

Simple ECG and MCG Devices for Biomedical Engineering Students

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Abstract. The paper presents a simple electrocardiograph (ECG) and a simple magnetocardiograph (MCG) device designed and built for teaching the undergraduate engineering students the basics of the ECG method. The ECG device is composed of two simple copper electrodes (sensors), common computer sound card (data acquisition), audio-recording software and open source real-time spectrum analysing software. Matlab is used for off-line data processing and generation of the heart activity in a spatial domain over the human's chest area. The MCG device consists of two fluxgate magnetometers and uses the ECG signal for digital signal conditioning. The two simple devices prove to be a valuable tool for teaching the students the basics of electromagnetism of the human heart activity, voltage and magnetic measurements, extraneous electromagnetic noise reduction, and filtering and processing of physiological signals.

Keywords: Magnetocardiogram, Electrocardiogram, Fluxgate magnetometer, Computer sound card, Human heart magnetic mapping.

Preprosti napravi EKG in MKG za študente biomedicinske tehnike

V prispevku sta opisani preprosti izvedbi elektrokardiografa (EKG) in magnetokardiografa (MKG). Namen prispevka je prikaz načrtovanja in izdelave orodja za učenje študentov tehniških ved osnov metode EKG. Zgrajeni merilnik EKG je sestavljen iz preprostih bakrenih elektrod (senzor), računalniške zvočne kartice (zajemanje podatkov), brezplačnega programa za obdelavo podatkov in za spektralno analizo signalov v realnem času. Za dodatno procesiranje in generiranje srčne aktivnosti v prostorski domeni je bil uporabljen program, napisan v Matlabu. Poleg EKG smo načrtovali in zgradili tudi preprosti MKG, sestavljen iz dveh Foersterjevih magnetometrov.

Obe napravi sta se izkazali kot uporabni orodji za učenje osnov elektromagnetike človeške srčne mišice, merjenja električne napetosti in gostote magnetnega pretoka, za prikaz zmanjševanja elektromagnetnih motenj, filtriranja in obdelave fizioloških signalov za študente tehnike.

1 INTRODUCTION

The electrocardiography (ECG) is a measuring method used to detect and record the electric potential generated by the heart electrical activity over a period of time (Figure 1). ECG, dating from the beginning of the twentieth century, is one of the oldest diagnostic tools used in medicine today. With the advances in instrumentation, ECG has become and remained a widely used clinical tool in the field of cardiac abnormalities evaluation, for being highly accurate and easy to interpret. The method is considered a golden

standard for measuring the human heart rate (HR). It uses conductive (usually Ag/AgCl) electrodes attached to the human's body in a prescribed standardized fashion.

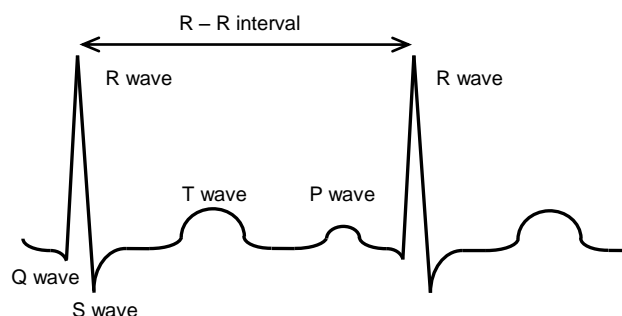


Figure 1. Typical parameters of the ECG method - interbeat interval (IBI) or R-R interval, an interval between the QRS complexes of a normal sinus depolarization.

Typically, in biomedical engineering laboratory exercises, a 12-lead ECG device is used for the students to learn about the measuring method itself, standardised positioning and attachment of electrodes, etc. In simplified versions a smaller number of leads is used; usually the Lead II ECG method (electrodes on both arms and a leg). The simplest is Lead I ECG method with only two electrodes attached to the human's body. The Lead I ECG method is used in this paper.

1.1 The ECG device

Our simple and low-cost contact Lead I ECG recording device is composed of two electrodes and a data-acquisition device. The measurements are made with two identical electrodes connected to a symmetrical input of a personal computer’s sound card, as shown in Figure 2. As the sound card has high-impedance (1 MΩ) inputs, no preamplifier is needed. The electrodes are made from copper-clad laminate boards with a surface area of 50 cm² (10 cm x 5 cm) each and an overall thickness of 1.5 mm. A common quality personal-computer sound card (E-MU 0404 USB by the E-MU Systems) is used as a data acquisition device with a bandwidth of up to 96 kHz and sampling frequency of up to 192 kHz [1].

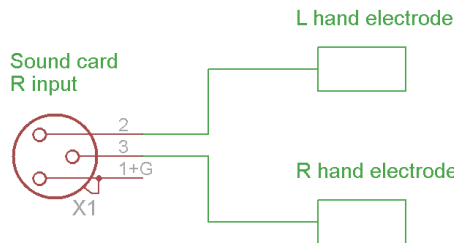


Figure 2. Schematics of our ECG device (electrodes connected to symmetrical inputs of the right channel of the sound card, the ground terminal is unconnected).

Prior to the measurements, the ECG device is evaluated. Evaluation was performed by comparing it to a commercial ECG monitor (Biopac ECG100C by the Biopac Systems Inc.) (Figure 3.).

Signal conditioning and filtering are performed as listed in Table 1.

Table 1. Results of a comparison between our ECG device (ecg) and the Lead II ECG device (Biopac).

	ecg hr / bpm	Biopac hr / bpm	Error / bpm
Max	84.45	84.39	0.14
Min	63.58	63.56	-0.20
St.dev.	3.40	3.40	0.05

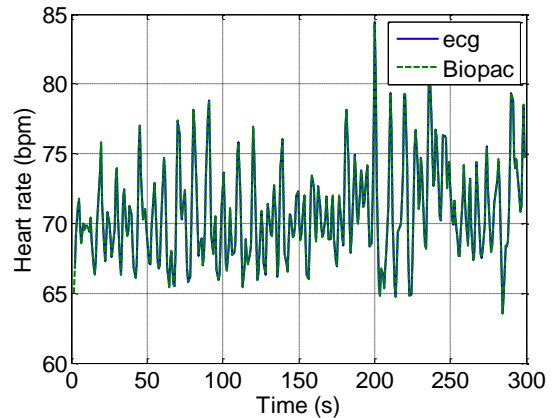
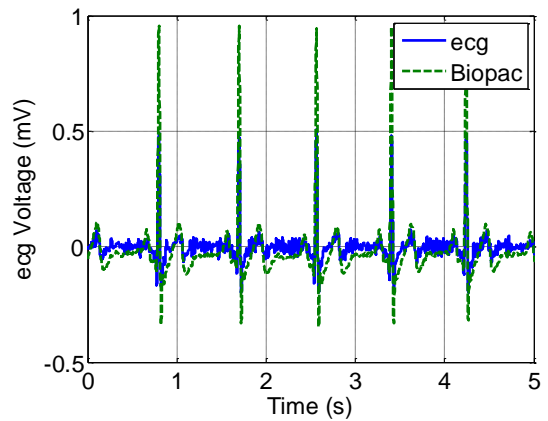


Figure 3. Comparison of our ECG device (ecg) and a commercial Lead II ECG device (Biopac). Above: ECG signals, Below: measured heart-rate in bpm (beats per minute).

The statistics of the HR comparison given in Table 1 shows a negligible difference between the signals, thus proving the suitability of our simplified Lead I ECG device for signal synchronization. The error is defined as the difference between the measured ECG HR (ecg) and HR measured by the Biopac system.

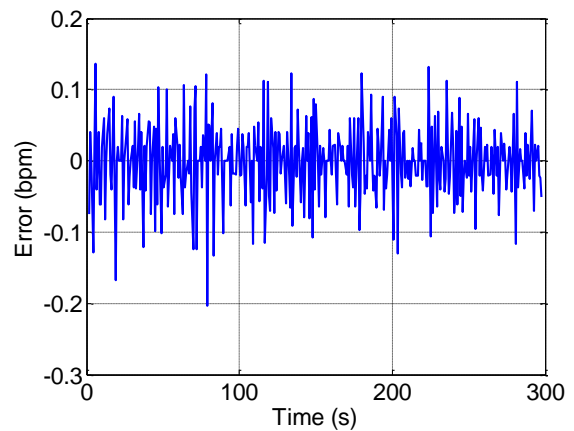


Figure 4. Time-dependence of the measuring error i.e. the difference between HR, measured HR with our ECG device and the Lead II ECG device (Biopac).

The measuring error of our device, i.e. the absolute maximum difference between HRs obtained with the Biopac ECG100C device and with our device, is 0.2 bpm with a standard deviation of 0.05 bpm in 300 seconds.

1.2 The MCG device

A magnetic version of the ECG heart activity is magnetocardiography. Measuring the magnetic activity of the heart muscle is nowadays performed by the SQUID magnetometers (superconducting quantum interference device) [2,3], which are costly and complex and require sophisticated non-magnetic facilities and electromagnetically noise-free laboratory environment. Due to the liquid helium or liquid nitrogen cooling, their operating costs are high and they are not suitable for experimenting in a pedagogical laboratory environment, affected by a lot of extraneous electromagnetic noise from power lines, electrical devices, transformers, larger ferromagnetic objects (e.g. elevators, building iron armature).

Another magnetic measurement option is using a fluxgate gradiometer [4]. Our gradiometer has two magnetometers which measure the magnetic-flux density in the vicinity of a human body.

First order Fluxgate gradiometer was composed of two triple axis fluxgate magnetometers, which were positioned in opposing directions above the human heart (Figure 5).

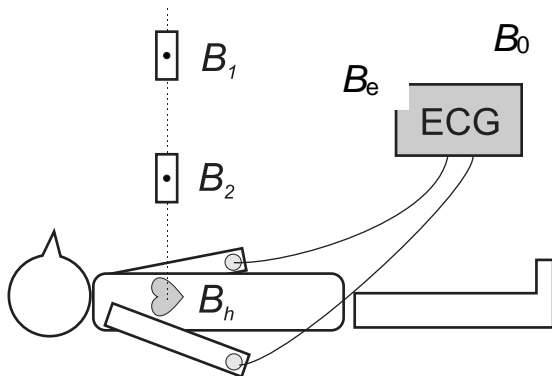


Figure 5. Measuring set-up for acquiring the ECG and MCG signals from the human heart (B_h), where grey circles indicate the ECG electrodes and B_1 and B_2 the fluxgate magnetometers. B_e are the unwanted extraneous magnetic fields (power grid) and B_0 were the magnetic fields of the environment (earth magnetic field).

In our measurements, the magnetometers are used only in one axis. Their base distance is adjusted to the distance between the heart and first fluxgate [5]. The used fluxgates (FL3-100 by the Stefan Mayer Instruments) have the measuring range of $\pm 100 \mu\text{T}$ at up

to a 2 kHz frequency range, noise density of $12 \text{ pT}/\sqrt{\text{Hz}}$ and measuring uncertainty of approximately $0.6 \mu\text{T}$ [6]. The magnetometers are connected as shown in Figure 5. The first magnetometer acquires magnetic flux density B_1 of the earth B_0 and of heart activity B_h . The second magnetometer measures flux density B_2 and is placed above the first one, at an adequate distance from the body not to sense any noticeable level of the magnetic heart activity (Figure 5). Our experiment took place in an environment with extraneous AC magnetic fields B_e . the extraneous earth magnetic field is suppressed by capacitor C1 in Figure 6 and the sound card by the in-built high-pass filter.

$$B_1 = B_0 + B_h + B_e$$

$$B_2 = B_0 + B_e$$

With the magnetometers connected in opposite directions using the potentiometer in Figure 6, the sum of their outputs is adjusted in order to cancel out the extraneous magnetic fields, thus zeroing the output of both magnetometers with no active human heart present.

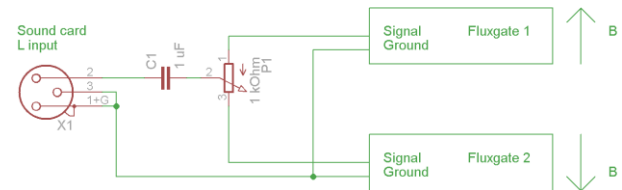


Figure 6. Circuit for summation of the fluxgate magnetometer outputs for cancellation of the extraneous magnetic fields. Lin is the left input connector of the sound card.

When zeroing, monitoring uses a free real-time spectrum analysis software by the DL4YHF's Spectrum Lab (Audio Signal Analyser) [7]. By monitoring the low frequency spectrum of the gradiometer signal, potentiometer P1 (Figure 6) is adjusted to the lowest-possible noise level. Now, a human body is introduced and the zeroed fluxgates measure only the magnetic flux densities generated only by the heart muscle, i.e. the MCG signal (B_h).

2 METHODS

After building, testing and evaluating our ECG and MCG devices, several measurements of the human heart activity are performed. A series of 5-minute measurement intervals is conducted on a healthy volunteer. The resulting data is pre-processed, filtered and processed.

The MCG and ECG signals are acquired using a sound card at a 48 kHz sample rate with a free open-source

software Audacity for recording and editing the sounds [8]. Any other suitable sound recording software can be used instead. Using the same software the recorded signals are now resampled at 4 kHz to reduce the size of the recorded audio files.

Resampled audio files are processed using the Matlab software by MathWorks [9]. Both audio channels are filtered using filter settings shown in Table 2.

Table 2. Filter settings for filtering the ECG and MCG signals. All filters were of the Butterworth type.
* for peak detection only

Type	Order	Corner freq. / Hz
Low-pass	4	40
High-pass	1	0.5
Notch	2	45 and 55
Notch	2	130 and 150
High-pass*	1	5

In order to observe the heart activity in a spatial domain, the same procedure is used for the sequential MCG measurements enabling a two-dimensional representation of the magnetic field homogeneity above human's chest area. 25 measurements are carried out at locations 5 cm apart from each other as shown in Figure 7.

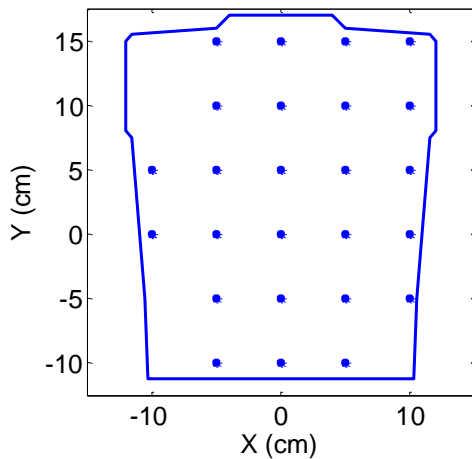


Figure 7. 25 MCG measurement points marked with an asterisk over the human's chest area.

By smoothing the averaged MCG signal it was possible to produce a short video showing the two-dimensional magnetic field over the chest area changing over the time (Figure 10).

3 RESULTS

In order to get reliable measurement results, the humans are in a relaxed state with their heart activity stable. The physiological stability of their heart activity is assessed by calculating HR in beats per minute (bpm). Figure 8 shows some statistics of 25 measurements taken during the experiment. The average value of the differences between the maximal and minimal HR values in each measurement is 17.5 bpm with a standard deviation of 3.2 bpm ($n=25$). The average HR value in each measurement is 55.9 bpm with a standard deviation of 2.5 bpm.

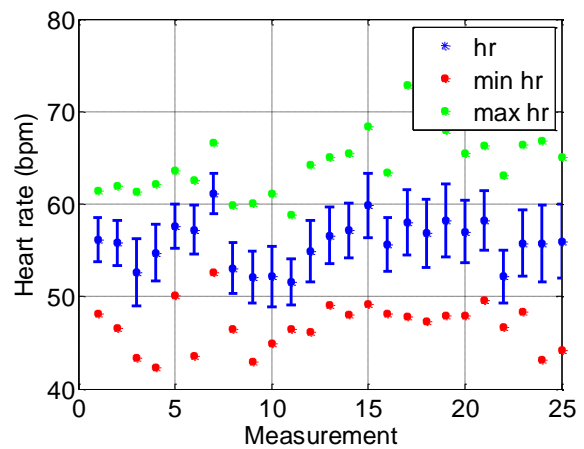


Figure 8. Statistics of the HR measurements during our experiment (hr - mean HR, min hr - minimal value and max hr - maximal value of the HR, bpm - beats per minute)

Signal processing of the raw physiological signals is made using filtering from Table 2. The R-peaks of the ECG signals are searched using the peak-detection function [10] and their location indices are stored for a further use with the MCG signal averaging. Using the stored indices of the Q-peaks in the ECG signal, averaging the MCG signal is performed by summing a 2-second signal window with a reference to the R-peak of the ECG signal. Figure 9 shows a typical form of the raw and filtered ECG and MCG signals in the time and frequency domain.

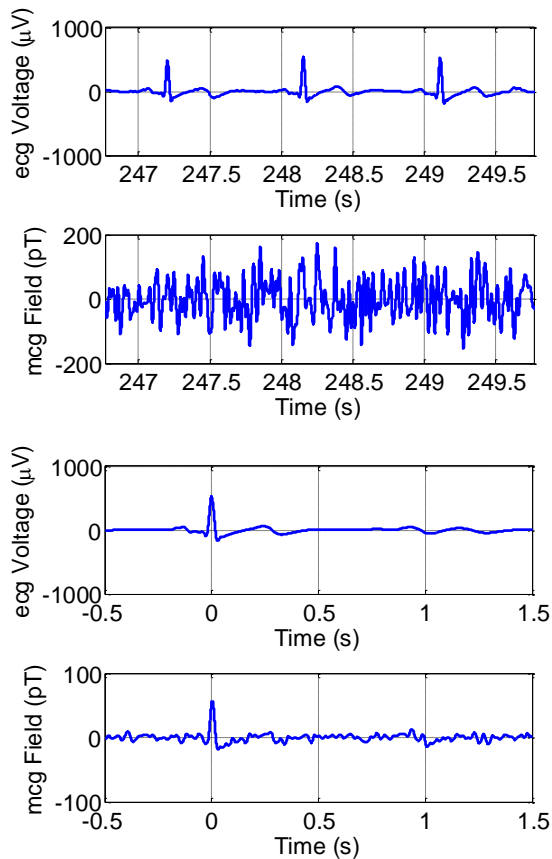


Figure 9. Unfiltered raw (left) and processed ECG signal (ecg Voltage) and MCG (mcg Field) devices (right).

Figure 10 shows two frames of a short video of a two-dimensional magnetic field over the human's chest area. The results show a good agreement with the results obtained by using a multichannel SQUID measuring system [11].

5 CONCLUSION

The paper describes a simple and efficient laboratory device for teaching the engineering, electrical engineering and biomedical engineering the undergraduate students the basics of physiological measurements, with an emphasis on acquiring cardiovascular parameters, such as the heart rate and heart-rate variability. It enables the students to gain a new knowledge in electrical and magnetic measurements, signal conditioning, triggering and filtering raw physiological signals and some practical aspects of the ECG and MCG methods. By measuring the human heart activity, the students learn about the measuring methods, which can be extended metrologically by estimating the repeatability, reproducibility and uncertainty budget of the measurement.

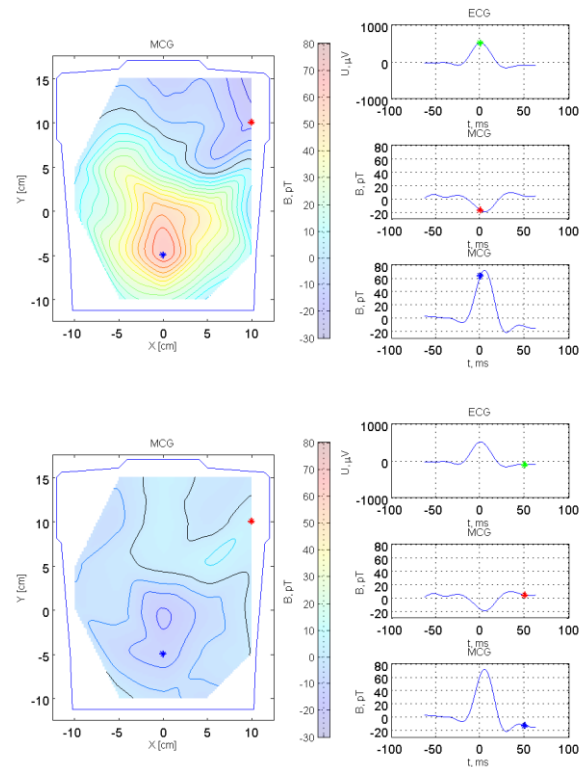


Figure 10. Two frames from a video of a time-variable two-dimensional magnetic field over a human's chest area representing a time-variable spatial distribution of the ECG and MCG signals (large 2D picture). The ECG and MCG values in a time domain are shown with their maxima marked by an asterisk (three smaller graphs).

The main advantage of the presented ECG device is that it requires a simple and low-cost laboratory instrumentation and uses simple copper plates as electrodes and a common personal computer sound card as a data-acquisition device. The MCG device has two fluxgate magnetometers. For the undergraduate students, the ECG signal processing and the MCG gradiometer principle are easy to understand and use. During the recent years, the presented ECG and MCG devices have provided numerous teaching and learning opportunities and projects for the electrical-engineering students at the University of Ljubljana. Their main value is in giving the students a simple and straightforward explanation of the measurement-related terms and definitions with an emphasis on measuring simple physiological parameters, such as the heart rate or heart-rate variability.

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Gregor Geršak je doktoriral leta 2003 na Fakulteti za elektrotehniko Univerze v Ljubljani. Njegovo raziskovalno področje obsega teorijo merjenja, precizijsko merjenje gostote magnetnega pretoka, tlaka in termometrije. Ukvarja se z meroslovjem biomedicinske instrumentacije, s psihofiziološkimi merjenji in senzoričnim merjenjem človekovega odziva.

Samo Beguš je diplomiral, magistriral in doktoriral na Fakulteti za elektrotehniko Univerze v Ljubljani v letih 2001, 2004 in 2007. Njegova področja znanstvenega raziskovanja vključujejo električna, akustična in ultrazvočna merjenja, precizijska magnetna merjenja in merjenja vlage v materialih, optične magnetometre in senzorske sisteme.