. The singled-out signals of separate systolic cycles were analyzed with the help of command scripts in the Scilab 6.0.1 mathematic analysis system (https://www.scilab.org) having similar capacities with those of the well-known Matlab commercial system. The authors used the guidelines and algorithms described in [9], [10] and [11]. The Inkscape 0.92 vector graphics package was used to create some illustrations.

Initially, the authors performed additional digital signal filtration with the 48-order digital Chebyshev filter to single out valid signals within the frequency band of 18-180 Hz. The form of typical systolic cycle signals cleared from noise and disturbance is shown in Figure 2.

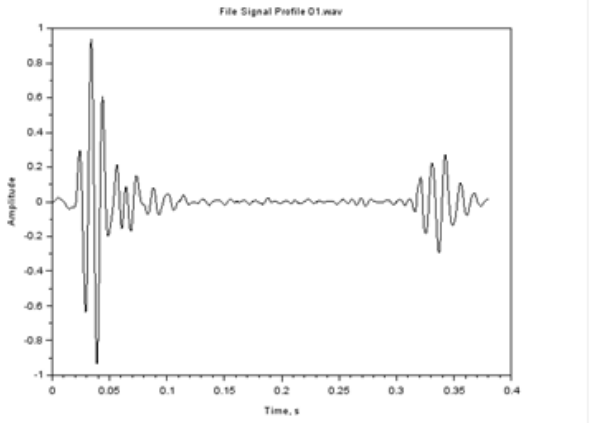

Fig. 2: Typical systolic cycle singled out of the PCG signal

Then every systolic cycle underwent a versatile spectral and time analysis. The spectral analysis of the signals was performed via the standard fast Fourier transformation (FFT) algorithm. A 1,024-point Kaiser window was used to create the spectrum of a reference signal with a sampling frequency of 44.1 kHz. This window is optimal for this purpose in a way, as it fits the frame length (23.2 ms). Such a window length limited the accuracy of localizing the time parameters of the analyzed signals and provided the guaranteed frequency resolution of 2 Hz. Reducing the window width increased the accuracy of time localization but decreased the frequency resolution due to Heisenberg's uncertainty principle. During the analysis of the authors' own data, after the completion of preliminary procedures used to filter and single out phonocardiogram fragments, the signals were re-coded from the RAV 12 bit stream into the WAVE format with a sampling frequency of 10 kHz and 11.6 kHz and 16-bit resolution. Signal resampling was performed with the method of cubic spline interpolation. No significant differences between the spectrum of initial and final signals were revealed for the frequencies specified. When the signals were represented as time sequences, the t-test value was $t > 0.1$ in all the cases, while the correlation coefficient was $rxy = 0.9…0.95$. At the same time, a quite low upper limit of the signals under study (180 Hz) did not allow carrying out a detailed time-and-frequency analysis of heart sounds even at the sampling frequencies specified. At the best, this analysis was limited to four 512-bit windows for systolic sound T1 and two windows – for diastolic sound T2 with a frequency resolution of 4 Hz. Spectral-time analysis findings were used to determine the most important signal frequencies where the amplitude was changing most significantly. After the targeted isolation and amplitude-time analysis of these frequencies, the authors created the families of time profiles that determined the moments of signal emergence, peak and extinction at the set frequency. In both cases, 42 systolic cycles from the library [7] and 42 randomly selected systolic cycles from the phonocardiograms obtained during the authors' own studies were analyzed. The flow chart of the PCG processing and selected systolic cycles analysis shown on Figure 3.

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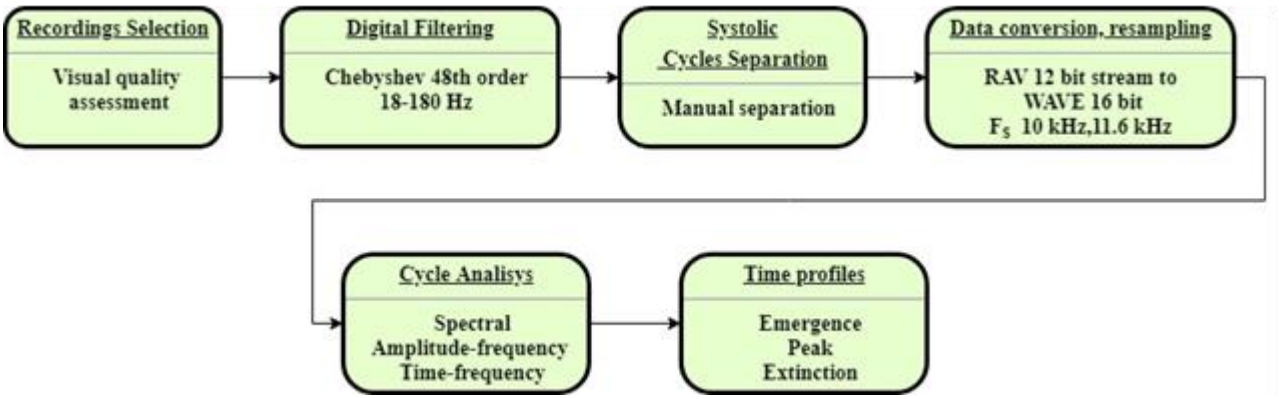


Fig. 3: PCG processing and systolic cycles analysis

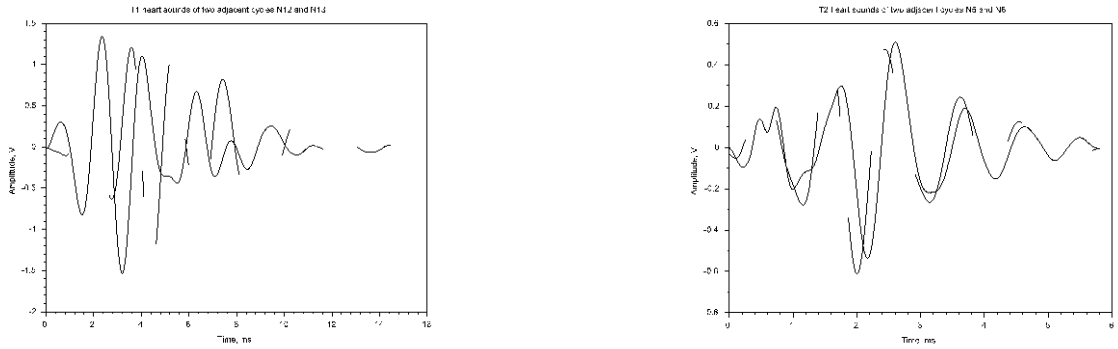
It is noteworthy that, in both cases, no fundamental qualitative differences between analysis findings were revealed.

III. RESULTS AND DISCUSSION

The detailed heart sound analysis allows making several conclusions that have not been mentioned in the existing literature sources yet. From now on, the first systolic heart sound will be defined as T1, and the second diastolic heart sound – as T2.

A. *Repeatability of physical heart sound parameters*

During auscultation examinations, physicians perceive heart sounds as rhythmic thumps that do not differ from each other by ear. However, the simplest PCG analysis reveals that heart sounds are very individual. This peculiarity manifests itself as a considerable difference in the share of even two adjacent heart sounds T1 and, to a smaller degree, diastolic sounds T2. For the purpose of comparison, two randomly selected adjacent sounds T1 and T2 from the same PCG record are shown in Figure 4.



A B

Fig. 4: Comparison of two adjacent, randomly selected heart sounds
A. Systolic sound T1 (N11 and N12). B. Diastolic sound T2 (N5 and N6).

The pair-wise comparison of the randomly selected systolic PCG cycles revealed a wide dispersion of the Pearson correlation coefficients within the range in modulus from rxy = 0.04 to rxy = 0.93 with the mean value rxy = 0.49±0.34 (N=42) for the signals from the 3M Library and from rxy = 0.03 to rxy = 0.98 with the mean value rxy = 0.42±0.28 (N=42) for the authors' own data obtained in the course of a medical and biological experiment. The correlation and comparison of the singled out and randomly selected systolic sounds T1 also revealed a wide dispersion of the correlation coefficients during the analysis of oscillation envelopes: from rxy = 0.03 to rxy = 0.91 with the mean value rxy = 0.14±0.58 (N=42) for the signals from the 3M Library and from rxy = 0.01 to rxy = 0.96 with the mean value rxy = 0.11±0.44 (N=42) for the authors' own data. As for diastolic sounds T2, the correlation coefficients were rxy = 0.37±0.66 (N=42) for the signals from the 3M Library and rxy = 0.34±0.57 for the authors' own data. At the same time, the authors did not detect any consistent patterns of changes in the correlation of the sequence of compared heart sounds. For instance, the first pair of systolic sounds could have the correlation coefficient r12 = 0.87, and a one-step shift gave the value r23 = 0.39. Looking ahead, one should note that pair-wise correlation for the spectra of these signals was significantly higher and appeared to be significant.Such a highly individual share of systolic sound T1 can be explained by the time dispersion of contractive myocardium properties. The authors proceed from the premise that the nervous and, even more so, humoral regulation of the contractive activity of the heart can hardly change during the period of diastole (500-600 ms). The time constant of neurogenic heart regulation and other autonomic reflex reactions amounts to several dozen seconds, while the cardiac reflex exists for no more than 15 minutes.

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The time constant of the humoral regulation of the cardiac muscle amounts to several minutes or several dozen minutes, but the duration of humoral action can amount to hours, days and more [12]. Therefore, such a highly dynamic nature of the physical parameters of heart sound T1 can be connected only with internal mechanisms that occur in cardiocytes and, in the authors' opinion, predominantly have a biophysical nature. These mechanisms are based on electro-mechanical and mechano- mechanical coupling. From the existing point of view, they are described in many articles and guidelines (e.g., in [13]) well enough, and there is no point in listing these mechanisms.

In the authors' opinion, the random nature of the physical characteristics of the T1 acoustic oscillations is primarily connected with the random nature of oscillations at the level of cardiomyocyte excitability, quality of intercellular junctions (nexuses) and condition of the cytoplasmic membrane as cellular factors, as well as the stochastic nature of regulation over the level of ionized calcium in mycoplasma and its release from intracellular depots that launches the process of contraction [13]. At the same time, it is necessary to take into account that the physiological and biophysical nature of the phenomenon observed lies outside the scope of this article and requires additional research studies.

B. *Spectral characteristics of signals*

A detailed spectral analysis was performed for reference signals from the 3M Library. Singled-out phonocardiogram sections were analyzed for 350 ms from the emergence of heart sound T1. A frequency grid from 14 Hz to 78 Hz with a step of 2 Hz was used to build the surface of spectral-time signal characteristics. Therefore, the surface of spectral-time signal characteristics had the shape of a 32x32-point square. Figure 5 demonstrates the spectral-time profile of six isolated successive heart sounds from the same phonocardiogram. All charts were created at the same angles of surface rotation and on approximately the same scale; the amplitudes of the spectra were normalized vs. the mean signal level.

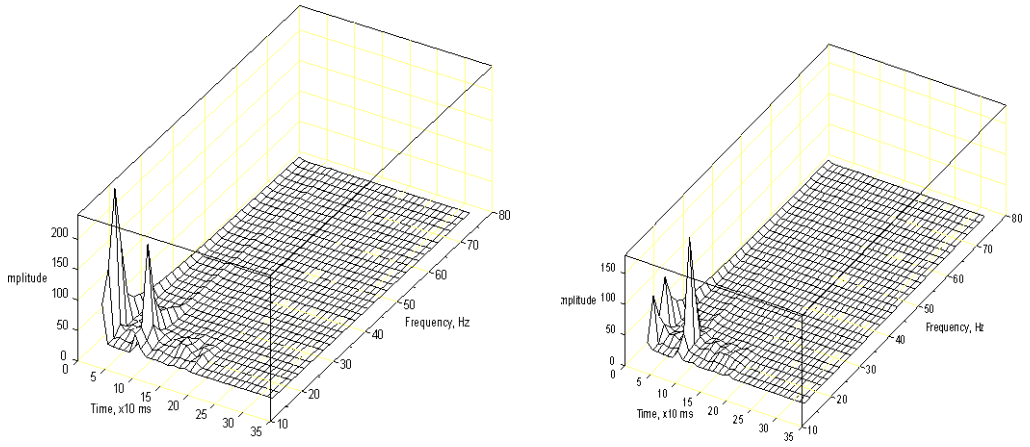

Fig. 5: Spectral-time profiles of two adjacent heart sounds from one and the same phonocardiogram (3M Library).

It is obvious that the first (systolic) heart sound T1 is characterized by extremely high spectral variability in terms of all its parameters: input of component harmonics, moment of their emergence and duration of existence. The T1 systolic sound practically does not contain oscillations with a frequency of higher than 32 Hz. This variability is definitely connected with the high changeability of the systolic tone the reasons for which have been discussed earlier. The second (diastolic) heart sound T2 is also characterized by an individual spectral composition, although to a smaller degree. The distinctive feature of this sound is the presence of a low-amplitude "tail" consisting of oscillations having the frequencies of higher than 40 Hz at the moment of maximum. In the authors' opinion, the existence of low-amplitude oscillations that coincide with the maximum of the second heart sound T2 in time within the frequency band of higher than 45 Hz can be explained by oscillatory phenomena emerging as the consequence of the fast closure of the aortal valve, a reflective wave caused by the arterial pressure spike (known as dicrotic notch in large arteria sphygmograms) and vibrations of the aortal wall, adjacent large vessels and anatomical structures. This assumption is testified to by the short-term existence of this frequency complex.

C. *Amplitude-and-frequency and time-and-frequency parameters of heart sounds*

In order to determine the moment of emergence, time of existence and point of extinction for the component frequencies of heart sounds, the authors analyzed changes in the spectral signal characteristics depending on both amplitude and time. The comparison of the experimental data with reference signals (3M Library) revealed that the difference between randomly chosen signal samples of the primary frequencies of heart sounds appeared to be insignificant according to Student's t-test. It allows suggesting if not complete identity but at least insignificant differences between the methods used to obtain reference phonocardiogram signals from the 3M Library [7] via a high-quality electret microphone [14] and signals registered during the authors' own research studies via a contact piezoelectric sensor [8]. The results of comparing the amplitudes and time parameters of primary frequencies are shown in Tables 1 and 2, respectively.

Table 1. Amplitude of primary heart sound frequencies (relative amplitude of signals, %)

Frequency, Hz	3M Library (N=42)		Own data (N=42)		Differences in the samples according to Student's t-test	
	Sound T1, %	Sound T2, %	Sound T1, %	Sound T2, %	Sound T1	Sound T2
16	100.00	44.22±41.31	100,00	41.22±47.29	> 0.1	> 0.1
20	68.8±38.61	52.23±34.48	74.24±35.14	48.18±38.42	> 0.1	> 0.1
24	54.79±18.88	64.41±48.18	52.18±17.31	55.9±55.39	> 0.1	> 0.1
28	41.35±13.47	76.18±19.22	43.28±14.42	68.19±22.87	> 0.1	> 0.1
32	39.24±12.12	49.72±14.73	35.16±13.98	41.39±10.02	> 0.1	> 0.1
36	31.23±9.12	34.34±14.89	29.08±12.12	36.36±9.14	> 0.1	> 0.1
38	21.16±9.84	29.17±7.17	24.92±9.17	30.1±7.92	> 0.1	> 0.1
42	16.16±9.1	17.36±5.23	18.21±11.37	16.34±7.11	> 0.1	> 0.1
46	12.29±4.2	14.86±2.89	11.91±5.79	13.37±5.12	> 0.1	> 0.1
50	6.11±2.8	8.73±2.14	5.71±3.59	11.92±4.15	> 0.1	> 0.1

Table 2. Time parameters of primary frequencies

Frequency, Hz	3M Library (N=42)			Own data (N=42)			Differences in the samples according to Student's t-test		
	start, ms	max, ms	end, ms	start, ms	max, ms	end, ms	start	max	end
16	0	1.6±0.96	170.2±52.8	0	1.6±0.96	168.8±42.8	>0.1	>0.1	>0.1
20	0	1.8±0.96	160.3±42.8	0	1.8±0.96	154.9±3.8	>0.1	>0.1	>0.1
24	0.96	4.8±0.96	228.8±44.8	0.96	4.8±1.92	209.7±34.8	>0.1	>0.1	>0.1
28	1.92±0.96	6.72±1.92	230.7±32.8	1.92±0.96	6.72±2.88	212.6±34.8	>0.1	>0.1	>0.1
32	1.92±0.96	19.6±1.92	169.7±35.6	1.92±0.96	9.6±2.88	137.6±25.6	>0.1	>0.1	<0,1
36	2.88±0.96	23.84±1.92	185.4±46.2	2.88±0.96	3.84±1.92	169.8±31.5	>0.1	>0.1	>0.1
38	2.88±0.96	3.84±1.92	196±37.6	2.88±0.96	3.84±1.92	174.4±44.4	>0.1	>0.1	>0.1
42	4.8±1.92	5.76±2.88	157.6±35.6	4.8±2.88	6.72±1.92	180.5±37.8	>0.1	>0.1	>0.1
46	7.68±2.88	13.44±7.8	114.4±22.8	7.68±2.88	15.36±4.6	132.8±34.8	>0.1	>0.1	>0.1
50	7.68±2.88	16.32±8.92	111.5±14.8	8.64±3.84	18.24±2.88	127.2±24.3	>0.1	>0.1	>0.1

It is noteworthy that the correlation coefficient of the primary frequencies from the spectra of adjacent systolic cycles was high and amounted to rxy = 0.84±0.19, although the dispersion of frequency spectrum amplitudes was insignificant from one cycle to another. Figure 6 shows the time profiles of component frequency 28 Hz of the systolic cycle obtained from reference signals from the 3M Library and the authors' own data: the differences between them, especially when it comes to the second heart sounds (after 80 ms), are insignificant.

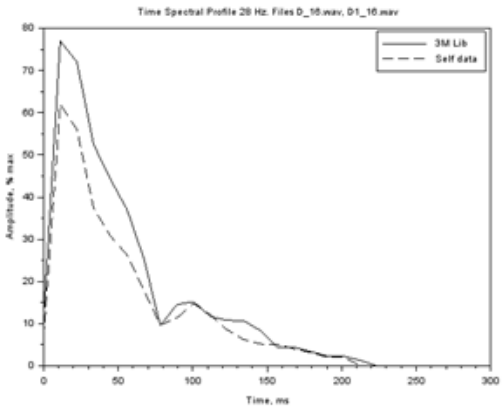

Fig. 6: Spectral and time characteristics of component frequency 28 Hz of the systolic cycle for a reference signal from the 3M Library (continuous line) and the authors' own data (dashed line). The amplitudes are shown in relative units.

IV. CONCLUSION

The authors have made the following conclusions as the result of their analysis of reference signals from the 3M Library and the authors' own findings obtained in the course of a medical and biological experiment:

1) A traditional amplitude-and-frequency and time-and-frequency analysis according to well-known and well-established methods allows preliminarily evaluating the key parameters of heart sounds on the basis of statistically significant data.

2) Even two adjacent heart sounds from the same phonocardiogram have an individual shape. However, this individuality levels off at the statistical level, including after the acquisition of spectral characteristics, and, in the worst-case scenario, it manifests itself as a dispersion of the moments of emergence, peaks and length of the harmonic components of heart sounds.

3) Systolic heart sounds T1 are characterized by the highest individuality, which can be explained by the active nature of the processes occurring in the cardiac muscle. In the authors' opinion, these processes are primarily influenced by the self-regulatory mechanisms of the cardiac muscle and intracellular "excitation-contraction" coupling processes. At the same time, the statistical nature of biophysical processes implies that contraction parameters fluctuate around some mean value.

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4) The less individual nature of diastolic heart sounds T2 can be explained by the emergence of these sounds as the consequences of vibrations with their own resonance caused by different anatomical structures (aortal walls, valves and surrounding tissues) as well as the tremor of the column of blood above the aortal valves. These vibrations emerge following the ejection of blood at the systolic phase. As the composition, density, shape and other parameters of these structures remain unchanged from one systole to another, the parameters of diastolic heart sound T2 are relatively stable.
5) The absence of significant differences between the primary amplitude-and-frequency and time-and-frequency parameters of reference signals from the 3M Library and signals obtained in the course of the author's own research studies allows regarding the registration of phonocardiograms via the authors' own equipment with a piezoelectric contact microphone as correct, and its findings – meeting necessary requirements to this research study.

V. CONFLICTS OF INTERESTS

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