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Wavelet-based denoising method for real phonocardiography signal recorded by mobile devices in noisy environment

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ABSTRACT

The main obstacle in development of intelligent autodiagnosis medical systems based on the analysis of phonocardiography (PCG) signals is noise. The noise can be caused by digestive and respiration sounds, movements or even signals from the surrounding environment and it is characterized by wide frequency and intensity spectrum. This spectrum overlaps the heart tones spectrum, which makes the problem of PCG signal filtrating complex. The most common method for filtering such signals are wavelet denoising algorithms. In previous studies, in order to determine the optimum wavelet denoising parameters the disturbances were simulated by Gaussian white noise. However, this paper shows that this noise has a variable character. Therefore, the purpose of this paper is adaptation of a wavelet denoising algorithm for the filtration of real PCG signal disturbances from signals recorded by a mobile devices in a noisy environment. The best results were obtained for Coif 5 wavelet at the 10th decomposition level with the use of a minimaxi threshold selection algorithm and mln rescaling function. The performance of the algorithm was tested on four pathological heart sounds: early systolic murmur, ejection click, late systolic murmur and pansystolic murmur.

1. Introduction

Despite a significant decrease in the mortality rate of people suffering from heart diseases in the European Union countries (in past decade about 30% [1]) cardiovascular pathologies are still the main cause of death [1]. Therefore, there is a need to find new and to improve existing auto-diagnostic and treatment methods. In our opinion, one of such methods, which in the future can improve the process of medical diagnosis by building intelligent cardiac monitoring systems, is phonocardiography (PCG). This method, thanks to a high availability and simplicity attracted attention of both cardiologists and engineers, who want to develop medical diagnostic systems.

Nowadays, technological development provides new tools able to eliminate noise from the signals with overlapping spectra (like in the case of real phonocardiography signals). Among them, wavelet denoising algorithms can be placed at the first place as the most widely used and giving encouraging results. In general, the origin of signal distortions can be divided into two groups – external and internal [2]. The external disturbances include a wide frequency and intensity spectrum of noise caused by speech and noise caused by motion, whereas the group of signals with internal origin disturbances consists mainly signals caused by digestive and respiratory processes. Moreover, there are many other types of noise, which during the measure may occur occasionally, such as vocal (coughing, laughing), physiological (muscle movements, swallowing), sensor (rubbing) and ambient (knocking at the door, ambient music, phone ringing, footsteps) [3]. On the other hand some of the heart sounds, which have similar character to noise, such as the late systolic murmur or the pansystolic murmur, the diastolic rumble, the ejection click, etc. may indicate the occurrence of a heart disease [3]. Therefore, the development of precise noise removal algorithms, capable to work in noisy environments is of great importance and is the research subject of many scientists.

1.1. Survey of related works

One of the first attempts to eliminate signal disturbances was made by Khan et al. who on the base of an adaptive filter principle build a multi-microphone array system [4]. This system, by measuring the intensity of breath and removing it from PCG signals, significantly improved the quality of the signals. However, its major drawback was the size of devices and the number (up to three) of additional sensors placed around the patient's neck.

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A similar approach was made by Zia, Griffel and Semmlow, who in order to remove the digestive sounds placed a microphone on the patient's stomach [5]. However, setting the microphone on the patient's body proved to be as uncomfortable as placing sensors around the patient's neck. Such solution may be problematic during designing home healthcare systems [6,7]. A huge impact on the development of effective home healthcare systems had a series of publications published by Naseri et al. [8–10]. In their first work, based on a wavelet-based thresholding algorithm and baseline wander removal, a binary quality assessment algorithm (accepted/rejected) was developed [8]. Later, technique of noise/spike detection based on a cyclic random process with a non-stationary period intervals ensuring sensitivity of 91.41% and positive predictive value of 92.86% were developed [9]. In their last work a system for recognition of S1–S4 heart sounds was worked out [10]. In preprocessing, to improve the quality of the signal, they used wavelet-based noise cancelation using desired coefficient and wavelet-based thresholding [10].

Further studies were focused mainly on the development of adaptive filtration methods [11]. One of the latest was a passive fatal monitoring system, which is based on adaptive wavelet denoising method [11]. A new dynamic PCG model combined with the Kalman filter was developed by Almasi et al. [12]. An advanced PCG system based on a two-channel recording process was developed by Várady et al. [13]. However, as the authors observed [13], a comprehensive evaluation and clinical validation is still needed. A wavelet shrinkage denoising method described by Zhao was able to remove noise from non-stationary PCG signals from clinic patients tests [14].

However, the most common methods and giving best results are the wavelet based denoising algorithms [15–18], widely used in electrocardiography signal filtration [19,20], PCG signal analysis [21,22], PCG feature extraction [23,24], and structural health monitoring [25,26]. A wavelet denoising method developed by Messer et al. [15] enabled independent manipulation on the recorded PCG signal and required no additional measuring operations. Therefore, the measuring device could be reduced in size and during examination, the patients were in comfort. Simulation studies [15–18] showed the advantage of the wavelet denoising methods over other adaptive algorithms. In the Messer, Agzarian and Abbott studies, the best parameters of wavelet denoising algorithms were specified as: *Coif* (4 and 5), *Daubechies* (11, 14, and 20), and *Symlet* (9, 11, and 14) wavelets, 5th decomposition level, *Rigruse* threshold selection algorithm and *sln* rescaling function [15]. In order to eliminate power and mechanical noises Liu, Wang and Wang use a wavelet thresholding algorithm [16]. They found that best removing noise was *Coif* wavelet basis at 8th decomposition level and the *minimaxi* threshold selection algorithm [16]. The results were also tested on pathological heart sounds [16]. Cherif, Debbal and Bereksi-Reguig noticed that the Discrete Wavelet Transform (DWT) more efficiently removes clicks and murmurs from PCG signals than the Packet Wavelet Transform (PWT) [17]. Recent research in this area was focused on the development of new wavelet basis functions capable to denoise fatal phonocardiography signals (fPCG) [18].

1.2. Problem statement and main contribution

Based on the parameters of the wavelet denoising algorithm determined by the Messer et al. [15], expected results during filtration of the real PCG signals recorded by mobile devices in a noisy environment were not achieved. The recorded PCG signals and the denoised signals are presented in Fig. 1. It can be easily observed that both waveforms are identical and each part of the signal is classified as noise. This may be caused by the nature of interferences, which were assumed to have a Gaussian white noise distribution [15]. In fact, these disturbances have no white noise distribution, what is shown in the further part of this paper. The noisy environment refers to the fact that during the recording no special attention was paid to eliminate environmental disturbances. During the measurement a TV set and a PC computer generating about 65 and 60 dB noise, respectively, were switched on.

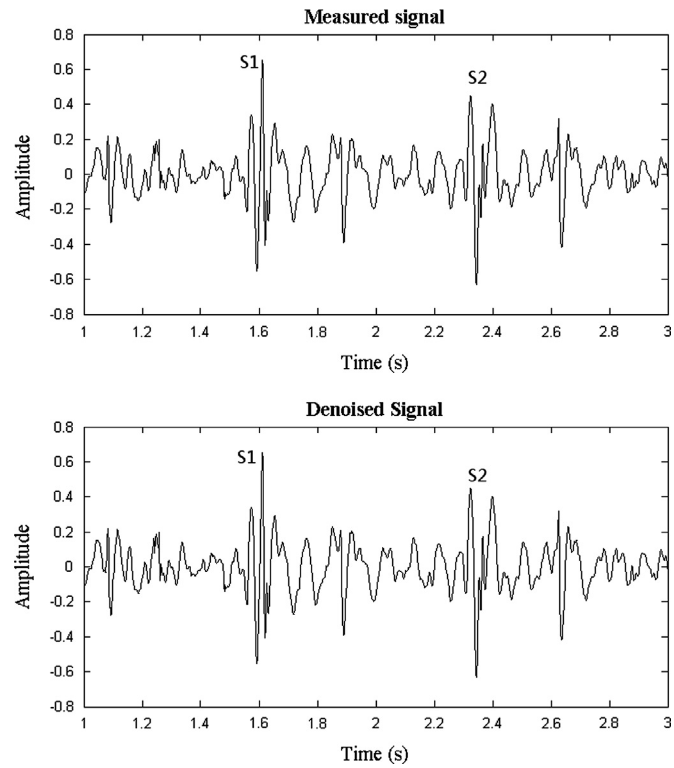

Fig. 1. A result of the wavelet denoising algorithm of a signal recorded in the noisy environment.

Referring to the problem mentioned above, the research question of this paper may be formed as an attempt to adapt the wavelet denoising algorithm for effective interference rejection (both, of external and internal origins) for real measurements of PCG signals recorded by mobile devices in noisy environments. It is crucial to consider the nature of the disturbances occurring during such measure.

2. Methods

The process of denoising PCG signals is divided into two parts. In the first, a signal acquisition system and preliminary stage of PCG signal processing, are presented. A wavelet denoising algorithm is described in the second part. Its main function is to remove the remaining noise (of internal and external origins) overlapping the spectrum of heart tones.

2.1. Preprocessing

Fig. 2 shows a measurement device, which allows heart sounds recording with the use of a mobile device. It is designed on the base of a classic acoustic stethoscope, Exacta, produced by Yavit Company [27] and a smartphone. In both stethoscope olives MIC 111 microphones [28], were placed. They are characterized by a bandwidth of 10 Hz–16 kHz and sensitivity of 58 dB ± 2 dB [28], which allows to record heart sounds effectively. Signal from the microphones are combined by a headphone splitter 1/8″ TRS and