Acta Polytechnica **53**(6):862–867, 2013
doi:10.14311/AP.2013.53.0862

available online at http://ojs.cvut.cz/ojs/index.php/ap

A NOVEL BCG SENSOR-ARRAY FOR UNOBTRUSIVE CARDIAC MONITORING

Anna Böhm*, Christoph Brüser, Steffen Leonhardt

Chair for Medical Information Technology, Helmholtz-Institute for Biomedical Engineering, Pauwelsstr. 20, 52074 Aachen, RWTH Aachen University, Germany

* corresponding author: boehm@hia.rwth-aachen.de

Abstract. Unobtrusive heart rate monitoring is a popular research topic in biomedical engineering. The reason is that convential methods, e.g. the clinical gold standard electrocardiography, require conductive contact to the human body.

Other methods such as ballistocardiography try to record these vital signs without electrodes that are attached to the body. So far, these systems cannot replace routine procedures. Most systems have some drawbacks that cannot be compensated, such as aging of the sensor materials or movement artifacts. In addition, the signal form differs greatly from an ECG, which is an electrical signal. The ballistocardiogram has a mechanical source, which makes it harder to evaluate.

We have developed a new sensor array made of near-IR-LEDs to record BCGs. IR-sensors do not age in relevant time scales. Analog filtering was neccesary, because the signal amplitude was very small. The digitized data was then processed by various algorithms to extract beat-to-beat or breath-to-breath intervals. The redundancy of multiple BCG channels was used to provide a robust estimation of beat-to-beat intervals and heart rate. We installed the system beneath a mattress topper of a hospital bed, but any other bed would have been sufficient.

The validation of this measurement system shows that it is well suited for BCG recordings. The use of multiple channels has proven to be superior to relying on a single BCG channel.

Keywords: ballistocardiography (BCG), unobtrusive measurement, cardiac monitoring.

1. Introduction

Vital signs such as heart rate and respiratory rate are recorded to determine the overall state of a patient. Typically, electrocardiograms (ECG) via Ag/AgCl electrodes are used to monitor heart rate and to identify unusual events, such as arrhythmias. However, before recording an ECG, the skin has to be properly abrased, sometimes even shaved, and a conductive gel is applied. The gel dries after a short period of time and the signal deteriorates. This does not allow for longer measuring periods, especially not at home.

The goal of this work was to develop sensors that can be placed in a patient's bed or in other everyday objects for heart rate monitoring.

An unobtrusive method from measuring heart rate is ballistocardiography (BCG). It involves measuring rhythmical mechanical movements of the entire body resulting from blood flow. The BCG's shape differs from an ECG because of its mechanical source. A BCG has a delay of roughly 100 ms to the ECG signal [1]. The signal shape is dependent on the measurement system, specifically on where the sensor is placed. If it is installed in a bed, the patients' position in the bed is a determining factor [2].

Many forms of ballistocardiographs have been proposed. Traditionally, measuring systems have been integrated into rigid tables and the longitudinal displacement of the bed has been measured [3]. Additionally, BCG systems have been placed directly onto the body [4]. Others have tried locations such as beneath pillows [5], mattresses [1] or embedded in other everyday objects [6].

In addition to heart rate estimation, they have been used, for example, to detect atrial fibrillation [7]. Existing BCG measuring systems can be made of various kinds of force sensors, optical sensors, acceleration sensors, position sensors, or pressure sensors. So far, only Maki [8] has developed an infrared-based sensor consisting of one emitter and a detector placed between the springs of a spring core mattress.

2. Methods

We designed a novel optical BCG sensor system with sensors using infrared light. The sensor is made of a small printed circuit board (PCB) with three IR-LEDs and one photo diode. The principle is based on light scattering inside the mattress. The radiation emitted by the LEDs enters the mattress, and the returning amount of IR-light is detected by the photo diode.

The sensing units of the ballistocardiograph can be be placed between the patient's mattress and the mattress topper at up to eight places. It is also possible to place the sensor directly under the mattress, but our setup yielded better results. An advantage compared to [8] is that the mattress does not have to be taken apart in order to install the system, see Fig. 1.

Figure 1. Sensor-system setup in a bed.

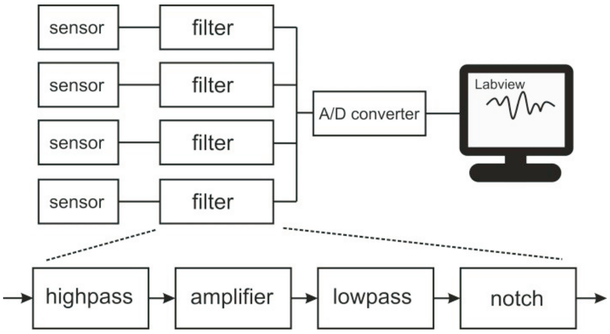

Figure 2. Analog filter chain.

The sensor units detect localized cardiac-related vibrations from the body. The single signals differ depending on the location of the sensors under the body. Breathing can be seen in the raw signal as a superimposed oscillation with a lower frequency if the sensor is placed below the thorax.

2.1. Measurement Setup

A block diagram of the measurement setup is depicted in Fig. 2. The measurement system is modular, so that multiple sensors can be connected at the same time. The signals are filtered with analog hardware filters for each channel individually. The resulting signals are digitized with a NiDAQ USB6009 device with 14 bit resolution (National Instruments, Austin, Texas, USA). Subsequently, the data of each channel is recorded with Labview (National Instruments, Austin, Texas, USA). The raw data is then processed with MATLAB (The MathWorks, Natick, Massachusetts, USA).

2.2. Working Principle

The sensors are made of three infrared light emitting diodes and one infrared detector centered between the LEDs. The wavelength of the LEDs is 850 nm (type SFH 4250, OSRAM, Munich, Germany). The silicon PIN photo diode has its maximum sensitivity at 880 nm (type BPW 34 FAS, OSRAM, Munich, Germany). Its radiant sensitive area dimensions are $2.65 \times 2.65\,\mathrm{mm}^2$. Our tests have shown that a 1.5 cm distance from emitter to detector is the best trade-off

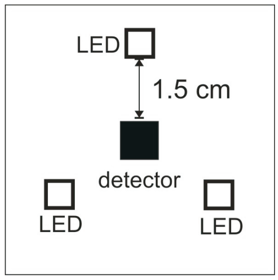

Figure 3. Sensor PCB.

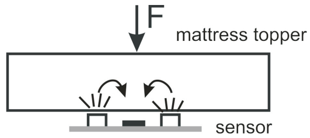

Figure 4. Sensor under a mattress.

in terms of signal quality and penetration depth of the light into the material, see Fig 3. If the distance between emitter and detector is larger, the resulting penetration depth becomes higher. However, the greater the distance, the lower the number of photons that reach the detector.

The working principle of the measurement setup is shown in Fig. 4. The light is emitted into the material, where it is scattered, absorbed or transmitted [9]. A synthetic foam mattress topper was used. When it is compressed by forces exerted by mechanical movements of the body, the air enclosures of the foam are deformed. Consequently, the path of the light also altered. The number of photons that are sensed by the detector changes according to the compression of the material.

2.3. Analog Filtering Techniques

As the AD-conversion is conducted with 14 bit, the quantization error equals 1.22 mV. The signal-to-noise ratio is very low, and analog filtering of the sensor signals is necessary. For our application, higher frequencies can be filtered out, as the heart rate is assumed to be between 0.67 and 3.33 Hz.

The light detected by the photo diode is converted to an electrical potential by a trans-impedance amplifier. This circuit converts current into the corresponding voltage. The signal is simultaneously low-pass filtered with a corner frequency of 160 Hz.

Additionally, it is high-pass filtered with a passive 1 Hz RC-filter in order to remove the baseline, so the operational amplifier does not saturate. Another operational amplifier sets the gain of the filter chain. High-frequency components are removed by a Sallen-Key low-pass filter with a corner frequency of 20 Hz. In addition, a 50 Hz Twin-T notch filter cancels out the line noise. The analog filter chain is depicted in Fig. 2.

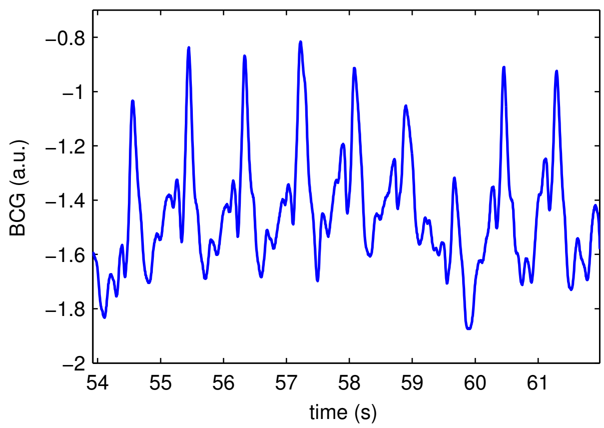

FIGURE 5. Raw BCG signal.

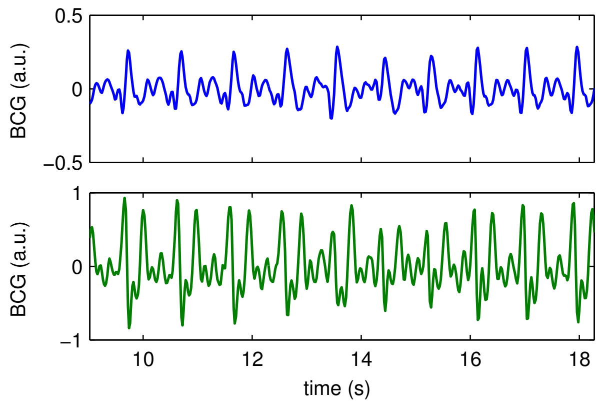

FIGURE 6. 2-channel BCG data (0.5–20 Hz)-filtered BCG Signal.

2.4. MULTI-CHANNEL ALGORITHM

Evaluating BCG signals is a challenging task. Due to the position and the sensor-dependent signal morphology, a robust algorithm has to be applied. It is not sufficient to find the peaks, as in an ECG signal. Analysing a BCG mostly relies on finding patterns that are similar and repetitive. A high-pass filtered signal with repetitive patterns of this kind is shown in Fig. 5. While this example exhibits rather clear deflections for each heart beat, this is not generally the case.

Beat-to-beat and breath-to-breath intervals are estimated using of an algorithm provided in [10]. The algorithm is capable of extracting intervals of signals that have different morphologies — even in signals that are so noisy that is not possible to find peaks manually. These intervals are computed for a given signal. They can be used to monitor heart rate and to determine heart rate variability, for example.

The algorithm preprocesses the signal by filtering with a Butterworth pass-band filter between 0.5 and 20 Hz. Instead of first detecting the location of heart beats and then computing the corresponding beat-to-beat intervals, the algorithm estimates the time-varying instantaneous heart rates from the raw signal using three short-time estimators (e.g. autocorrelation). These estimators are applied to an adaptive moving analysis window and then combined using a Bayesian approach. In addition, artifacts are detected based on adaptive amplitude thresholding and automatically discarded. The results of the algorithm are the beat-to-beat intervals reconstructed from the signal.

Based on the algorithm in [10], a multi-channel version was further developed to select the channels that perform best for beat-to-beat estimation. The channels are selected on the basis of certain criteria e.g. calculation of standard deviation. If the standard deviation

$$\sigma_x = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \overline{x})^2}$$

of a given signal is much lower than the standard deviation of the other channels, low information density is expected.

The second method is kurtosis. Kurtosis expresses the extent to which the distribution of a signal is peaked or flattened. The kurtosis of an ECG is usually around $K = 5$, so we also adapted this value for BCG [11]. Kurtosis can be calculated as follows:

$$K = \frac{1}{N}\sum_{i=1}^{N}\Big(\frac{x_i - \mu_x}{\sigma_x}\Big)^4.$$

Finally, the estimated beat-to-beat interval of each individual channel has to be within an accepted threshold: $f_{\mathrm{HR}} = [0.67; 3.33]$.

3. RESULTS AND DISCUSSION

Signals were recorded with a prototype optical BCG system. Simultaneously, an ECG was obtained as a reference. The signals were recorded with a sample rate of 400 Hz.

In the following sample measurement with 2 channels, repetitive patterns can be seen (Fig. 6). The time between the dominant peaks is equal to the heart-rate interval. The shapes of the signals are different, as they were taken by sensors located in two different positions.

Fig. 7 shows the influence of respiration. The subject had a respiratory rate of approximately 9 breaths per minute, which can also be seen in the BCG signal. The recording was made while the test subject was lying on his back.

3.1. SIGNAL MORPHOLOGY

According to a study mentioned in [12], eight different sleeping positions exist.

In a trial, four different positions were analyzed: supine, on the left side, on the right side, and prone. The test subject lay in each position for one minute and then turned around.

The transitions from one position to another were clearly visible in the measured signal. That is because

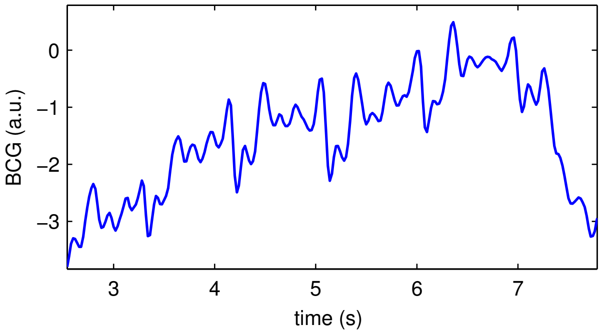

Figure 7. Band-pass filtered BCG data (0.5–20 Hz) with respiratory influence.

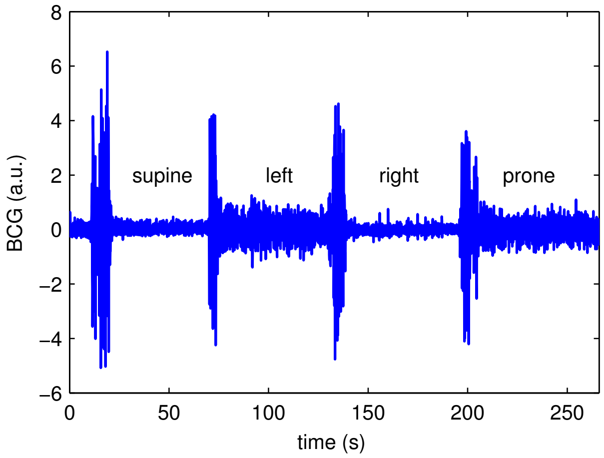

Figure 8. BCG with different lying positions.

the movement artifacts have much higher amplitudes than the normal signal, as can be seen in Fig. 8.

The patients' contact area with the mattress topper determines the signal shape. Different positions resulted in very dissimilar signals. Some positions were more advantageous for estimating the heart rate than others, see Fig 9.

The peak-to-peak voltage was approximately 1.5 V in every case except for the right side where it resulted in a peak-to-peak voltage of 0.4 V. Furthermore, periodic signal patterns could be identified in the supine, left and prone positions. The left and prone positions also showed repetitive dominant peaks. The reason for the reduced signal quality while lying on the right side is unclear. It may be due to the larger distance from the contact area of the body to the heart.

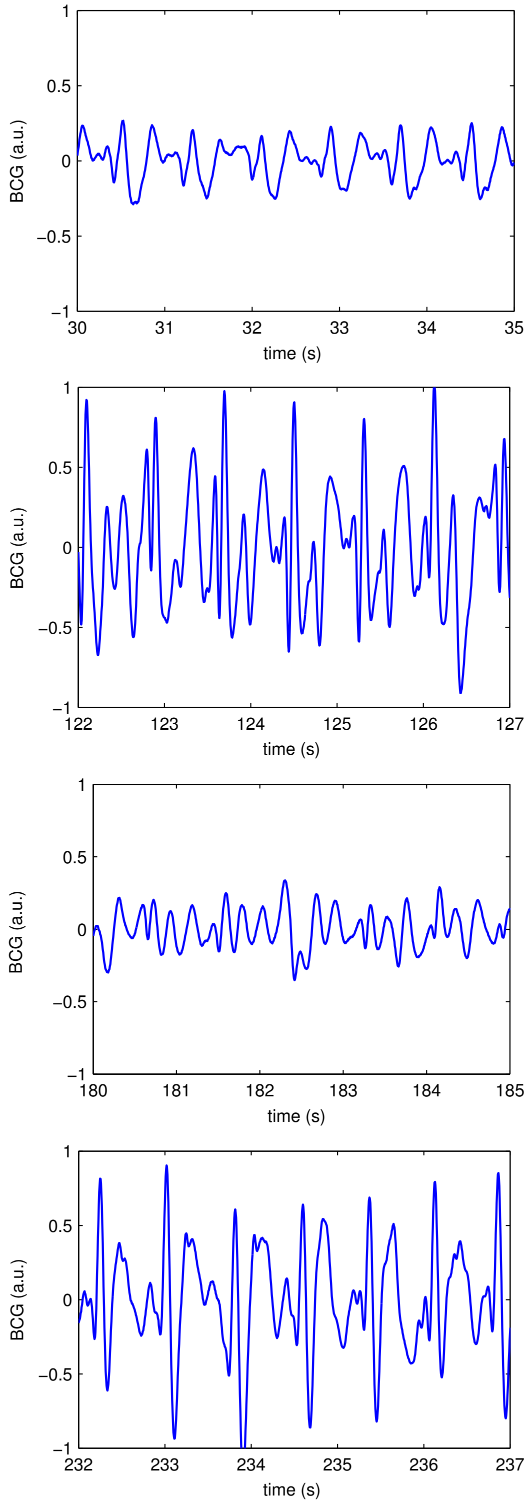

Figure 9. Five close-ups of BCGs, from top to bottom: supine; left; right; prone.

3.2. Sources of Artifacts

The source of different artifacts was examined. A common problem of BCG systems is that they are susceptible to external vibrations. We therefore investigated whether these vibrations cause artifacts in the optical BCG signal. However, our tests showed that optical BCGs are also subject to these vibrations. The heart rate cannot be estimated if a movement artifact occurs, because the operational amplfier saturates.

Another test was conducted to comprehend the influence of external light sources, i.e. incandescent light. Due to the fact that the working principle of the sensors is based on radiation, external light sources may cause artifacts or baseline changes. The experiment was performed by switching on and off the lights in a darkened lab without any test subject in the bed. The test showed that incandescent light had no influence on the BCG signal.

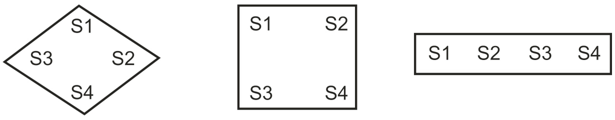

Figure 10. Different sensor configurations.

	Coverage	Rel. error
Best channel	87.01 %	1.46 %
Worst channel	18.61 %	25.7 %
Multiple channels	89.16 %	0.67 %

Table 1. Comparison of estimations of intervals for the best/worst channel to an estimation of intervals using multiple channels.

3.3. Sensor-Array

Up to eight sensors can be connected to the current system. Three different sensor configurations beneath the mattress topper were tested with a 4-channel setup. A diamond shaped configuration, a square, and a line were tested, see Fig. 10. In each case, it seems beneficial to place the sensors below the patient's torso, because of the proximity to the heart. The closer the sensors are to the diaphragm, the more dominant the breathing component becomes.

The diamond configuration was chosen, because the largest part of the torso is covered with only 4 sensors and the probability that the subject lies on one or more of the sensors is higher in any chosen position.

3.4. Heart Rate Estimation

The optical BCG was evaluated with a single channel measurement during a 15-minute trial and a simultaneous ECG. Compared to the ECG, the coverage of the BCG equaled 89.35 %, and the relative error of the estimated intervals was 1.58 %. Fig. 11 shows a comparison of ECG beat-to-beat estimated intervals (Pan-Tompkins [13]) and BCG estimated intervals within a certain time frame. In this specific case, the estimations overlap almost perfectly.

The multi-channel system was evaluated with a 4-channel measurement in a 20-minute trial recorded at 200 Hz. The results in Tab. 1 show that one channel had a poor signal with only 18.61 % coverage. The channel was therefore automatically excluded from the estimation by the algorithm most of the time. The best signal in terms of coverage had a relative error of 1.46 % compared to the ECG. The best result was achieved by combining multiple channels for the estimation.

4. Conclusion

The proposed BCG system is a new method for BCG measurements in bed. The advantage of BCG is that it works without direct contact to the patient's body. By using near-IR-optical sensors, ageing of the material

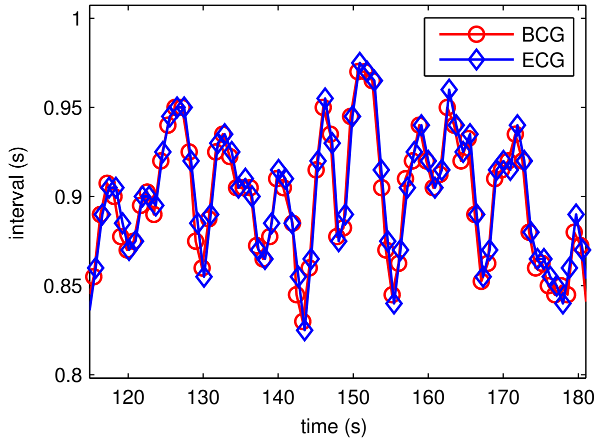

Figure 11. Comparison of BCG and ECG beat-to-beat interval estimation.

can be excluded as a reason for deterioration of the signal quality.

Heart rate, beat-to-beat intervals and in principle respiration rate and breath-to-breath intervals can be extracted from the signal, which is essentially based on small vibrations of the body.

However, optical sensors are prone to movement artifacts, as are other BCG sensors. When the subject turned, it was not possible to estimatie the heart rate or the heart beat intervals. Nevertheless, the results are promising, because high coverage and low relative error were achieved by optical BCG.

So far, only a single prototype is available, and only a limited number of recordings have been obtained. A larger study should be conducted to further investigate this concept.

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