High-resolution phonocardiogram parameters

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Abstract. The article describes the results of studying and analyzing phonocardiograms (PCGs) obtained during a physiological experiment with Blu-ray standard equipment. It provides the findings of a spectral and spectral-time analysis for signals with a sampling frequency of 10, 44.1 and 192 kHz. It shows that the differences in the PCG spectra of identical signals are unreliable. The article specifies the onset and disappearance moments of the harmonic components of heart sounds. It also provides recommendations on the sampling frequency and bit resolution of digitized PCG signals for telemetric systems.

1. Introduction

The World Health Organization reports that, in 2016, 17.9 million people died of cardiovascular diseases (CVDs) in the world. It is about 31% of all fatal cases. 85% of these fatal cases were caused by heart attacks and strokes. Many experts believe that up to 60% of the fatal cases caused by a premature stroke and infarction could be prevented if deceased patients from the risk groups were provided with professional medical care in due time. Apart from unhealthy living, one of the primary mortality causes is late diagnostics, including the lack of easy-to-use, effective and reliable home control devices, which is important to people with limited mobility and senior persons [1]. The development of equipment utilizing up-to-date cardiologic signal analysis approaches, including artificial intelligence elements, requires a test signal library. Such a library should include not only normal, physiological signals but also potential pathological changes in electrocardiograms (ECGs) and phonocardiograms (PCGs). The development of such a library itself is a serious challenge requiring the involvement of high-cost experts and a sufficient amount of records to choose the most illustrative examples. Such libraries are often used for educational purposes: for instance, PCG records meant for medical students are freely available (e.g., [2]). These records contain all known heart sounds and pathological side tones.

Unfortunately, the PCG records from such libraries are available in the widespread MP3 audio signal coding format, with a loss of quality and sampling frequency of 10–22 kHz. The authors believe that it is sufficient to represent natural sounding. However, the MP3 format uses the physiological features of our sense of hearing masking the intentional loss of the “fine signal structure” with loud

sounds [3]. Unfortunately, the modern digital signal processing (DSP) approaches are sensitive to such signal structure "simplifications." That is why the developers of CV diagnostic equipment need libraries of high-quality cardiologic signals with no loss in quality or tools to generate reliable signals.

As it has already been mentioned, the development of such libraries requires too considerable resources. A simpler solution, the development of software-based signal generators, is based on corresponding mathematic models that are able to imitate high-quality signals. Normal and pathological ECG modeling is quite well-developed. However, the authors of this article have not found the description of realistic PCG models in available literature. Indubitably, the initial development of such a model requires a thorough study of the structure of high-quality PCGs registered in laboratory settings. This article describes the preliminary findings of several experiments of this kind.

2. Materials and Methods

2.1. Signal registration

PCGs were recorded at the laboratory of clinical diagnostics with the participation of patients aged 18–36 years old. During the recording process, the patients were in a lying position. Recording was started after a 5–7-minute adaptation period. In total, 300 records with a length of 19–56 minutes were obtained. PCGs were recorded at Botkin point via a contact piezoelectric sensor with an electric capacity of 27 nF. This sensor is able to register signals within a range of 10 Hz to 2.2 kHz. Signals were recorded by means of the ASUS X75A Intel CORE i3 6GB laptop in an on-battery mode to prevent electric shock accidents.

Signals were transmitted from the sensor to a charge-to-voltage converter based on the AD8610 low-noise operational amplifier [4] via a coaxial cable. Then signals were transmitted from the output of the converter through the buffer amplifier of the OP07 integrated circuit [5] to the input of the Creative SBX Prostudio sound card connected to the laptop via a USB channel. To reduce the level of noise, the converter was shielded and powered (±9 V) from two Duracell 6LR61 batteries. Signals were registered in the Windows WAVE 24 bit 192 kHz sound file format with no loss in quality (Blu-ray standard level). The experts, i.e. the leading clinical employees, claim that the records did not differ phonetically from reference samples from verified MP3 signal libraries. The sampling frequency of 192 kHz and the window width of 512 samples allowed obtaining the time resolution of spectrogram signals amounting to 2.67 ms. It would be impossible to ensure such a resolution with the "standard" sampling frequency of reference files amounting to 44.1 44.1 kHz and especially 10–12 kHz.

2.2. Digital signal processing (DSP)

The obtained PCG signals were processed and analyzed by means of a computer equipped with the Intel CORE i5 8600 processor, 16GB RAM and 2GB hard drive under Linux Debian 9 64 bit. All the used programs are free software available under the GNU license.

Preliminary signal processing was performed via the Ardour 5.1 and Audacity 2.3 audio editors. This processing implied the elimination of sounds under 16 Hz. The upper limit of the working frequency range was chosen individually in each case depending on the level of noise and interference and varied from 180 to 450 Hz. For further analysis, individual heart sound complexes were randomly singled out from the PCG records and saved as WAVE files with the same resolution.

The processed signals were analyzed via the Scilab 6 system by writing command scripts in a high-level internal language. The same system was used to create the charts and graphs introduced in this article. Standard Scilab function libraries were used to build spectrograms. The data were formed into blocks with 512 samples via the *window*() function with the *beta* parameter = 6, which made its properties close to those of the Kaiser Window according to the Scilab Help system.

3. Research results

The experimental stage of this work took long time, so some patients were examined several times. An expert carried out the analysis of experimental data by a detailed study of the results obtained after constructing spectrograms. The findings of these examinations were analyzed separately: first of all, the authors analyzed the stability and repeatability of spectral and time PCG properties. In total, four episodes of this kind were registered during the experiment: two patients underwent tests twice, and two patients underwent them thrice.

3.1. Influence of the signal sampling frequency on PCG characteristics

The primary question determining the need for further research endeavors was the influence of the signal sampling frequency on the reliability of their assessment. It was planned to carry out comparative tests of PCGs with the sampling frequencies of 192 kHz (Blu-ray standard), 44.1 kHz (music CD standard) and 10 kHz (the frequency used in specific electronic telemedicine stethoscopes, e.g., CMS-VESD, Contec Medical Systems). To do this, the authors created the spectrograms of one and the same randomly chosen PCG segment containing 10 heart sound cycles with the initial sampling frequency and spectrograms of this segment after the procedure of resampling to a necessary frequency via the Audacity audio editor. All the output signals were saved in the WAVE format with no loss in quality. The spectrograms of one and the same signal for the sampling frequencies of 192 kHz, 44.1 kHz and 10 kHz are shown in Figure 1.

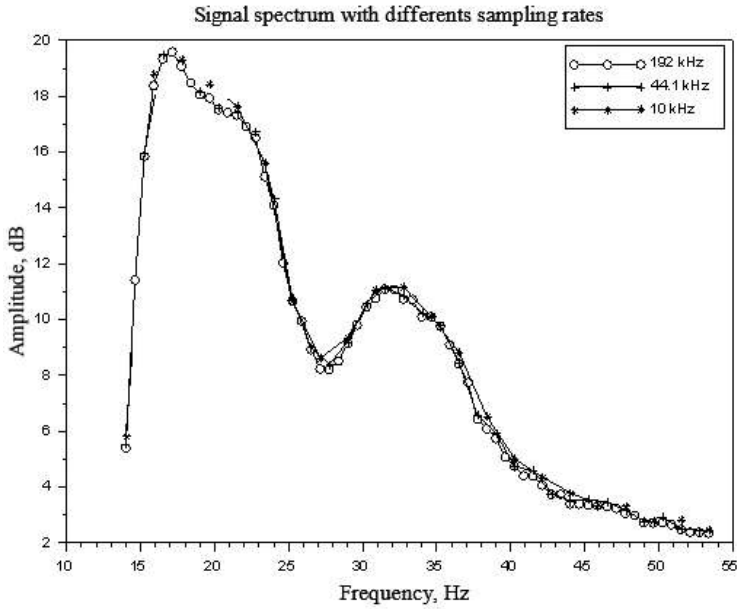
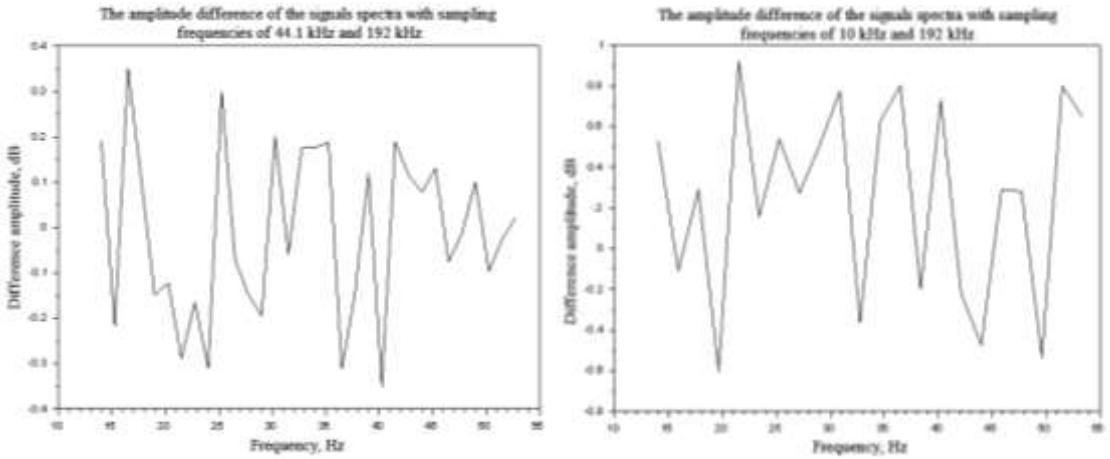


Figure 1. Spectrogram family for one and the same PCG signal with the sampling frequencies of 192 kHz (a), 44.1 kHz (b) and 10 kHz (c).

Figure 2 shows corresponding differential spectrograms for randomly chosen signals with the sampling frequencies of 192 kHz and 44.1 kHz (Figure 2*a*), and 192 kHz and 10 kHz (Figure 2*b*).

As one can see from these spectrograms, the differences in the signal energy are insignificant. The comparison of the findings of the tabular integration for the spectra of the same PCGs at different sampling frequencies shows that the difference in the signal energy was insignificant and amounted to 0.43% ±0.57% ($P>0.1$, $N=18$) for the sampling frequencies of 192 kHz and 44.1 kHz and 0.88% ±0.68 ($P>0.1$, $N=18$) for the sampling frequencies of 192 kHz and 10 kHz.



a) b)

Figure 2. Differential spectrograms of the signals with the sampling frequencies of 192 kHz and 44.1 kHz (a), and 192 kHz and 10 kHz (b).

3.2. Spectral-time PCG characteristics

The moments of emergence, duration and extinction of the harmonic components of heart sounds are essential to understand the fine PCG structure. Previously, the authors already reported on the preliminary research findings obtained during the analysis of signals with the sampling frequencies of 10 kHz and 11.6 kHz [6,7]. In their research study [7], the authors carried out a spectral-time analysis within a frequency band of 14…78 Hz at 2Hz intervals over a period of 350 ms with an accuracy of 10.93 ms, which appeared to be absolutely insufficient to obtain precise time parameters for the characteristic marks of heart sound harmonics. Increasing the signal sampling frequency up to 192 kHz allowed enhancing the time positioning accuracy of harmonics approximately by 3.5 times, up to 2.67 ms with the fast Fourier transform (FFT) data window width of 512 samples. As a result, the analysis of the PCG segments being 340 ms long allowed building a 128×128-point surface. A relevant area was a 32×128-point segment representing a signal spectrum within the range of 16–80 Hz over the entire duration of heart sound existence: the energy of the higher-frequency components was at the level of noise (Figure 3).

Table 1 shows the fine time profile of the harmonics of heart sounds based on the findings of 48 measurements. The table 1 demonstrates time marks for the harmonics that form 95% of the spectrum energy. The boundaries of harmonic existence were set as the time period when its amplitude was higher than 5% of the maximum value. Lower levels were taken as 0.

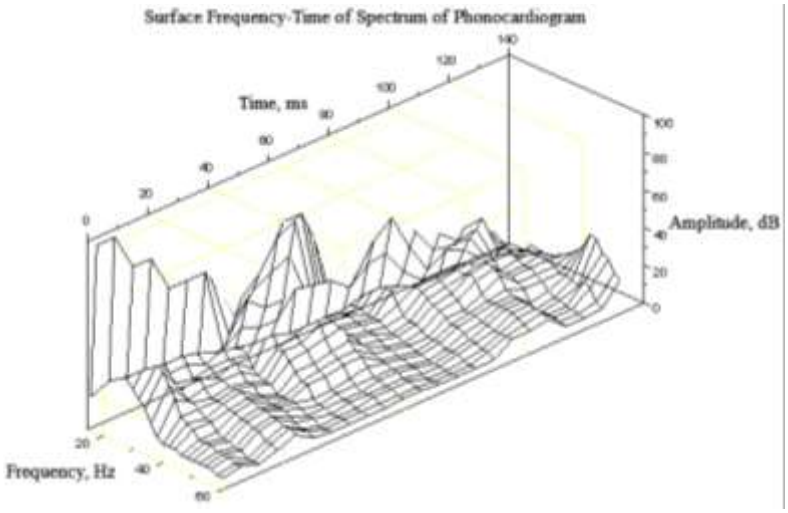


Figure 3. Typical high-resolution spectral-time profile for heart sounds I and II.

Table 1. Fine Time profile of the harmonics of heart sounds.

Frequency, Hz	Time marks (N=48)		
	Start, ms	Maximum, ms	End, ms
16	0	1.44±0.88	178.2±43.3
18	0	1.76±0.89	158.2±22.4
20	1.74±0.90	2.14±0.93	160.2±42.8
22	1.96±0.64	3.48±1.01	248.2±63.6
24	1.94±0.92	4.74±0.92	228.2±44.8
26	1.96±0.43	5.65±1.73	248.2±93.4
28	1.98±0.84	6.91±1.34	231.7±33.9
30	2.08±0.76	17.45±1.95	198.8±51.6
32	2.14±0.96	19.7±2.16	174.7±43.11
34	2.35±1.02	21.33±2.17	194.4±49.66
36	2.88±1.14	23.92±2.65	188.2±49.13
38	2.94±1.12	3.84±1.99	197.8±41.3
40	3.42±1.1	5.78±2.92	183.2±91.15
42	4.16±1.41	5.66±2.89	208.2±83.16
44	4.74±1.53	11.14±4.12	196.2±73.17
46	6.52±1.59	13.48±7.46	218.2±91.6
48	7.64±2.11	15.23±8.1	285.2±109.2
50	8.02±2.41	16.32±6.15	278.2±133.2
52	10.1±2.96	21.12±6.12	306.4±147.1
54	10.58±2.71	27.47±5.53	348.2±143.3
56	11.1±1.18	38.74±10.8	392.2±190.8
58	13.74±4.91	71.95±11.19	377.2±181.2
60	17.4±8.11	101.43±16.6	378.2±140.5

As compared with the data introduced in [7], it was found out that not all low-frequency harmonics emerged at the first moment: fluctuations within the range of 26…32 Hz emerged earlier than others, while fluctuations with other frequencies emerged only 8…10 ms after that. Overall, the high-

resolution spectral-time profile matched with the profile obtained from the signals with a sampling frequency of 44.1 kHz with minor deviations.

4. Discussion

The reliable absence of differences in the spectra of identical signals with the sampling frequencies of 192 kHz, 44.1 kHz and 10 kHz confirms that the sampling frequency of 10 kHz is sufficient to digitize heart sounds with no loss in quality. If the goals of the experiment and data analysis were expanded, it would be possible to determine the minimum permissible frequency of PCG signal digitizing, when the level of spectrum energy would reduce vs. that of the reference 192 kHz signal by a substantial value, e.g., 2% or 5%. Probably, it will be the goal of one of the subsequent research studies.

Such issues arise during the development of equipment meant for telemedicine applications and autonomous operations: sampling frequency reduction definitely leads to a reduction in the volume of collected and transferred data. However, at the same time, it is necessary to ensure a balance between this system parameter and requirements to input signals on the part of a software signal detection complex. Excessive data transferred by wireless communication channels slow down system operations, and low-resolution signals can cause detection failures and unpredictable errors [8].

Another important issue connected with the selection of sampling frequencies is the elimination of noise and interference where the frequency is higher than the doubled sampling frequency. This is an additional parameter of ADC-based signal digitizing and a very efficient filter. For instance, digitizing signals having the frequency of 500 Hz suppresses all interferences with the frequencies of over 250 Hz [9].

Speaking about the time resolution of signal spectra, the following can be noted. Without doubt, there is a specific boundary PCG sampling frequency that makes a further increase in this parameter senseless. In the authors' opinion, the sampling frequency of 192 kHz, a standard option for the hi-fi Blu-ray audio reproduction, will also be optimal for detection systems. As for the Blu-ray format, music experts cannot differentiate between "live" music and reproduced audio fragments. Therefore a further increase in the time resolution of signals can hardly be justified [10].

The same approach can be used to determine the number of bits during signal digitizing. Being part of inexpensive mass market digital data collection systems, analog-to-digital converters with the number of bits of 10…12 theoretically cover the dynamic range of ECG signals. However, digitizing errors and limitations typical of this procedure make digital signals either artificial, nuance-free (coarsening) or having a high level of noise due to a high sampling interval. The authors believe that the best option for ECG signals is ADCs with a conversion capacity of no less than 14 bits or, optimally, 16 or 18 bits with a sampling frequency of 192 kHz.

5. Conclusion

In the authors' opinion, for the recognition of physiological PCG heart tones recorded signals must satisfy the conditions Nyquist theorem. For conducting a full and qualitative analysis of PCGs, the sampling frequency should be at least 8 kHz, the resolution of the ADC should be 16 bits.

At the same time, while placing high demands on systems for recording and collecting data parameters of the acoustic sensors should be taken into account as well. So, the best models of measuring electret microphones, for example, Panasonic WM-61A, have a dynamic range of 62 dB with a sensitivity of -35 dB [11]. Contact microphone CM-01B for medical purposes with a piezoelectric transducer has an equivalent dynamic range of 44 dB at a sensitivity of -32 dB [12]. Preference should be given to modern small-sized acoustic sensor MEMS type: they combine a wide frequency band and a large dynamic range with high sensitivity. For example, MEMS microphone ADMP441 [13] with a built-in 24-bit ADC has a high sensitivity -24 dB bandwidth of 60 Hz to 15 kHz and a dynamic range of 61 dB. Built-in microphone allows the driver to directly connect it to a digital input of the microcontroller via the I2C bus. Thus, all necessary conditions currently exist for the registration and analysis of high-resolution PCG using inexpensive and available technical means.

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