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Usefulness of the Matching Pursuit Method in Phonocardiographic Signal Analysis

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Abstract This paper presents a phonocardiographic signal analysis with special emphasis on the Matching Pursuit method. To the knowledge of the authors, this method has not been used before to analyze PCG (phonocardiogram) signals. For this reason, its usefulness for this signal type was tested and a dictionary of Gabor atoms was created. Based on these findings, PCG signal analysis was performed as a Wigner-Ville distribution and compared with a spectrogram. Observing the obtained graphs, it was found that the Wigner-Ville map gives more detailed information about the frequencies which make up the given signal and the time of their occurrence. This method can be used to detect anomalies and pathologies of the heart.

Keywords: heart sounds, phonocardiographic signal, matching pursuit, stethoscope

1. Introduction

The heart was already auscultated in ancient Greece by putting an ear to the patient's chest. From the 19th century, this test began to be enhanced by the first stethoscope, i.e., a cylinder made of wood through which the heart tones were perceived. Based on further experiments, it was improved by changing its design into a funnel shape. Thanks to these advancements, the phonocardiographic signal obtained was cleaner and clearer. With the development of technology, there had been continuous improvements made to this device, until in 1964 Dr. David Littmann obtained the patent for the stethoscope he proposed, currently used by doctors today [1]. The signal obtained by auscultation is called a phonocardiographic signal.

Heart sounds are created as a result of two basic mechanisms. The first is the sudden build up or scattering of blood. The acceleration and deceleration of blood in the heart chambers is mainly influenced by the opening or closing of heart valves and the sudden stretching of the anatomical structures of the heart (walls of the heart chambers, chordae tendineae, papillary muscles). The second mechanism that generates sound is turbulent blood flow caused by anatomical obstacles along its path. Such obstacles include local vasoconstriction, flow from a larger diameter vessel to a smaller diameter vessel, high flow velocity, or pathological blood flow pathways (e.g., ventricular or atrial septal defect or damage) [2]. Individual heart sounds are formed at specific moments during the heart cycle and their names are associated with the order in which they occur (Figure 1). There are two basic heart sounds. The first appears to be the systolic sound of the heart (first heart sound) designated S1. It is heard at the beginning of the ventricular contraction phase, when their volume is the largest. S1 is the result of the vibration of the leaflets of the closing atrioventricular valves. This sound consists of two components: M1 and Tv1. The occurrence of components is caused by the simultaneous closing of the mitral and tricuspid valves.

The mitral valve closes slightly earlier, with a value of about 20 ms. Under physiological conditions, this split is elusive to the human ear. The duration of the this sound is 140 ms, and its frequency varies between 35-50 Hz. The diastolic sound of the heart (second heart sound) designated S2, appears at the end of the ventricular contraction phase. It arises as a result of vibrations of the closing semilunar valves of the aorta and pulmonary artery. S2 also has two components: A2 and P2. The first component is the aortic component (representing aortic valve closure), which is louder and under physiologically normal conditions precedes the pulmonary component (associated with pulmonary valve closure) by about 30 ms. The second sound lasts 110 ms and its frequency is in the range of 50-70 Hz. The time measured between S1 and S2 corresponds to the length of the ventricular contraction phase. The time between S2 and the next S1

determines the duration of the diastolic phase. In addition to S1 and S2, there may also be a third heart sound (S3), and a fourth heart sound (S4). S3, also known as the protodiastolic gallop or ventricular gallop, appears immediately after S2. It is the result of an increase in the diastolic volume of the ventricles. It is a diastolic sound that appears in the early diastolic phase. The third heart sound is a physiological (normal) tone in young people due to the large diastolic capacity of the ventricles. The sound disappears in men and women around the ages of 20 and 30 years old, respectively. Hearing this sound in people over the age of 40 indicates a pathological change. The fourth heart sound is similar to S3, but appears immediately before S1, in the late period of the ventricular diastolic phase. Ventricles that receive extra blood from contracting atria can generate low-frequency vibrations (ventricular pre-diastolic vibrations) heard as S4. Physiologically, it can occur in young athletes, because they have an increased diastolic heart capacity. Otherwise, its presence indicates heart disease.

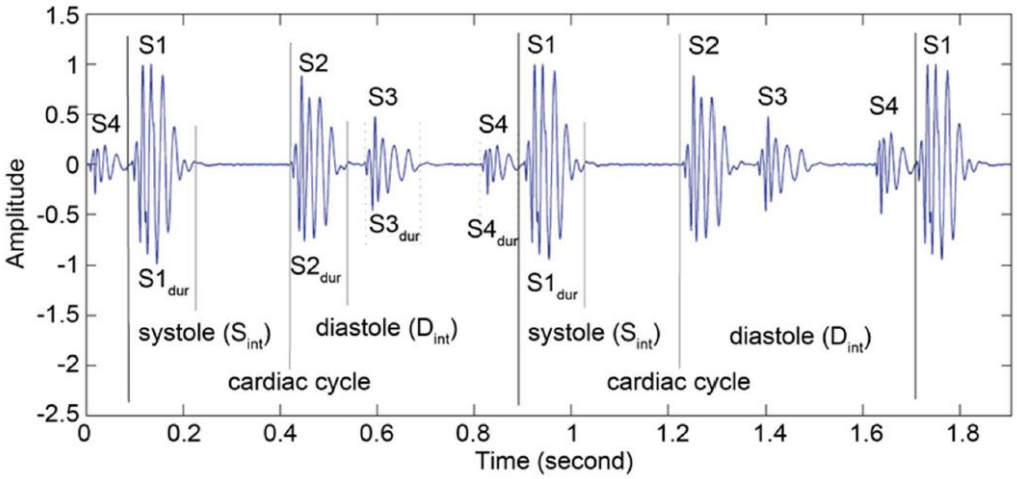

Fig. 1. Example of a time domain heart sound signal [3].

A stethoscope is a quick and simple tool for the initial diagnosis of heart disease. An accurate diagnosis by the doctor is crucial. Inattention, fatigue or lack of appropriate experience are factors that can affect its correctness. To support doctors in their training and diagnoses, they could be offered engineering support that provides them the opportunity to confirm their decision. The Matching Pursuit method is one of many time-frequency analyses. As its name implies, it pursues through the signal in search of the best signal match to the base functions. Thanks to its application, one have the opportunity to collect information about the heart signals of healthy and sick people in the time and frequency domains, which can be helpful for the doctor making decisions about further, more detailed tests.

2. Matching Pursuit method

The Matching Pursuit method is a relatively new type of analysis. It was proposed in 1993 by S. Mallat and Z. Zhang [4]. The algorithm is based on a non-linear procedure of splitting the signal into a linear sum of wavelets that belong to a redundant dictionary of base functions. In subsequent iterations, it walks through the signal and selects the best matching wavelets [5] for the dictionary. In the STFT analysis, the accuracy of observation depends on the window width, which is selected by trial and error, while in the wavelet analysis the original signal is mapped with the same wavelet that changes its parameters.

In the Matching Pursuit analysis, the dictionary of base functions (atoms) is extensive and redundant. In order to prevent multiple matching of a given fragment with atoms of a similar nature, the best-fit atom is subtracted from the signal and is not used in further approximation [6,7]. Basic functions usually take the shape of Gabor atoms, i.e., a Gaussian distribution modeled by the sine function (Figure 2).

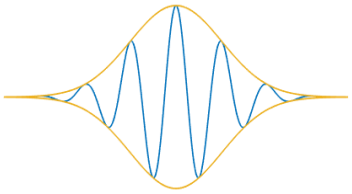

Fig. 2. Diagram of the Gabor atom.

Similarly to wavelet transform, they can be translated, scaled, but also frequency modulated:

$$g_\gamma(t) = \frac{1}{\sqrt{|a|}} \cdot g\left(\frac{t-b}{a}\right) e^{i\xi t}\xi, \tag{1}$$

where: a – scale factor, b – translation factor, $e^{i\xi t}$ – complex exponential function, γ – index specifying the set of parameters for a given atom, $\gamma = (a, b, \xi)$, t – time, ξ – frequency modulation.

The best-matched atom is the one with the largest scalar product with the signal. It is subtracted from the signal, and the obtained residue takes the place of the signal and the operation of searching for the next best-matched atom is repeated 6). It is assumed that the zero-order residue forms the tested signal. The Matching Pursuit algorithm continues until the specified amount of energy is clarified or the number of iterations reached. Let Rx be the residual vector after approximating x in the direction of g_{γ_n} and $R^0x = x$

$$R^n x = \langle R^n x, g_{\gamma_n}\rangle\, g_{\gamma_n} + R^{n+1}x \tag{2}$$

where: $R^n x$ – nth order residue, for $n \geq 0$.

After the m[th] iteration, the signal can be presented by the sum (3), while the sum of the energy of the matched time-frequency atoms gives the signal energy according to the energy conservation principle (4):

$$x = \sum_{n=0}^{m-1} \langle R^n x, g_{\gamma_n}\rangle\, g_{\gamma_n} + R^m x \tag{3}$$

$$\|x\|^2 = \sum_{n=0}^{m-1} \left|\langle R^n x, g_{\gamma_n}\rangle\right|^2 + \|R^m x\|^2. \tag{4}$$

Subsequent iterations mean increasingly better signal mapping, so the residual value decreases (5). Finally, the original signal can be represented by using Gabor atoms (6).

$$\lim_{m\to\infty} \|R^m x\| = 0 \tag{5}$$

$$x = \sum_{-\infty}^{\infty} \langle R^n x, g_{\gamma_n}\rangle\, g_{\gamma_n}. \tag{6}$$

The method uses Wigner-Ville (WV) imaging. To obtain it, an estimation of the signal energy density is calculated based on the definition of the Wigner-Ville transform (7) and signal development using the matching pursuit method [8].

$$W_x(t,f) = \int_{-\infty}^{\infty} x\left(t+\frac{\tau}{2}\right) \cdot x^*\left(t-\frac{\tau}{2}\right) e^{-i2\pi f\tau} d\tau \tag{7}$$

where: $x(t)$ – time domain signal, τ – time lag.

3. Implementation

The most important thing in the Matching Pursuit algorithm is to create an appropriate dictionary of atoms. A base function was created, which is a cosine function with a frequency of f = 1Hz modulated by Gaussian distribution (8). The parameter σ was responsible for the scale factor, and μ for the translation factor:

$$g_{\mu,\sigma}(t) = e^{-\frac{1(t-\mu)^2}{2\ \sigma^2}} \cdot \cos\left(\frac{2\pi t f}{\sigma}\right). \tag{8}$$

The value of σ was chosen in such a way as to obtain a higher resolution of narrow and smaller wavelets. Therefore, three sublists of sigma parameter were created for narrower, medium and longer wavelets, respectively. Each sublist consisted of evenly spaced values within a given interval from start to stop value with defined step, described in Table 1. In this way, dictionary of 43 wavelets were obtained that best represented the 22 tested base PCG signals. A dictionary consisting of more atoms means longer computation time, therefore the most universal atoms for the base signals were selected. Then the obtained atoms were normalized to meet the condition ||g|| = 1.

Tab. 1 Values of the parameter σ.

	start σ [s]	stop σ [s]	step [s]
sublist 1	$\frac{13}{3000}$	$\frac{13}{540}$	$\frac{13}{8000}$
sublist 2	$\frac{13}{540}$	$\frac{13}{360}$	$\frac{13}{7200}$
sublist 3	$\frac{13}{360}$	$\frac{13}{120}$	$\frac{13}{2400}$

Next, obtained atoms were translated in such a way that the next atom overlapped 2/3 of the length of the previous one and the dictionary was extended with identical atoms shifted in phase by π.

After creating the dictionary, the procedure of matching atoms to the signal began. An example of the PCG signal is shown below with the three best matched wavelets marked.

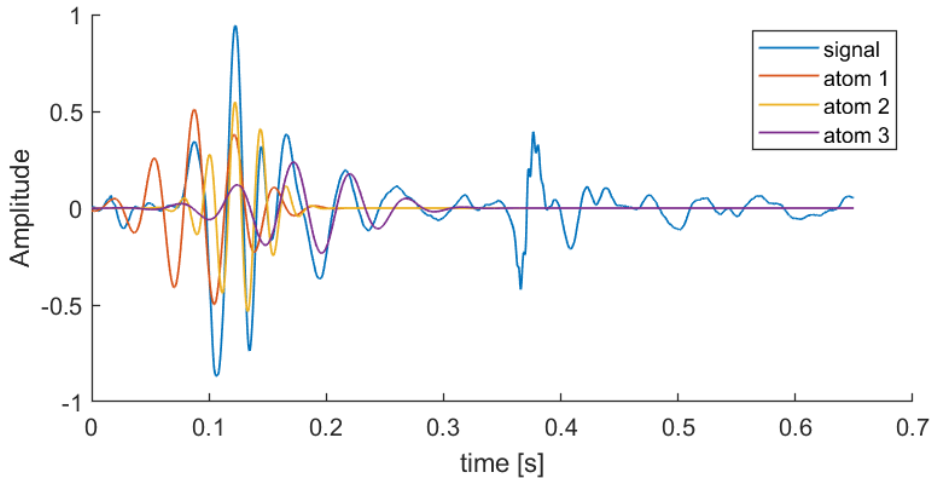

Fig. 3. Example of the three best-matched wavelets for the heart sound signal without S3 and S4.

After 30 iterations of the algorithm, the original signal mapping was obtained. The number of iterations was selected in such a way as to obtain a satisfactory representation of the original signal, while maintaining the shortest computation time.

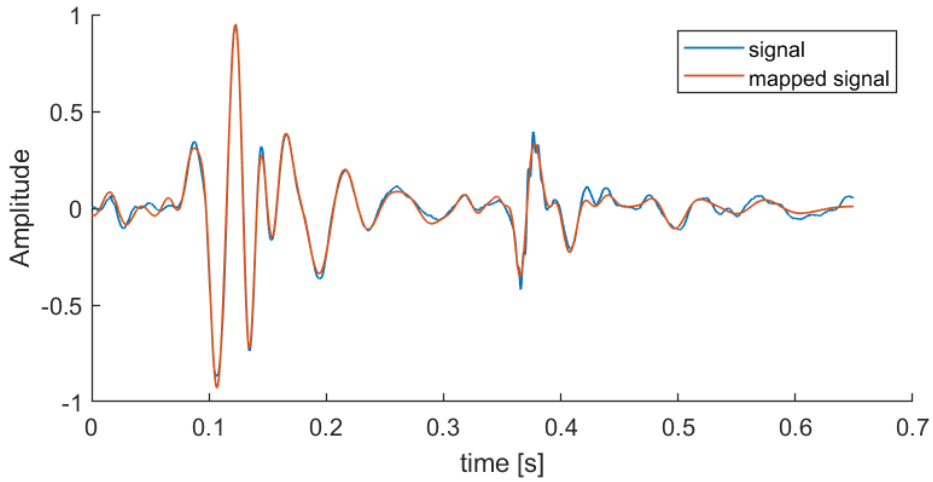

Fig. 4. Example of heart sound signal mapping with Gabor atoms.

Each atom was subjected to a Wigner-Ville transform, and the sum of transformations received was presented on a Wigner-Ville map. Like the spectrogram, its axes are time and frequency, while the amplitude is the signal energy density.

4. Results

The PCG signals obtained with a stethoscope were subjected to STFT analysis and the Matching Pursuit method. Phonocardiographic waveforms were mapped successively to thirty best-fitting Gabor atoms from the created dictionary described in the Implementation section. Obtained signals mapped over 90% of energy of each of tested base signals. This means that the Matching Pursuit algorithm is useful in PCG signal analysis. In Figure 5. and Figure 6., the obtained Wigner-Ville imaging and spectrograms for selected signals were compared.

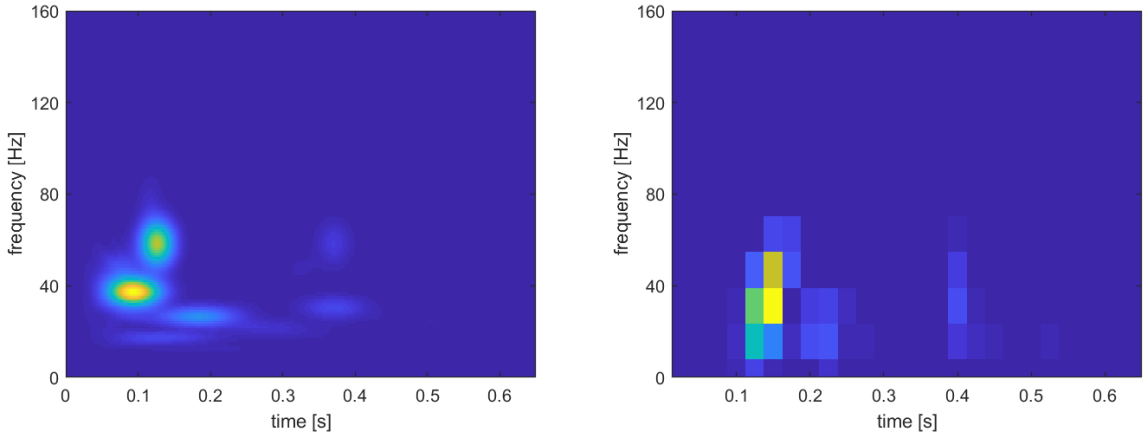

Fig. 5. Time-frequency analysis of heart sound signal: a) Wigner-Ville distribution b) spectrogram.

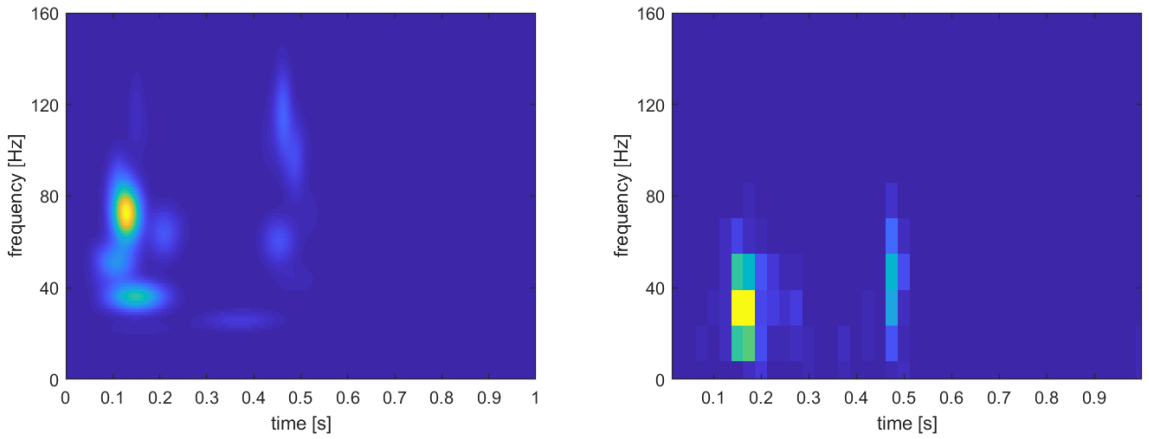

Fig. 6. Time-frequency analysis of heart sound signal: a) Wigner-Ville distribution b) spectrogram.

The STFT analysis was performed for a 50 ms wide window and 50% overlap. Imaging on a Wigner-Ville map gives greater accuracy to the results observed on spectrograms with the same sampling frequency. The Gabor atoms used for the mapping are represented by colored spots. The color intensity indicates the value of energy density represented in different frequency bands. For each of the signals shown, the brightest spot can clearly be seen at the beginning of the signal. It indicates the occurrence of the first heart sound (S1), characterized by the highest energy density. At a similar time, a second spot can be seen, usually a bit darker, with a higher frequency band (around 75 Hz) and shorter duration. Approximately 200-300 ms later one can see brighter spots again, but they are definitely less intense. They are in quite similar frequency bands to the spots indicating S1 and indicate the occurrence of a second heart sound (S2).

A set of recordings from people with heart disease was subjected to a similar time-frequency analysis using the same atoms dictionary. The high quality of the mappings may indicate the usefulness of the Matching Pursuit method in recognizing selected diseases. From the database of recordings from sick people, two irregularities were selected, whose WV imaging was presented in charts and compared with a chart from a healthy person.

5.1. The third heart sound

The third heart sound has a similar energy to the second one, which is why it is clearly visible in both charts on Figure 7. More detailed information on the frequency components of the signal and the time of their occurrence was obtained from WV imaging than on the spectrogram.

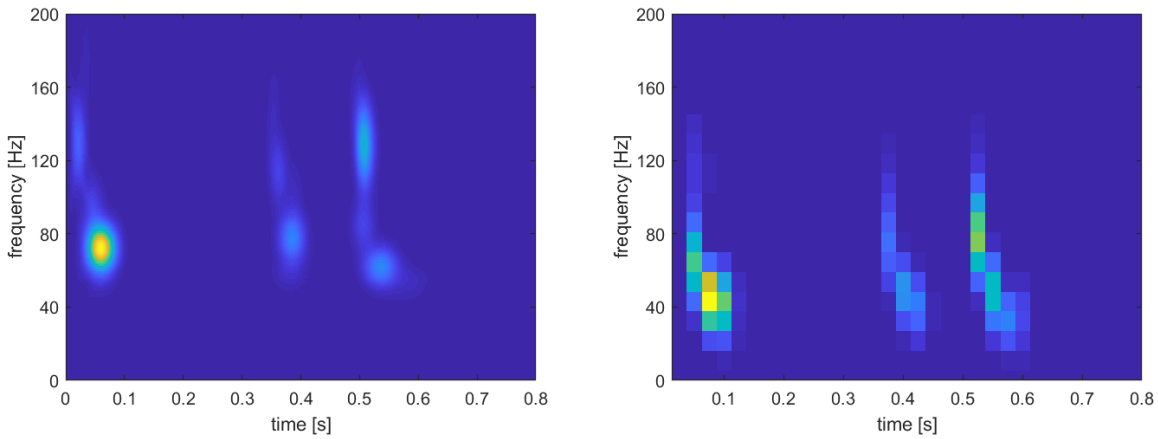

Fig. 7. Time-frequency analysis of an example heart sound signal with occurrence of S3: a) Wigner-Ville distribution b) spectrogram.

5.2. Diastolic rumbling

In Figure 11. showing WV imaging of a signal characterized by diastolic rumbling, one can observe a clear difference in the area of S1 occurrence relative to the signal map of a healthy person. In the correct course, the first heart sound is reproduced with approximately two brighter circular areas occurring at a similar time, while the diastolic rumble is characterized by many smaller spots of energy present in this place. This means that the signal has been mapped with several successive atoms explaining a large part of the original signal's energy. This may serve as an indicator to the doctor that the signal has some abnormalities during the first sound. In order to accurately classify the WV imaging of this disease, however, one should analyze by means of the MP method a much larger amount of data in order to be able to determine the characteristics of this disease in detail.

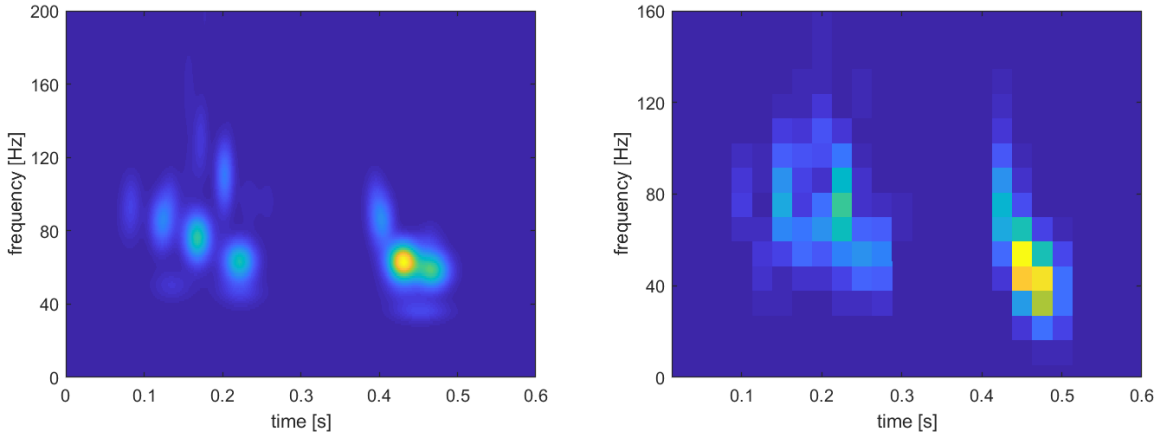

Fig. 8. Time-frequency analysis of heart sound signal with diastolic rumbling: a) Wigner-Ville distribution b) spectrogram.

6. Summary

The proposed dictionary reproduced the examined signals in a satisfactory way. The resulting Wigner-Ville map can be compared to a spectrogram, but provides more detailed information. STFT analysis has some limitations resulting from the choice of window length, which results in the inability to accurately observe the signal in the time or frequency domain. On the Wigner-Ville map such ill-defined values were not obtained and the information about the frequency components of the signal and the time of their occurrence are more readable. What is more, the Matching Pursuit method may make it possible to detect certain pathologies and monitor disease progression. These factors taken together showed the Matching Pursuit method as useful in the analysis of phonocardiographic signals. Further research to be undertaken in cooperation with cardiologists is planned.

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Additional information

The authors declare no competing financial interests.

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