

Graphic Representations and Frequency Parameters of Heart Sound Signals

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Abstract—Sounds produced by acoustic activity of the heart are series (sequences) of quasi-periodic events which are repeated throughout life, one period (cycle) of these events lasts less than one second. The advancements in technology have enabled us to create various tools for audio and graphic representations of these events. Physicians, by using such tools, can more accurately determine diagnosis by interpretation of heart sound and/or by visual interpretation of graphic displays of heart sounds. This paper presents frequency parameters and graphic illustrations of heart sound signals for two groups of heart murmurs: innocent Still's murmur and pathologic heart murmur of Ventricular Septal Defect (VSD). Also, on behalf of the frequency analysis of acoustic cardiac signals with Still's murmur was given a medical explanation of cause and origin of Still's murmur.

Index Terms—Heart Sound Frequency Parameters, Heart Sound Graphic Representation, Heart Sound Spectrogram, Phonocardiogram (PCG), Still's Murmur, Ventricular Septal Defect (VSD).

I. INTRODUCTION

Our body transmits sound messages and „speaks“ about the state of our vital organs (heart, lungs,..). Physicians listen and interpret these sounds. Auscultation is a medical term for listening of internal body sounds and the procedure of listening is mainly done with a stethoscope. That term originates from the Latin word *auscultare*, which means to listen. The beginning of auscultation started back in 1816 when French physician René Th  ophile Hyacinthe Laennec

(1781-1826) invented the stethoscope and introduced the term auscultation into medicine [1].

Heart auscultation is very subjective because diagnosis of heart sounds could be interpreted in several ways depending on how a physician interprets the sound. Due to limited opportunities of heart auscultation, it is necessary to help the human ear and make a graphic display of the heart sound. Visual representations of heart sound signals can help physicians to better understand, determine and evaluate heart sound cycle events.

Despite numerous heart sound graphic representations, vast majority physicians do not really use them. One of the most common graphic representations of heart sound signals is phonocardiogram (PCG) (the time display of heart sound amplitudes). Other display of heart sound signals is the heart sound spectrogram which allows better heart sound interpretation, but it is hardly perceived or used by physicians.

With this purpose, authors in [2] introduced a solution for graphic display of heart sounds called HSLs (Heart Sound Lines). Authors believe that graphic display of heart sound signals like this could be a useful tool for the heart sounds interpretation and can assist physicians for a more precise diagnosis of innocent and pathologic murmurs (auscultation-visual diagnosis). The advantage of HSLs graphical display over other methods is in its easier interpretation by their parameters: murmurs color line, numerical value of murmurs index and lines shape.

The paper is organised as follows. In Section II recordings of heart sound signals and Goertzel algorithm are shortly presented. In Section III are shown the spectral compositions (spectral energy distributions) of Still's and VSD's murmur and their frequency parameters. Graphic representations of heart sounds are in Section IV. Section V concludes the paper with final remarks.

II. MATERIALS AND METHODS

While examining the children in an outpatient clinic by pediatric cardiologists, their heart sounds were recorded with an electronic stethoscope. All children were additionally examined with ultrasound for an accurate diagnosis of congenital heart disease. The recorded heart sounds were classified into three groups: heart sounds without heart murmur – Normal (10 records), heart sounds with physiological Still's innocent murmur – Still (20 records) and heart sounds with pathological murmur associated with congenital heart disease – VSD (20 records).

Heart sounds were recorded with the sampling frequency of $f_s=8000$ Hz and resolution of quantization of 16 bits. Further more, in a process of determination of frequency parameters of the murmurs, the complete systolic duration was isolated (by hand using software tool Audacity) from the heart audio files. An energy spectrum of the heart sound data was obtained by applying Goertzel algorithm.

A. Basic Goertzel algorithm

The algorithm was introduced by Gerald Goertzel (1920-2002) in 1958 [3]. Equation (1) describes the signal flow for the basic Goertzel algorithm as each sample is processed [4]. The signal flow of the algorithm produces an output y_0 for each processed sample.

$$y_0 = x_0 + y_1 \times 2\cos\left(\frac{2\pi m}{N}\right) - y_2 \quad (1)$$

In the equation (1), y_0 denotes the current output, x_0 denotes the current input sample, y_1 denotes the output that is previously processed, y_2 denotes the second previously processed output, N denotes the size of input block, while m denotes bin number in the frequency domain. Each sample of the input block (of size N) is processed according to the equation (1) and at the end of each block the spectral energy of each frequency bin is computed by the equation (2). This process continues over the next block (of size N) until the last block is processed.

$$E = y_1^2 + y_2^2 - 2y_1y_2\cos\left(\frac{2\pi m}{N}\right) \quad (2)$$

In equation (2) y_1 is the last processed output (iteration N) equation (1) and y_2 second-last processed output (iteration $N-1$).

The advantage of the Goertzel algorithm is that it can process the input data as it arrives. The output value is only needed for the last sample in the block unlike the Fast Fourier Transform (FFT). The FFT has to wait until the entire sample block has arrived. If the number of frequency bins is a lot smaller than N , the Goertzel algorithm reduces the data memory which is required significantly. The Goertzel algorithm is more efficient than FFT only when a small number of frequency bins M need to be calculated ($M < \log_2 N$). The motivation for using Goertzel algorithm is in possibility of selection of parameters m by which we can easily change and adjust

frequency resolution and frequency band of analysed signal.

III. SPECTRAL COMPOSITION AND FREQUENCY PARAMETERS OF HEART MURMURS

The basic events of a heart sound cycle are first heart sound ($S1$), second heart sound ($S2$) and time periods between them. A time between $S1$ and $S2$ is called a systole and a time period between $S2$ and $S1$ is called a diastole. If there is a sound (noise) which is heard through the systole or diastole, that phenomenon is respectively called systolic heart murmur and diastolic heart murmur.

When murmurs appear, they can last only a small part or entire systole i.e. diastole. The time interval of murmur appearance is very short. At children age, a systolic time interval is around 200 ms and diastolic time interval is little longer.

Spectral composition of heart sound signals is very useful in detection and heart murmur diagnosis. Majority of authors in their studies mostly used FFT and/or Wavelet Transform for a spectral analysis of the heart sounds [5-7]. Heart sound spectral analysis with Goertzel algorithm is proposed in [8-9].

In this analysis Goertzel algorithm was applied with the sample block size of 160 samples. When using a sampling frequency of 8 kHz, 160 samples ($N=160$) in discrete time represent the time frame of 20 ms in real-time. The bin bandwidth frequency is determined by sampling frequency and sample block size ($B=f_s/N$). The overlapping of bins (frequency resolution) is adjusted by the selection of coefficient m in equations (1) and (2). Figures 1 and 2 illustrate the results calculated by the frequency resolution of 5 Hz.

Frequency parameters of heart murmurs carry information about the health status of patient's heart and these parameters are determined and evaluated in heart sound computational diagnosis. Analysed frequency parameters of heart murmurs (in this article) are:

- Frequency of spectral extremes i.e. frequency on which murmur spectrum has the highest energy (peaks);
- Frequency bandwidth;
- Intensity of spectral energy on resonant frequency (spectral energy of peaks).

A. The spectral compositions of Still's and VSD murmur

The heart sound graphic images represent heart sound intensity in time and/or frequency besides that time display of heart sound amplitudes does not give information about heart sound frequency and heart sound energy. Display of heart sound spectral energy is a useful for determination and evaluation of heart murmur. Fig. 1 and Fig. 2 illustrate the distribution of spectral energies of isolated systoles for three typical Still's murmurs (Fig. 1) and for three typical VSD murmurs (Fig. 2). Fig. 1 represents three Still's murmurs (low frequency - Still1, high frequency - Still3 and common - Still2) and Fig. 2 represents three VSD-s (high energy - VSD1, medium energy VSD2 and low energy - VSD3).

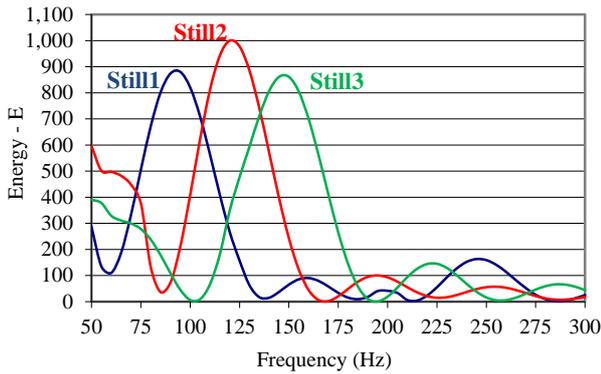


Fig.1. Three typical Still's murmurs

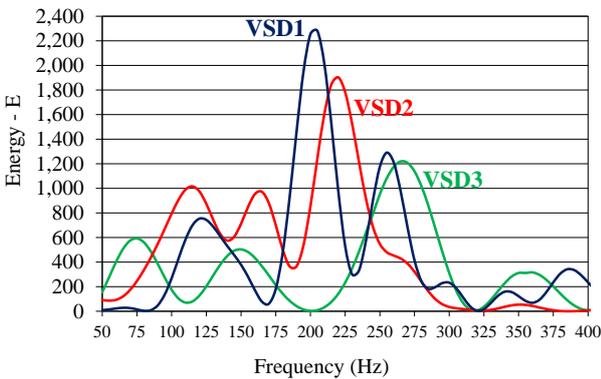


Fig.2. Three typical VSD murmurs

It is clearly visible in Fig. 1 that the information about Still's murmur occurs in a lower frequency bandwidth (80-170 Hz). It is obvious that the frequency of Still's peak is lower than 200 Hz while the highest VSD peak has the frequency above 200 Hz.

If we compare spectral compositions of Still's and VSD murmur, information about VSD murmur is in a wider frequency bandwidth and in most cases VSD murmur has a distribution of the spectrum energy in bandwidth (90-300 Hz).

B. Frequency parameters of Still's murmur

Innocent murmurs are common in children and the most frequent is Still's murmur [10], which occurs and is audible at the beginning of the systole. For every pre-recorded heart sound signal, every systole is manually located and secluded for spectral analysis. In Fig. 3 secluded time interval is represented (red rectangles-three heart sound cycles). Also Fig. 3 shows a PCG display of one Still's murmur before processing (top picture) and after processing by 3M Littmann sound analysis software (bottom picture).

Signal after processing (Low pass filter) has more emphasized murmur and better visual impression. 3M Littmann sound analysis software has three heart sound signal processing option filters (Low pass, High pass and Band pass). Low pass filter is suitable for Still's murmur emphasizing and a high pass or band pass filter for VSD murmur.

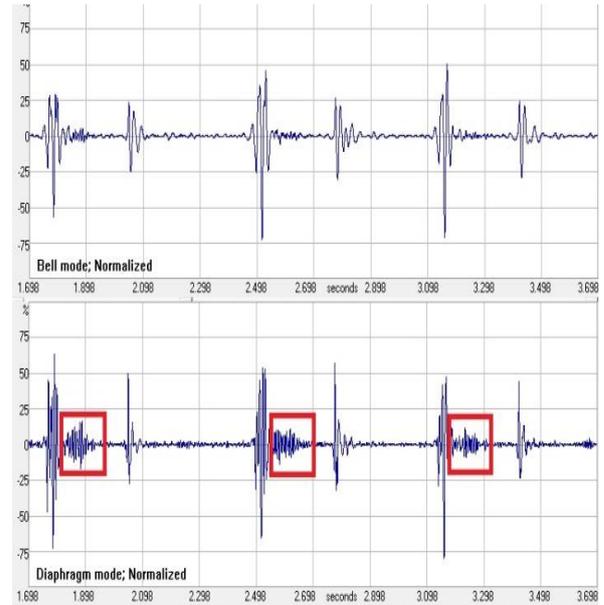


Fig.3. Time interval of Still's murmur

Spectral energy is calculated for the secluded time interval that lasts cca. 100 ms with frequency resolution of 5 Hz in time frames (intervals) of 20 ms. The point where Still's murmur has the maximal spectral energy in time interval of 20ms is selected as the final position of Still's murmur. That time frame represents the location of Still's murmur and the frequency and the bandwidth of Still's murmur are calculated in this time frame. The final position of Still's murmur i.e. the frequency at which it has maximal spectral energy (the peak) is usually in the bandwidth (B) between 110 and 130 Hz. The frequency bandwidth (B) ($B = f_{max} - f_{min}$) is obtained in a way that the frequency of the final Still's position (the peak) falls in half of strength f_{min} (left of the top of curve) and f_{max} (right of the top of curve) [9].

Fig. 4 illustrates the graphic representation of frequency parameters of Still's murmur. It shows that peak of the murmur's spectral energy is at the frequency of 147,5 Hz on 880 units (values obtained by Goertzel algorithm), f_{min} is at the frequency around 124 Hz and f_{max} is at the frequency around 168 Hz. Therefore, the frequency of this Still's murmur is 147,5 Hz, the bandwidth is cca. 44 Hz and the spectral energy is 880.

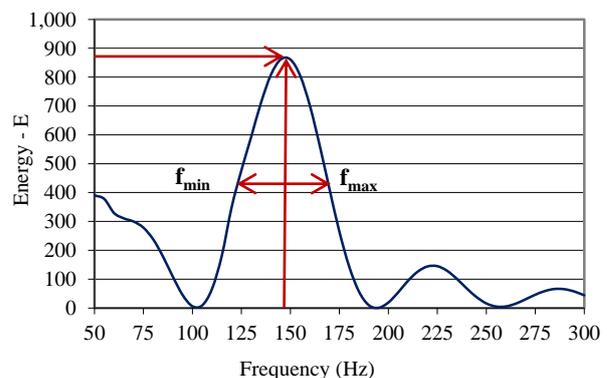


Fig.4. Frequency parameters of Still's murmur

C. Frequency parameters of VSD murmur

VSD murmur is audible in the whole systole. VSD can have a couple of peaks (mostly two or three) which have a slightly lower energy than the uppermost peak. For the VSD with two or more peaks, f_{min} is to the left of the uppermost peak and f_{max} is to the right of the uppermost peak. Fig. 5 shows one VSD murmur in the final position (maximal energy of uppermost peak).

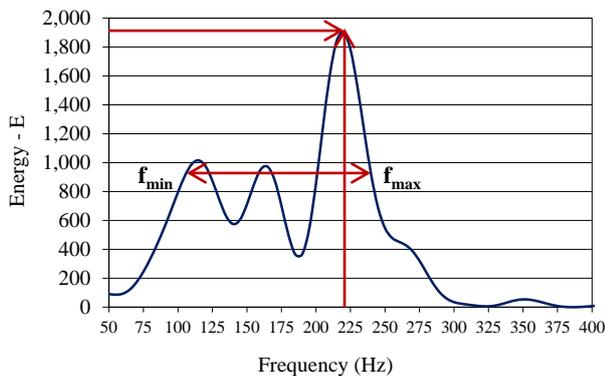


Fig.5. Frequency parameters of VSD murmur

The Fig. 5 shows that the spectral energy of this VSD murmur is at the frequency of 220 Hz and its energy is 1902,4 units, f_{min} is at the frequency around 107 Hz and f_{max} is at the frequency around 239 Hz. Therefore, the frequency of this murmur is 220 Hz, the frequency bandwidth is 132 Hz and the spectral energy is 1902,4.

IV. GRAPHIC REPRESENTATION OF HEART SOUND

The author [11] tested 126 medical students and 20 pediatricians and found that those participants who could play musical instrument or sing in a chorus identified more murmurs correctly than those who had no practical musical skills. A graphic representation of heart sound signal provides a visual image of the heart sound. The PCG shows a change in amplitude of heart sound in time. It is a considerable source of information that can lead by its analysis, to the detection and the identification of several heart abnormalities [12]. Each event in the heart sound cycle (sounds and murmurs) changes the amplitude of PCG base line and physicians can see that change. However, by PCG we can only detect heart sounds and murmurs and show their position and shape in time. A heart sound spectrogram shows the frequency components of heart sound signals and the distribution of spectral energy of heart signals in time. Each event in the heart sound cycle ($S1$, $S2$ as well as murmur if it exists in systole or diastole) has its own spectral energy distribution. The spectral energy of first $S1$ and second $S2$ heart sound is mostly distributed in bandwidth under 100 Hz. Heart sounds $S1$ and $S2$ are the loudest events (the highest energy) in cardiac cycle. That is the reason why they have the highest amplitude in PCG representation of heart sounds cycle. Likewise, if a murmur appears in heart sound cycle then each murmur has a unique PCG and spectrogram shape.

Different heart murmurs have different time amplitudes and spectral energy distributions. In this article we graphically presented only two murmur types (Still and VSD). The spectrogram was created using Matlab. Fig. 6 illustrates graphic representations (PCG and spectrogram) of Still's murmur and Fig. 7 illustrates graphic representations (PCG and spectrogram) of one cardiac signal with VSD murmur.

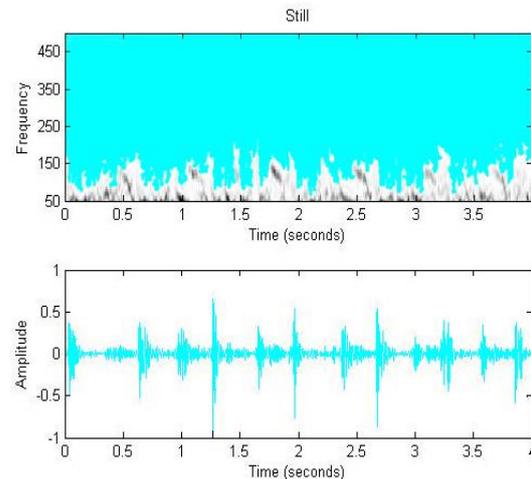


Fig.6. PCG and spectrogram representation of Still's heart murmur

Heart sound signals are mainly unsteady signals in time span. Spectral energy of Still's murmur in Fig. 6 is distributed in bandwidth 100-150 Hz. On PCG representation Still's murmur has a diamond (crescendo-decrescendo) shape. That shape is a result of increasing and decreasing of the sound generated by Still's murmur. Crescendo and decrescendo are expressions taken from music art. Still's murmur is silent at the beginning then it becomes louder in the middle and then declines and stops.

There are no common views on the occurrence of the Still's murmur. The doctors (physicians) haven't yet established reliable genesis of the occurrence of that murmur, answering which heart structures and during which heart developments for the duration of systole that tone is created. Authors' opinion, based on the acoustic analogy, is that this sound can be generated by some string (thread) which vibrates in the appropriate resonator. The hypothesis that the Still's murmur appears during vibrations of cords in the heart is also stated by other authors (physicians) in [13-14]. Cords are thin structures (like threads) within the heart and during the contraction of heart muscles with which they are connected, the cords are vibrating, and at the same time (systole) the ventricles are emptying creating resonator box in which the cords are vibrating and generate sound which we can hear as the Still's murmur. Therefore, alike live instrument, the heart, or more precisely vibrating cord in the heart, starts to play silently, then louder and after maximal loudness starts to appease and stops playing. During diastole, there is no contraction of the heart muscle and no actuation (vibration) of cords. Since cords are not vibrating during diastole, the Still's murmur in diastole is not generated.

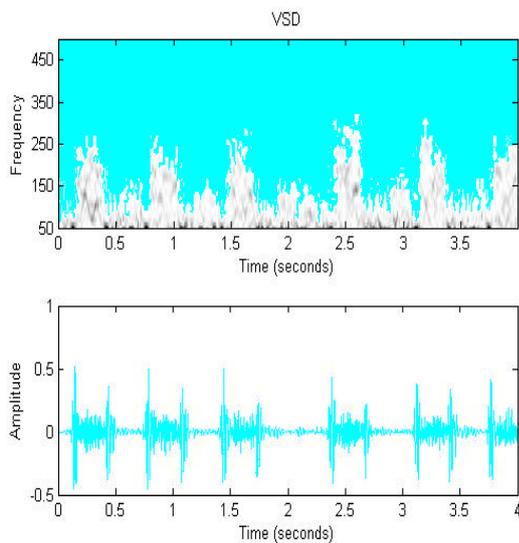


Fig.7. PCG and spectrogram representation of VSD heart murmur

Still murmur is vibratory, musical sound without any evidence of turbulent flow. VSD is harsh systolic murmur of ventricular septal defect (VSD) caused by turbulent blood flow through a defect („a hole”) in ventricular septum. Ventricular septum separates right and left ventricle. In healthy children and adults septum is intact [8].

In PCG and spectrogram it can be noted that Still and VSD are located in the systole. Heart sounds *S1* and *S2* have higher amplitudes in PCG display than the amplitudes of Still's and VSD murmur. The spectral energy of Still's murmur is distributed in a narrow frequency bandwidth, which is very close to heart sound bandwidth where the energy of tones *S1* and *S2* is expressed. In many cases these two bandwidths are overlapping. Therefore, this makes the detection of Still's murmur difficult. This is also the reason and explanation why physicians mostly give a wrong diagnosis by auscultation alone when it comes to Still's murmur.

It is obvious that there is a masking of frequency in Still's murmur and therefore many physicians can't even hear it. The spectral energy of VSD is distributed in a wider frequency bandwidth 80-300 Hz and it lasts throughout the whole systole. Band of VSD is separated from band of tones *S1* and *S2*. VSD murmur is not masked by tones *S1* and *S2* so physicians mostly do not have difficulties in recognition of VSD murmur by auscultation technique.

Frequency distribution of heart sounds (*S1* and *S2*) bandwidths and heart murmur bandwidth have the best representations on 3D heart sound spectrogram. Fig. 8 illustrates a 3D graphic spectrogram together with PCG for one cardiac signal with Still's murmur and one with VSD murmur.

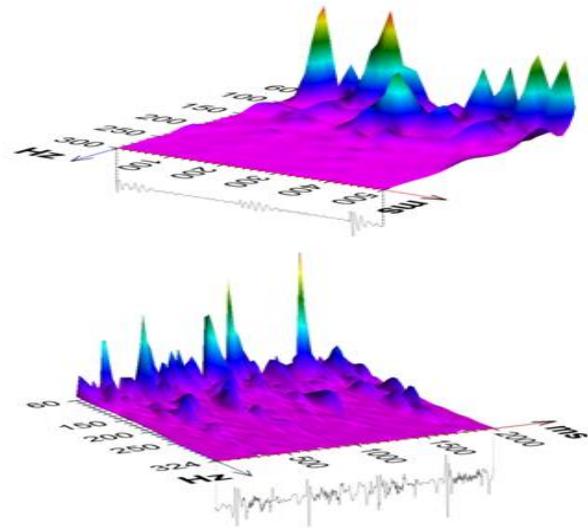


Fig.8. 3D spectrogram with time domain representation of Still's (top picture) and VSD heart murmur (bottom picture)

The top picture shows 0,5 seconds of a spectrogram of one-half cardiac cycle of one heart sound signal with Still's murmur (*S1* – Still's murmur in systole – *S2*). The frequency bandwidth of heart sounds (*S1* and *S2*) is shown by hills above base-plane in bandwidth 60-100 Hz while Still's murmur is shown by one hill of a smaller amplitude than heart sounds in frequency bandwidth 100-150 Hz. On 3D representation is visible a small distance between heart sounds and Still's murmur bandwidths. The bottom picture shows 2 seconds of spectrogram of almost four heart sound cycles of one heart sound signal with VSD murmur. Heart sounds bandwidth and VSD murmur bandwidth have a large enough distance.

Generally, by spectral analysis of heart sound signal we can recognize and classify heart murmurs by comparing spectral energy in the defined frequency bandwidth. The graphic displays of Still's and VSD murmur are clearly different, and that is what enables their visual classification. They have different acoustic and frequency parameters and their graphics are different. However, in real medical practice there are many types of murmurs and there are some types of murmurs which have similar frequency parameters with similar graphic displays.

With HSLs graphic representation physicians can easily make murmur classifications (innocent or pathologic) by comparing different lines i.e. their color and value, by comparing values of index murmur and estimating duration of the murmur. HSLs graphic representation shows three pictures: PCG signal on top, heart sounds locations (black line) and murmur evaluation (blue and red lines) on middle and murmur index lines and values on the bottom picture. Fig. 9 illustrates HSLs of one innocent Still heart murmur and Fig. 10 illustrates HSLs of one VSD murmur.

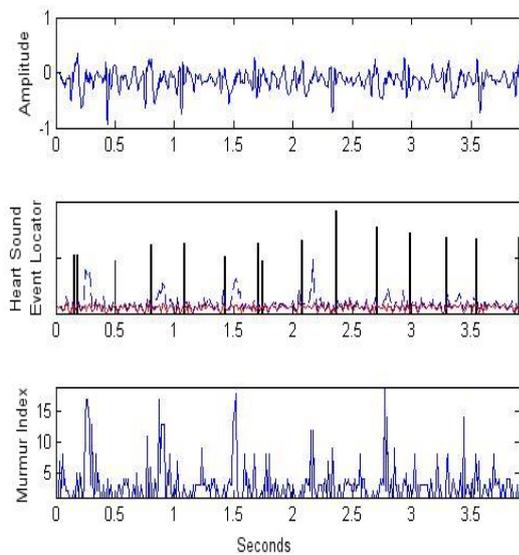


Fig.9. HSLs of Still's heart murmur

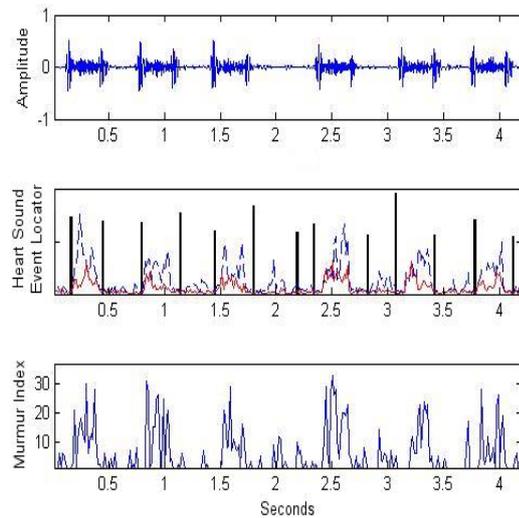


Fig.10. HSLs of VSD heart murmur

Authors created a spectrogram in Matlab and program solution for graphic representation of heart sounds and classification of heart murmurs. The detailed classification procedure of pathologic and innocent heart murmurs by using HSLs tool is described in [2]. HSLs parameters of Still murmur are: blue line, murmur index < 20 and duration of murmur < 60%. These are also parameters of innocent murmurs. HSLs parameters of VSD murmur are: blue and red lines, murmur index > 20 and duration of murmur > 60%. These are also parameters of pathologic murmurs. Authors are assuming that HSLs can be used to precisely recognize heart murmur as well as to determine heart rhythm and variation of heart rhythm

The average values of frequency parameters as well as HSLs parameters for 20 Still's murmurs and 20 VSD murmurs are given in Table 1.

Table 1. Parameters of Still's and VSD murmurs

Frequency parameters	Still	VSD
Average tone frequency (Hz)	118,75	240,82
Average bandwidth (Hz)	40,75	168,1
Average spectral energy of the peak	998,51	1648,65
HSLs parameters	Still	VSD
HSLs color lines	blue	Red and blue
Murmur index	<20	>20
Murmur duration	<60%	>60%

Average frequency parameters of Still's and VSD murmur are notably different. The frequency of Still's murmur is 118,75 Hz and of VSD murmur is 240,82. The frequency bandwidth of Still's murmur is 40,75 Hz and of VSD murmur 168,1 Hz. The spectral energy of Still's murmur is 998,51 and of VSD murmur is 1648,63. Therefore, all frequency parameters of Still's murmur have lower values than VSD murmur.

Most of pathological murmurs have sounds of higher frequency than innocent. In spectrogram's representation of one Innocent vibratory murmur peak frequency 149 Hz was recorded [15]. Kudriavtsev et al. [16] demonstrated that Still's murmurs have narrow spectral bandwidth, with this being a significant feature differentiating them from abnormal murmurs. In [17] are presented spectrogram and frequency parameters of three Still's murmurs. Obtained frequency parameters are: peak frequency of first is 102,28 Hz and bandwidth is 32,1 Hz, peak frequency of second is 124 Hz and bandwidth is 22 Hz and peak frequency of third Still's murmur is 127,1 Hz and bandwidth is 46 Hz. Similar results has also been reported in [18-20].

V. CONCLUSION

One of the leading causes of human death is due to cardiovascular diseases. The first step to prevent such diseases is to have an effective method of collecting, monitoring and maintaining the health data of the patient [21]. Biomedical signal processing is an important tool for medical diagnosis and it can help give a medical explanation of cause and origin of medical phenomena. The information such as the temporal location of the heart signals, the number of their internal components, their frequency content, the importance of diastolic breaths and systolic devices can be studied directly on the Phonocardiogram (PCG) signal by the use of signal processing techniques [22].

In this study it is presented that graphic representations of heart sounds can be a reliable assistance tool for heart diagnosis. During heart diagnosis, (classification of heart murmurs) physicians have to recognize the type of murmur. When recognizing heart murmur, both visual and audio, frequency content of a murmur carries murmur information but it is required to know the time interval of a murmur's appearance too (systole or diastole). A spectrogram display of the heart sound gives (enables)

insight to both domains and provides an additional perspective on the recorded heart sound.

Graphic representations of heart sound signals enable visual murmur displays and their visual classification. Thus, physicians who cannot clearly hear a sound of a heart, with the help of the visual display, will be able to see a sound and then make a diagnosis.

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