INFLUENCES OF DIGITAL BAND-PASS FILTERING ON THE BCG WAVEFORM

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Abstract: The band pass filter is used to attenuating breathing originated signal from the heart originated BCG signal. The bandwidth of the both signals slightly overlap, hereby the complete attenuation of the breathing is not possible without also altering the heart originated BCG waveforms and the parameters which are obtained from the BCG. In our study we investigated the optimal lower cut-off frequency, and 1.3 Hz was found as the reasonable compromise between the attenuation of the breathing and the altering of the heart originated BCG.

1 INTRODUCTION

The developments in sensors, recording devices, and signal processing techniques, experienced over the past two decades, significantly increase the analysis possibilities of the ballistocardiogram (BCG). The potential of BCG to provide valuable information about the condition of the heart was clearly demonstrated even from early stages, when it was used to predict the evolution of ischemic myocardial diseases. Other clinical studies in which BCG proved useful include prognosis, monitoring, physical conditioning, stress tests, evaluation of therapy, and cardiovascular surgery (Marinelli 1991). The use of BCG has also been reported in epidemiological and cardiovascular screening studies (Star and Wood, 1961; Kiessling, 1970; Lynn and Wolf, 1974). Because during the signal measurement stage, no electrodes need to be attached to the body of the subject, BCG presents great potential for modern healthcare, especially in the case of home care monitoring.

The majority of modern BCG analysis methods rely on two separate stages, the signal measurement and the offline signal analysis with the help of a digital computer. When this is the case, one can closely look into the measured signal and decide about the filtering methods appropriate for each particular measurement. Such offline or visual analysis of BCG signals is time consuming and the costs associated with it are considerable. A better solution was offered by the advances of computers and electronic technology that provide a good basis for automatic cardiac performance monitoring and heart disease diagnosis, by assisting clinical practice and thus saving diagnosis time.

Because the raw BCG signal is usually corrupted with breathing and movement artifacts, a pre-processing of the raw data is necessary before the interpretation stage can take place. For a real-time automatic BCG analysis system, one should know in advance how this preprocessing will affect the BCG waveform. In the mid sixties the subjects were asked to hold their breath for some part of the recording, in order to eliminate the respiration effect on the BCG signal. Although this technique increases the quality of the raw BCG signal, it cannot be performed over long periods of time and it is rather uncomfortable for the subject. For these reasons digital filtering was proposed as an alternative, but was not pursued until recently due to the limitations of computing power at that time.

This study was made to investigate how bandpass filtering the raw BCG signal at different cut-off frequencies affects the BCG waveform, with respect to the BCG waveform parameters usually taken into consideration as meaningful diagnostic information.

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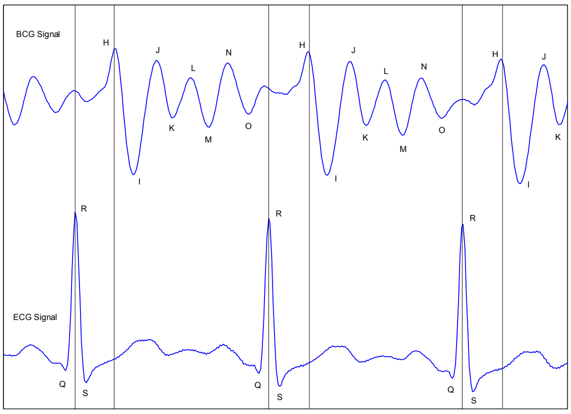

Figure 1: One dimensional BCG (top) and ECG (bottom) signals from a normal healthy subject during breath suppression.

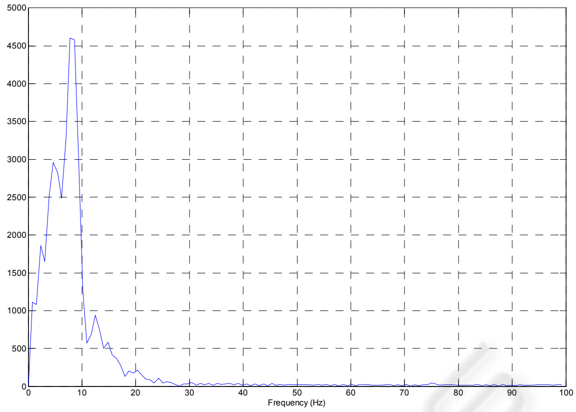

Figure 2: Power spectrum of the BCG wave shown in Fig. 1. As it can be seen, the spectra power are mostly within 20Hz.

2 THE BALLISTOCARDIOGRAM

BCG is a measure of the heart's mechanical activity associated with the flow of blood out of the heart's chambers. It was studied very actively from the 1940s until the mid-1970s when research activity in this area ended almost completely due to the technical limitations of sensors, signal conditioning electronics, recording devices and the high diagnostic value of the already available electrocardiogram (ECG). With the advance of technology, BCG signals can now be easily recorded, unobtrusively, both on supine and sitting positions using noninvasive modern techniques.

The idealized BCG waveform consists of seven components, labeled the H through N wave (Starr and Noordergraaf, 1967) with the IJK-complex being the predominantly identifiable segment (see Fig. 1). In time, typically the BCG will trail the ECG by about 0.1-0.3s (Braunstein and Thomas, 1953).

A simple spectral analysis of the BCG signal shows that the spectra power of the BCG waveform is mostly within 20Hz (see Fig. 2) but in literature is was reported that the BCG waveform lies between 0.1 Hz and 40 Hz.

BCG waves change with respiration and from one patient to another making BCG analysis a rather difficult task. Moreover, usually the raw BCG signal is also corrupted with movement artifacts, which makes the recognition of characteristic BCG waveforms almost impossible (see Fig. 3). In order to eliminate the respiration effect, seen as a drift from the baseline of the signal, various bandpass digital filters have been used and reported in literature with the most common frequency range being between 1 Hz and 20 Hz. Filtering above 1 Hz should eliminate the respiration effect but as different people have different respiration frequencies the filter could be selected at a lower or higher cut-off frequency, depending on the parameters studied. Because the BCG signal has components below 1 Hz as well and any kind of digital filtering will affect those components, it is important to know how the BCG waveform will be affected by filtering at different cut-off frequencies in order to know the tradeoff between the selected cut-off frequency and the changes suffered by the BCG waveform due to filtering.

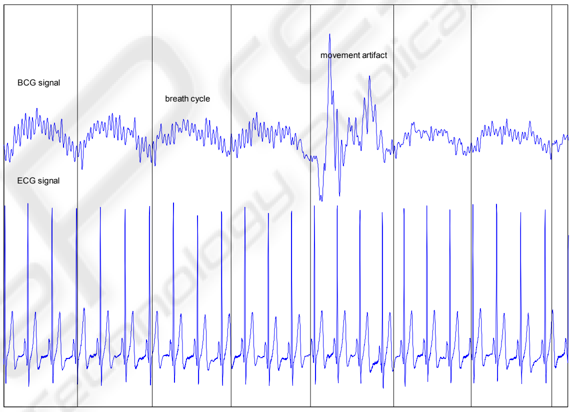

Figure 3: One dimensional BCG (top) and ECG (bottom) signals from a normal healthy subject. Notice the breathing effect on the BCG signal as a drift from the baseline and the movement artifact that causes abnormalities in the signal and makes the detection of the BCG peaks difficult.

Traditionally the physicians interpret different parameters of the measured BCG waveforms and calculate relevant indicators to determine whether or not the heart shows signs of cardiac diseases.

The various reported off-line analysis methods use different relations between the BCG peaks to classify the waveforms. The average cardiac stroke volume can be estimated as follows (Starr et al 1940):

$$ACSV = 7\sqrt{(3I + 2J)AC^{3/2}} \qquad (1)$$

where I and J are the BCG waves (in mm), A the subject's aortic internal diameter (in cm^2) and C the duration of the cycle (in seconds). From the ACSV, the cardiac output can be further calculated (Brown, Hoffman and De Lalla 1950, Starr et al 1940).

The amplitudes of the H-I, I-J, and J-K segments and their expiratory and inspiratory ratios HI_E/HI_I, IJ_E/IJ_I, JK_E/JK_I were used to express respiratory variation in BCG waves and the HI_M/IJ_M and JK_M/IJ_M ratios of the averaged mean amplitudes were used as amplitude ratios (Onodera 1964, Scarborough 1953, March 1955). The time amplitudes (TA) obtained by dividing the amplitude of a segment by its interval measured in expiratory and inspiratory phases investigated on H-I, I-J, and J-K intervals have also been reported. Other intervals measured in the literature are: the P-H interval measured from the beginning of the P wave of the electrocardiogram to the tip of the H of the Ballistocardiogram the Q-H, Q-I, Q-J and Q-K measured from the beginning of the Q wave of the electrocardiogram to the H, I, J, and K tips of the Ballistocardiogram (Onodera 1964).

3 PATIENTS AND METHODS

In this study we used a subset of 15 subjects from the signal database recorded during the ProHeMon project (Koivistoinen et al. 2004). All the measurements were conducted by an experienced research nurse at the Department of Clinical Physiology of the University Hospital from Tampere, Finland. The study protocol was approved by the Ethical Committee of Tampere University of Tampere and a written consent was obtained from each subject measured. Part of the measurement protocol included the parallel measurement of ECG, impedance cardiogram (ICG) and two BCG channels. The subjects were divided into three groups (5 subjects in each group):

1. 20-30-year old healthy students
2. healthy 50-70-year old men
3. 50-70 year old men with myocardial infarct in their medical history

Figure 4: Recording setup. In this case, no ICG leads were connected.

All measurements were done with CircMon™, a commercially available circulation monitor (Jr Medical Ltd). The ECG and ICG leads were connected to their own dedicated channels of CircMon and two BCG signals were connected to auxiliary input channels. A measurement chair with electromechanical film (EMFi™) (Kirjavainen 1987) foils and a dedicated BCG amplifier specially designed and built for this study were used to record and amplify the BCG signals from the back and the seat of the chair (Junnila et al 2004, Barna et al 2005, Junnila et al 2005). The quality of the signals was visually inspected and assessed by specialist medical doctors. In this setup CircMon functioned as an A/D converter and a sampling frequency of 200 Hz was used for each recording. The recordings lasted for about 13 minute per subject. At the beginning of the recording, the subject was placed in supine position and no BCG signal was recorded. This study does not include the study of the ICG signals obtained. The gain of the BCG amplifier was increased after the first group was recorded, so the absolute signal values between groups are not comparable.

The BCG signal, was filtered offline with a Parks-McClellan optimal equiripple band-pass Finite Impulse Response (FIR) filter designed in Matlab® 7.2 (The MathWorks Inc.). The advantage of using an FIR filter is that the phase of the input signal is not distorted and the delay introduced by the filter can be easily calculated, the information about the time location of the BCG waveform being preserved. The lower cut-off frequency of the pass-band was varied between 0.7 Hz and 4.6 Hz with a step of 0.1 Hz and the upper cut-off frequency was fixed at 20.5 Hz. A ripple of 0.1 dB was set for the pass-band and attenuation of 60 dB for both stop-

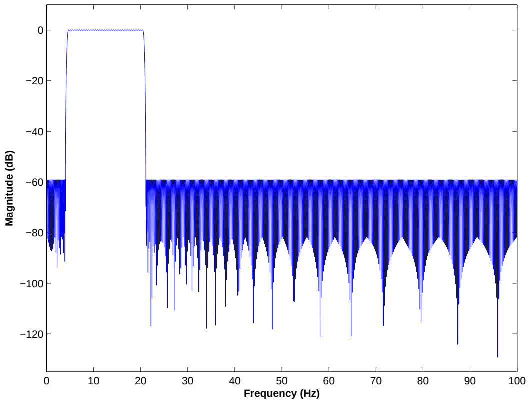

Figure 5: One FIR filter used in study. This filter have passband from 4.6 to 20.5 Hz.

bands. The transition band width was set to 0.6 Hz (see Fig. 5 for example). The order of the filters used was rather high (N = 848), which resulted in a high computation time at filtering.

After filtering, the locations of the BCG waveforms were determined using the R spikes of the parallel ECG tracing. The BCG signal was divided into sections of 151 samples. A mean BCG waveform ($BCGM_{NB}$) was calculated as the mean of 50 % of the most similar BCG waveforms found from the artifact free epochs of the recording. Cross correlation was used as the measurement of the similarity, and no visual inspection was involved. For each mean BCG waveforms the following parameters were calculated:

- the amplitudes of the mean H-I and I-J waves
- HI_M/IJ_M ratios of the mean H-I and I-J waves

4 RESULTS

In this section, a sample recording is first analyzed, followed to an overall assessment for all the recordings involved in this study.

In the Figure 6, the original signal (A01) with six heartbeats is shown. The respiratory signal can be clearly seen as a low frequency drift from the baseline of the signal. In this example, the measurement of characteristic BCG waveforms is not difficult, because the heart originated component has relatively high amplitudes compared to the respiratory signal. Figure 7 shows the same section of the BCG signal, band-pass filtered at different cutt-off frequencies. When the lower cut-off frequency is between 1.3 Hz (row one, column two) and 2.5 Hz (row four, column four), the shape of the signal is almost constant. Therefore, an optimal lower cut-off frequency of about 1.3 Hz is recommended. By studying the changes in amplitudes of the different waveforms and HI_M/IJ_M ratio, we can find a more accurate cut-off frequency.

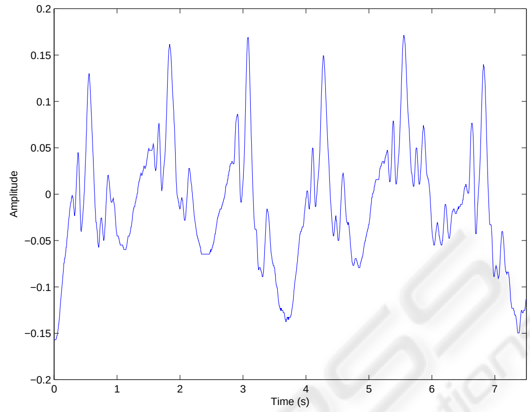

Figure 6: Raw BCG signal (subject A01).

The changes of different parameters resulted from filtering, and expressed as function of the lower cut-off frequency are shown in figure 8. As seen from the previous graphics, the parameters remain relatively constant between 1.3 Hz and 2.5 Hz, with significant changes occurring between 1 Hz and 1.2 Hz, and after 2.6 Hz. A lower cut-off frequency can be therefore selected between 1.3 Hz and 2.5 Hz without greatly compromising the BCG parameters.

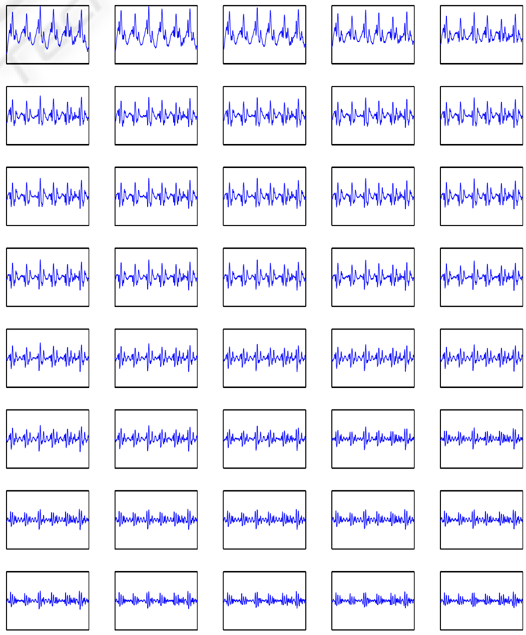

Figure 7: The section of the BCG-signal filtered with 40 different band pass filter. In the upper left corner is the output of the filter with pass band from 0.7 Hz to 20.5 Hz, and in the lower right corner is the output of the filter with pass band from 4.6 Hz to 20.5 Hz.

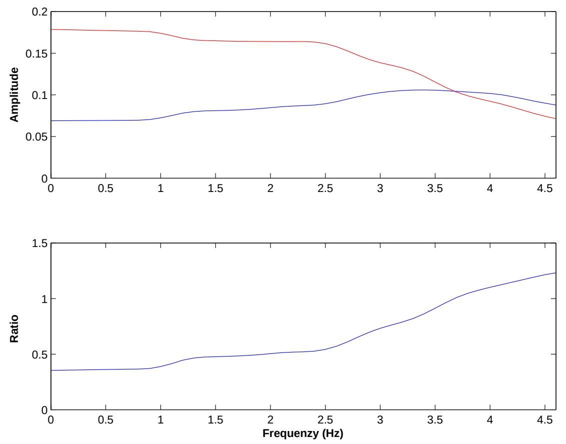

Figure 8: The different parameters as the function of the lower cut-off frequency. Up: mean I-J amplitude (red) and mean H-I amplitude (blue). Down: HI_M/IJ_M ratio.

Figure 9, shows the HI_M/IJ_M ratios of the all recordings used in this study. In the most cases, HI_M/IJ_M ratios present a flat section between 1.3 Hz to 2.2 Hz, the mean HI_M/IJ_M ratio and approximate derivative of the mean HI_M/IJ_M, shown in Figure 10 supporting this observation.

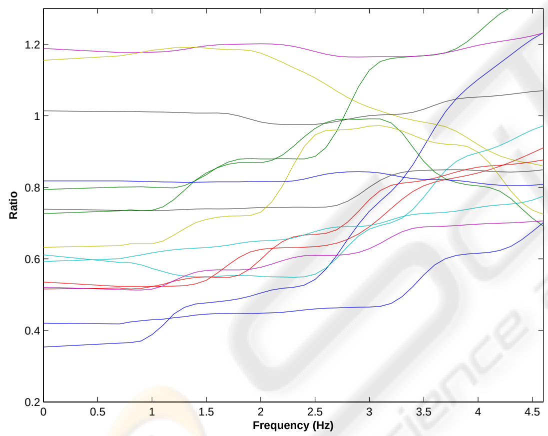

Figure 9: HI_M/IJ_M ratios of the recordings used in this study. Although up to 1Hz the ratios remain rather flat and between 1Hz and 1.3Hz they get significantly changed, when filtering at 1Hz the effect of respiration is still visible in the signal, but at 1.3Hz this effect gets eliminated (this being better for a visual inspection of Starr classes).

Based on the observations made upon the entire set of BCG recordings employed, the optimal lower cut-off frequency recommended is of 1.3 Hz. For this value, most of the signal remains unaltered, and the major effects of the respiration are removed.

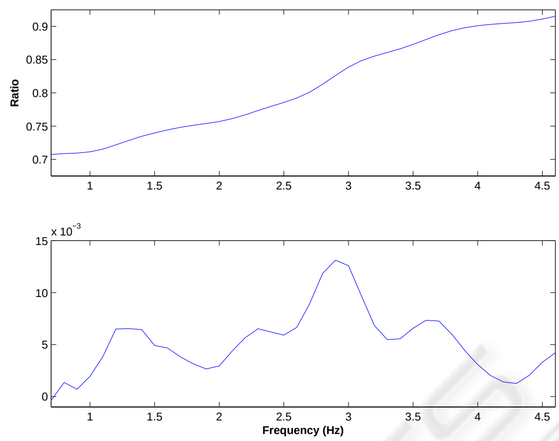

Figure 10: Up: the mean HI_M/IJ_M ratio. Down: Approximate derivative of the mean HI_M/IJ_M ratio.

5 DISCUSSION

Setting the cut-off frequency of the BCG band-pass filter is a trade-off between attenuating breathing and altering the heart-originated components of the raw BCG signal. Individual cut-off frequencies might be optimal, but that would make the comparison between patients more difficult. By using a cut-off frequency 1.3 Hz, a reasonable compromise was found.

Our results also show that changes of BCG components as a result of filtering can be estimated and accounted for in reporting BCG derived measures and ratios. By analyzing BCG data from recordings involving breath suppressed epoch, we expect to refine our results in a future study.

In this study no attempts have been made to link the amplitudes and ratio calculated from the BCG signal to any of the cardiovascular variables such as stroke volume

The equation presented in section "The Ballistocardiogram" for the average cardiac stroke volume was not feasible because no calibration has been performed for the BCG system used and the subjects were recorded in sitting position, unlike Starr et al, in which the recordings were performed in supine position. As future improvements, we plan to combine the information available in the ECG and ICG recordings with the one obtained from BCG..

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