THE ANALYSE OF THE HEART SOUNDS FOR AUTOMATED DIAGNOSIS

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Abstract: Cardiovasculary diseases are affecting a constantly growing number of people. Due to this reason we are continously looking for new ways of investigations. The processing of the heart's audio signals also belong to this category. Along this paper the authors present the results of the combined time-frequency analysis for short-time periods applied to cardiac signals useful for diagnosis in medical practice.

Keywords: heart sound, spectral analyse, fault detection, fault isolation, automated diagnosis.

1. INTRODUCTION

The possibility of automating monitoring and diagnosis in intensive-care unit patients is an important objective, since it will increase both safety and efficiency of treatments, especially in difficult, unexpected and time-critical situations.

Human heart sounds are very natural signals, which have been applied in the doctor's auscultation for health monitoring and diagnosis. Although Dr. Laennec's invention, the stethoscope, has been in clinical use for more than 180 years, and electronic stethoscopes with variable amplification gain have been available for over 80 years, it is still difficult to understand the heart sounds (Rappaport, Sprague, 1941), (Tavel, 1996). The phonocardiogram, first developed in 1894, visualizes auscultatory signals (Selig, 1993), (McKusick, Webb, O'Neal Humphries, Reid, 1955), (Leatham, 1970).

Phonocardiography and electronic stethoscopy attempt to improve the diagnostic accuracy of the cardiac auscultation. In the most recent studies, digital acoustic analysis has demonstrated the validity of these methods (Tavel, Brown, Shander, 1994), (Tavel, 2006). Since the 1980's, phonocardiographic research activity had decreased due to the improvements of the echocardiography, which yields more visual information. During the past few years, however, the improvements of personal computers have made it possible to design new low-cost, high-quality phonocardiographic devices (Lukkarinen, Noponen, Sikiö, Angerla, 1997).

Spectral phonocardiography emulates the ear and may be ideal for teaching clinical stethoscopy. The phono-spectrogram combines traditional phonocardiogram with time-frequency distribution presentation of the signal. The spectrogram was introduced for heart sound analysis as early as 1955 by McKusik et al, but was afterwards almost forgotten (McKusick, Webb, O'Neal Humphries, Reid, 1955), (Tavel, 2006).

Recent advances in information technology systems, in acoustic signal processing and in pattern recognition methods have inspired the design of systems based on electronic stethoscopes and computers (Guyton and Hall, 1994), (Tavel, 2006). In the last decade, many research activities were

conducted concerning automated and semi-automated heart sound diagnosis, regarding it as a challenging and promising subject.

2. MECHANISMS FOR HEART SOUND PRODUCTION

Heart sounds are hearable vibrations determined by hemo-dynamic phenomenon of the heart and by large blood vessels during the cardiac cycle. These sounds are complex signals with numerous components and short-time intervals. Cardiac sounds are characterised by tone (frequency), intensity (decibels), duration (seconds) and pitch (depending on the number of harmonics that accompany the background noise). In the forming of cardiac sounds a series of elements play their own part:

- Muscular elements: the contractions of the ventricular muscles;
- Valvular components: the shutting of the valves (mitral and tricuspid closed inside of the first sound - S1 and aortic and pulmonar closed inside of the second sound - S2) is done in the direction opposed to the blood circulation and therefore generate much stronger noises than the same valves openings which are done in the same direction as the blood flow;
- Hemodynamic vibrations: the clash between to blood masses with different accelerations values lead to turbulence (the blood flows from the atrium in the ventricle);
- Vascular components: the vibrations of the vascular walls of the aorta and pulmonary artery during rapid ejections;

In medical practice the cardiac sounds are:

- Systolic: sounds 1 and 2;
- Diastolic: sounds 3 and 4.

Sound 1 (*S1*) has low frequency, marks the beginning of the ventricular systole and it is characterised by:

- Duration: 0.08 to 0.12 seconds,
- Frequency 80 Hz
- It occurs at 0.02 to 0.04 seconds from the q wave (ECG)
- It consists of a pre-segment, a main segment and a post-segment. The main segment has 0.06 to 0.10 seconds, 80 Hz and is generated by muscular contractions and mitral and tricuspide valves closing and pulmonary and aortic valves opening. The most important valve component of this segment is the closing mitral component. The post-segment lasts from 0.02 to 0.04 seconds, with a frequency between 25-50 Hz and is generated by the distension and vibration of the aorta and pulmonary artery during fast ejection.

Sound 2 (*S2*) has high frequency, marks the end of the ventricular systole and the beginning of the ventricular diastole and it is characterised by:

- It occurs from 0.02 to 0.04 seconds from the T wave (ECG),
- It lasts between 0.06 to 0.10 seconds
- Frequency between 100-120Hz
- It is composed of a pre-segment, a main segment and a post-segment. The main segment lasts between 0.05 to 0.07 seconds and is generated by the valve components, aorta and pulmonary valves closing from which the component aorta closing is more important, being responsible for 80% of the sound. Between these two components there is a delay of 0.02 seconds. The post-segment is seldom heard, lasts 0.04 seconds, has a frequency of 30 Hz and is generated by the tricuspide and mitral valves closing.

Sound 3 (*S3*) occurs at 0.13 seconds from sound 2, lasts between 0.04 to 0.06 seconds with a frequency of 25 to 50 Hz. It is generated by the hemodynamical component, appearing at the rapid fill of the ventricle. It is not heard constantly, but it is always recorded when it occurs at the mitral area at children or youngsters with a thin thoracic wall and at pregnant women, towards the end of the pregnancy. Over the age of 40 the occurrence of this sound is considered having a pathological significance.

Sound 4 (*S4*) occurs at 0.02-0.04 seconds after the P wave (ECG), has a low frequency (20Hz), low intensity and it is generated by the hemodynamical component, from the clash between a moving blood masse and the blood found stationary in the ventricle. It is never heard by the human ear. It is recorded inconstantly. It is considered physiologic only at youngsters up to 20 years old.

3. PHONOCARDIOGRAM

The phonocardiogram (PCG) is a display of the heart sound signal showing that heart sounds and murmurs can provide useful information to the physician by complementing cardiac auscultation (fig. 2).

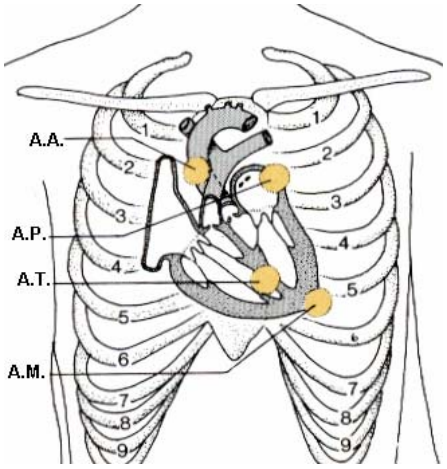

Fig. 1. Typical auscultation sites to place microphones (after Ganong, 1981).

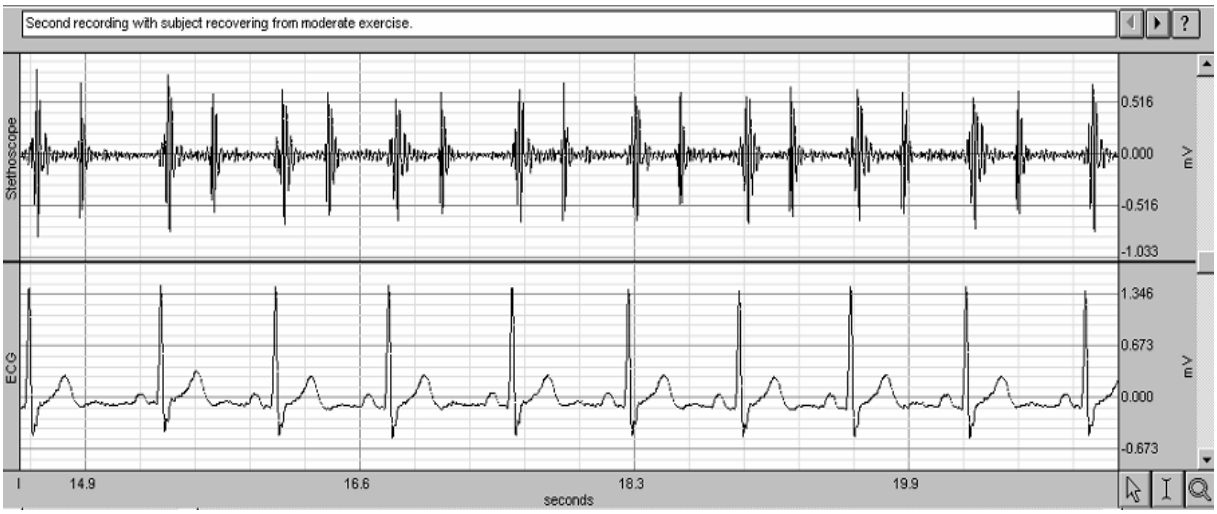

Fig. 2. Recording obtained with the BIOPAC Lab equipement which corresponds to the phonocardiogram and DII ECG.

Basic methodology of distinguishing cardiac murmurs from the PCG is the same as interpreting murmurs from auscultation. However, it provides additional information about timing of cardiac phases and events as well as serving as a digital record that can be utilized to characterize dynamic changes associated with therapy and course of the disease. PCG complements auscultation. The major PCG clinical drawback is that it does not present information on frequency of heart sounds and their components, one of the major deciding factors for murmur clinical interpretation. It does not have the ability to differentiate separate multiple (folded) frequencies of various sounds and presents no information concerning dynamic changes of energy stored in the sound. Other deficiencies arguably include signal filtration effects (change of visual representation due to filtration) and presence of artifacts and noises that can visually mask weak sounds (Kudriavtsev, Polyshchuk and Roy, 2007).

Advantages of the phonocardiogram

- Low frequency noises that we are unable to hear with the open ear are played back stronger;
- Documentary advantage through the following of the evolution, chronological timetable for each noise, blow and their morphology;
- It can estimate the degree of a valve injury;
- It can estimate the miocard contraction force;
- It can record inter-cavity noises;

Disadvantages of the phonocardiogram

- The recorder is not calibrated in regard to amplifying;
- It does not record high-pitched noises;

4. OPTIMAL FILTERING OF HEART SOUNDS

Let consider the model represented in fig. 3, intended for estimate the form of a continual signal. For the input of optimal filter, we have the next relation:

$$z(t) = u(t) + n(t) \tag{1}$$

with $u(t)$ instrumental signal and $n(t)$ the noise. The filter has the purpose to generate a signal, which must be an optimal approximation of the signal $u(t)$:

$$q(t) = u(t) + \varepsilon(t) \tag{2}$$

where $\varepsilon(t)$ is a very small error of estimation process and

$$\lim_{t\to\infty} \varepsilon(t) = 0 \tag{3}$$

The quadratic average error of estimation process must be minimum, or equivalent:

$$E(\varepsilon^2) = E\left\{\left[u(t) - q(t)\right]^2\right\} \tag{4}$$

$$q(t) = \int_0^\infty h(t-\tau) z(\tau) d\tau \tag{5}$$

where $h(t)$ represent the response of the filter when the input is the Dirac impulse. The solution of this problem is represented by the Wienner-Hopf equation:

$$\int_0^\infty h(t-\tau) R_{zz}(\tau) d\tau = R_{uz}(t) \tag{6}$$

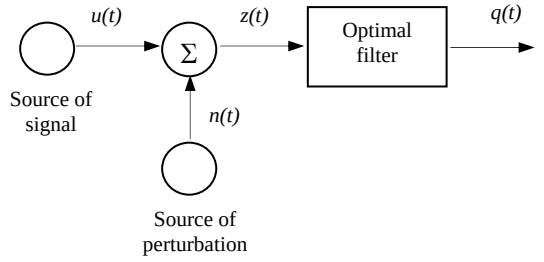

Fig. 3. The structure for optimal filtering

If the acquisition process generates the stochastic series:

$$u=\begin{bmatrix} u_0 \\ u_1 \\ \vdots \\ u_{N-1} \end{bmatrix},\ n=\begin{bmatrix} n_0 \\ n_1 \\ \vdots \\ n_{N-1} \end{bmatrix},\ z=\begin{bmatrix} z_0 \\ z_1 \\ \vdots \\ z_{N-1} \end{bmatrix} \tag{7}$$

the filtered signal has the expression (Spataru, 1987):

$$q(t)=\mathbf{H}z(t) \tag{8}$$

where **H** it is a matrix with the form:

$$\mathbf{H}=\begin{bmatrix} h_{00} & h_{01} & \cdots & h_{0,N-1} \\ h_{10} & h_{11} & \cdots & h_{1,N-1} \\ \vdots & \vdots & \cdots & \vdots \\ h_{N-1,0} & h_{N-1,1} & \cdots & h_{N-1,N-1} \end{bmatrix} \tag{9}$$

In (Spataru, 1987) is demonstrate for the matrix **H** the next expression:

$$\mathbf{H}=\mathbf{C}_u(\mathbf{C}_u+\mathbf{C}_n)^{-1} \tag{10}$$

where $\mathbf{C}_u$ - is the covariance matrix of input and $\mathbf{C}_n$ - is the covariance matrix of the perturbation.
A possibility to choice the covariance matrix is the next:

$$\mathbf{C}_{ym}=\begin{bmatrix} \sigma^2 & C_{11} & \cdots & C_{1,N-1} \\ C_{21} & \sigma^2 & \cdots & C_{2,N-1} \\ \vdots & \vdots & \cdots & \vdots \\ C_{N-1,1} & C_{N-1,2} & \cdots & \sigma^2 \end{bmatrix} \tag{11}$$

or

$$\mathbf{C}_{ym}=\sigma_y{}^2\begin{bmatrix} 1 & \rho_1 & \cdots & \rho_{N-1} \\ \rho_1 & 1 & \cdots & \rho_{N-2} \\ \vdots & \vdots & \cdots & \vdots \\ \rho_{N-1} & \cdots & \cdots & 1 \end{bmatrix} \tag{12}$$

where $\rho_{|i-j|}=\dfrac{C_{ij}}{\sigma_y{}^2}$ (Spataru, 1987).

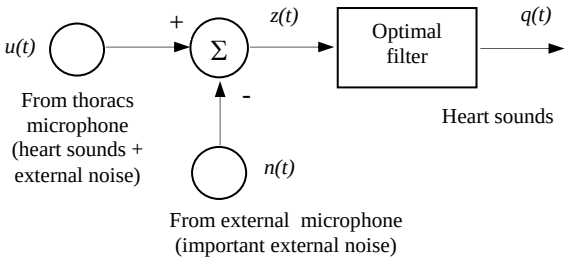

Fig. 4. The structure for the practical acquisition and filtering of heart sounds.

If we accept to consider the perturbations like a "white" noise, the covariance matrix has the form:

$$\mathbf{C}_n=\sigma_n{}^2\begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \cdots & \vdots \\ 0 & \cdots & \cdots & 1 \end{bmatrix} \tag{13}$$

A practical structure which can be used for signal heart acquisition and processing is represented in fig. 4.

5. HEART SOUNDS PROCESSING

Pathological sounds are frequently produced by heart valvular lesions, congenital heart imperfections, arithmic disease and heart failures. The PCG of the heart murmurs sounds caused by the valvular lesions are presented in fig. 5. The PCG show the intensity and the modifications of the sounds during the cardiac cycle.

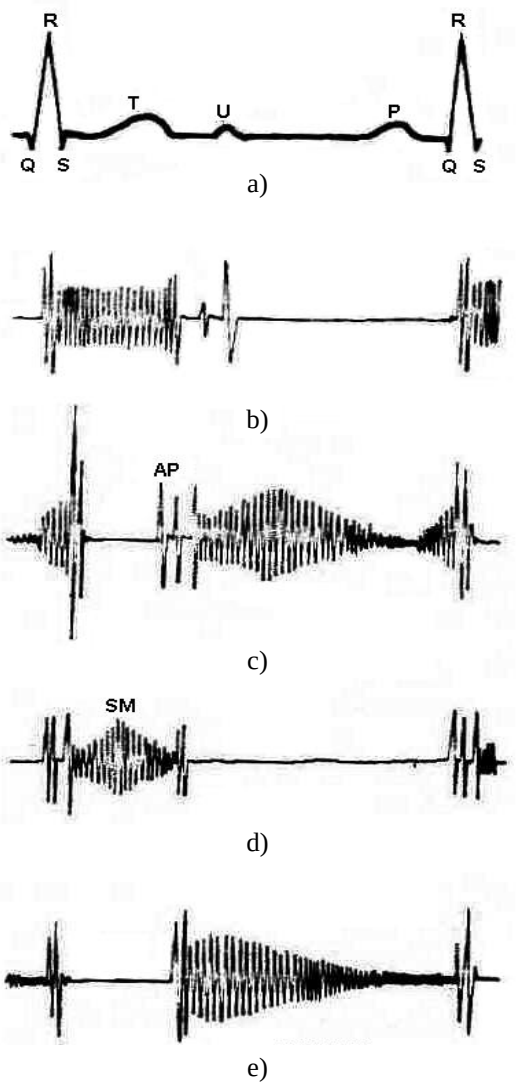

Fig. 5. The aspect of PCG in valvular lesions:
a) ECG; b) mitral regurgitation; c) mitral stenosis; d) aortic regurgitation; e) aortic stenosis. (after Gusti, 2003)

Many times, we are interested in details of the temporal process represented through $x(t)$ in certain time intervals as well as details as the spectral density in certain frequency bands. In these cases, the analysis needs to be done very specifically, in time intervals or in the frequency bands that we are interested in. Such situations can occur, for example, in the analysis of the vocal signal, in recordings of electrocardiogram signals, seismic signals and so on. Obviously, for the extraction of a window from a $x(t)$ signal we can use the "windowing" process with a function $w(t)$. The "windowed" signal:

$$x_w(t) = x(t)w(t) \tag{14}$$

is defined on a shorter time interval. In the case of analogical moving signals, the instantaneous frequency is variable in time. This is what happens, for example, in the case of frequency or phase modulated signals with a harmonic carrier.

The concept of heart sound spectral display was first introduced by McKusick in 1955 (McKusick *et al.*, 1955). Unfortunately, these method must use various forms of the *Short Term Fast Fourier Transform* (*STFT*) to obtain instantaneous frequency characteristics of signals and due to this reason it is not very accurate. As a result of this situation, a new concept has taken shape, becoming known under the name of heart energy signature (*HES*). The energy of a signal *x*(*t*), including both acoustic and PCG signals, is proportional to the squared amplitude of the signal. The signal energy *E*, contained at the time interval [*t*, *t*+*T*] is computed as:

$$E = \int_{t1}^{t1+T} |x(t)|^2 \, dt \tag{15}$$

The time plot of the heart sound PCG displays the amplitude of the sound at each instant, i.e. no information about the energy is displayed. An accepted principle in acoustics is that the energy of the single frequency acoustic signal at each instant is proportional to the squared amplitude of the signal and the squared frequency of the signal. The best method to compute heart sound energy is to utilize joint time-frequency distribution (*JTFD*). A heart energy signature is essentially a high-resolution 2D spectrographic image of the heart sound signal that is based on the Wigner-Ville joint time frequency distribution (Polyshchuk *et al.*, 2005) of recorded heart sound signal. *JTFD* reflects the distribution of the signal energy in the time-frequency plane (Cohen, 1989), (Mertins, 1999). The Wigner-Ville Distribution (*WVD*) has the mathematical expression:

$$WVD(t, f) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} x_w(t + \frac{\tau}{2}) x_w^*(t - \frac{\tau}{2}) e^{-j2\pi f\tau} \, d\tau \tag{16}$$

Unlike speech signals, where the vocal track is changing after each 20-25ms, heart sounds are more stationary and therefore the window length should be larger. The optimal window length was found to be about 500ms. It is recomaded to use only the information in the spectral magnitude and ignore the phase components which are typically more sensitive to the noise. Heart sound spectrum is concentrated within the range of 20 to 150 Hz. The simulation results are presented in figures 6, 7 and 8.

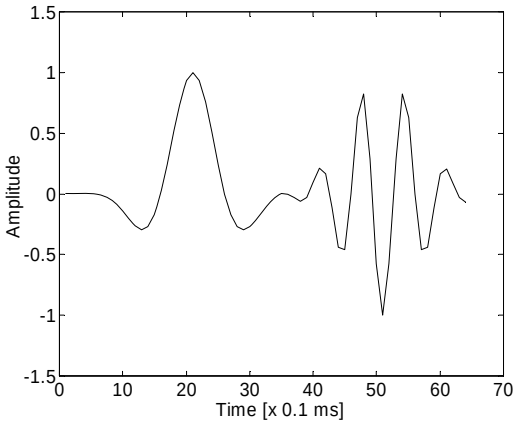

Fig. 6. The heart sound (simulation).

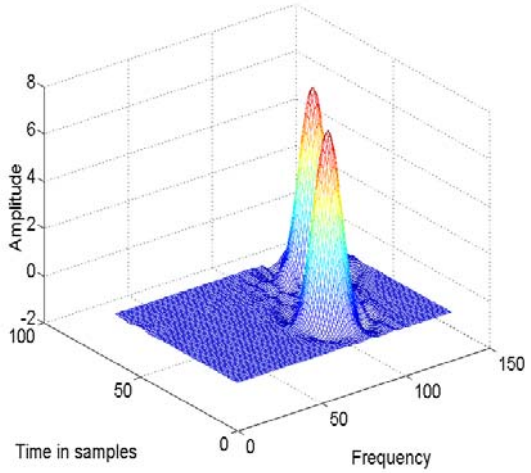

Fig. 7. Wigner-Ville distribution of the heart sound. (3D representation).

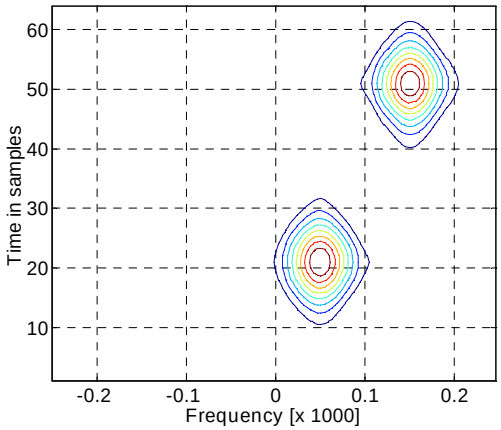

Fig. 8. Wigner-Ville distribution of the heart sound. (2D representation).

V. CONCLUSIONS

New technologies like echocardiography, color Doppler, CT, and MRI provide more direct and accurate evidence of heart disease than heart auscultation. However, these modalities are costly, large in size and operationally complex. Therefore these technologies are not suitable for use in rural areas, in homecare and generally in primary healthcare set-ups. The spectral phonocardiogram has proven to be a reliable tool that gives information of whether or not the murmur is pathological. The proposed method is an analytical solution to one of the most important problems of the automation: the confidence in data acquisition process and the avoidance to process of false information. Therefore this is an efficient decision support systems and would be very useful for supporting clinicians to make better heart sound diagnosis, especially in primary healthcare.

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