ProHeMon

Proactive Health Monitoring

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Final report of the research project in the Academy of Finland Proactive computing research program

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Introduction

The ProHeMon project belongs to the category of proactive computing for technology in medicine. New sensors, such as the thin EMFi[1] foil sensor [Kir87] offer the possibility to monitor some physiological variables from humans quite unobtrusively. This project developed a normal-looking chair with sensitive sensors, a wireless data link and information processing methods to analyse the ballistocardiogram (BCG) of a patient sitting on the sensor chair for a relatively short time. The system is proactive in the way that the measurement can be started as the person sits down on the chair and the results can be output without anybody pressing any buttons if so desired.

The project can be divided to two subprojects. The medical research project was performed by the Department of Clinical Physiology of Tampere University Hospital and the technology development project was performed by the Institute of Signal Processing of Tampere University of Technology. The medical part consisted of recording a large number of normal subjects and patients and the visual analysis of the recordings. The technological part consisted of designing and building of measurement devices capable of recording BCG and of the design of algorithms and methods for the analysis of the recorded signals.

Objectives

On the medical side our goal was to develop an easy, reliable and non-invasive method for studying respiratory and cardiovascular diseases, which could enable screening of subclinical diseases in a normal general practice. Our goal was also to select target areas in which BCG has diagnostic value.

On the technical side the final goal was to design and build a working prototype of a proactive measurement chair which could record and analyse the BCG of a person sitting on it without the person even noticing that a measurement is being done. Meeting the final goal set a number of subobjectives for the study. These were:

- design, implementation and certification of a measurement device capable of recording 12 channels of ECG and three channels of BCG using the EMFi sensor
- design, implementation and certification of a measurement device capable of recording two channels of BCG using the EMFi sensor with low power consumption
- implement a wireless ballistocardiographic chair, which would look like ordinary office chair, and could measure the BCG using the EMFi sensors and transmit the measurement signals to a nearby PC wirelessly
- detect the presence of a person on the chair by analysing the EMFi sensor signals
- detect the heart rate of the recorded BCG signal without any other reference signals
- determine the methods to separate the heart-originated signal components from those caused by the respiration of the person sitting on the chair
- design a method which calculates quantitative data or more generally, clinically significant information of the measured BCG
- design methods which classify the recorded BCG recordings to different categories automatically even though there are occasionally various types of artifacts present in the signal

[1] EMFi is a registered trade mark of Emfit Ltd, Vaajakoski, Finland.

Methods

Medical subproject

Eight groups of subjects were recorded for the study. The groups were:

Group 1: 20-30-year old healthy students (n = 16). Reference group for the other groups.
Group 2: Healthy 50-70-year old men (n = 20). Reference group for the groups 2B, 3, 4 and 5.
Group 2B: Healthy 50-70-year old men with blood pressure over 140/90 mmHg (n = 15). The purpose of the group was to evaluate the effects of high blood pressure to BCG.
Group 3: 50-70 year old men with myocardial infarct in their medical history (n = 18). Purpose of the group was to evaluate the effects of myocardial infarct to BCG.
Group 4: 50-70-year old men with asthma (n = 9). Purpose of the group was to evaluate the effects of asthma in the baseline signal of BCG.
Group 5: 50-70-year old men with dialysis treatment (n = 14). Purpose of the group was to evaluate the effects of poor circulation status to BCG.
Group 6: Healthy young adults 20-35-year old (n = 36). Purpose of the group was to evaluate the effects of changes in posture (supine vs. sitting) in BCG.
Group 7: Re-measurement of the Group 1 (n = 10). Purpose of the group was to evaluate reprocibility and repeatability of the BCG measurement.

The study protocol for all subjects was the following:

1. Interview of the subject.
2. Measurement of weight, height and blood pressure.
3. Measurement of 12-lead ECG in supine position.
4. Measurement of blood pressure in supine position.
5. Measurement of impedance cardiography, 1-lead ECG and BCG in supine position. Duration of the measurement 5 min.
6. Measurement of blood pressure in supine position.
7. Subject sits on the measurement chair which measures BCG. ICG and 1-lead ECG are measured continuously.
8. 5 min rest on the chair.
9. Measurement of blood pressure in sitting position.
10. Measurement of BCG, ICG and 1-lead ECG in sitting position for 5 minutes.

In the group 6 BCG measurements were done also in supine position.

The measured ICG signals were visually inspected for good technical quality by MD Tiit Kööbi. The measured ECG signals were inspected for heart diseases by MD Kalle Sipilä. BCG signals were classified to four Starr classes by researcher Teemu Koivistoinen, MD Joel Hasan and research nurse Marjaana Ylhäinen. Starr classification divides BCG signals in four different categories on the basis of the quality of the signal. The main idea of Starr classification is that subject with good heart and circulation status belongs to class 1 and subject with extremely abnormal heart and circulation status belongs to class 4.

Technical subproject

In the beginning of the project it was necessary to construct measurement devices which could be used to collect BCG and ECG data simultaneously from the group of normal subjects and patients. The EMFi sensors cannot be connected to a normal physiological signal amplifier directly because a charge amplifier is required which led to the decision of building a self-made amplifier for the project. The first version of such a device was based on the expansion of the

measurement device built earlier, before the project [Ala01]. As the construction of this device capable of performing a 12 lead ECG recording together with the EMFi sensor based BCG measurement took much longer than expected, a simpler version of a two-channel EMFi signal amplifier was designed and built more quickly to get the measurement series started. This system was first published in [Jun04a] and later a more detailed analysis of the whole measurement system was published in [Jun05]. A second version of the charge amplifier was later built to be used in testing and prototyping at Institute of Signal Processing as the first device was used in Tampere University Hospital. Both the (the 12 lead ECG & 3 channel BCG amplifier and the 2 channel BCG) devices passed the inspection required by the University Hospital of devices to be used in patient measurements.

In order to find a suitable mechanical construction for the BCG chair looking like a normal chair a number of existing chair models available in Tampere University of Technology were inspected for their rigidity and potential for use with the EMFi sensors. The help of an upholsterer was used to tailor the upholstery in such a way that the sensors obtain a good signal still being hidden from the eye.

The development of a wireless link from the chair to the PC which analyses the signals was an important part of the project. First, a survey of the different wireless technologies was made, and results were published in [Jun03]. The survey suggested the use of Bluetooth as Zigbee devices were unavailable at that time. The small battery powered charge amplifier unit [Jun04a] was mainly intended to be used in a wired measurement system implementation but it also served as a test platform for the measurement electronics used in the final wireless system. The charge amplifier circuit was fine tuned using this unit and the same fine tuned circuitry was used in the later designs, along with some of the power supply implementation parts.

During the development of the measurement electronics, the first Zigbee/IEEE 802.15.4 devices had surfaced. A choice was made to change from Bluetooth to Zigbee, and evaluation modules of the Chipcon CC2420 circuit were ordered. Using the second version of the charge amplifier, a very simple one channel wireless prototype was constructed in fall 2004, which demonstrated that the idea works in practice. This was published in [Jun04b]. The construction of the final wireless measurement chair and its measurement electronics was done in fall 2005, and is still unpublished. The final chair features armrest electrodes and ECG amplifier, which are used to detect the R-spike position from the ECG. It has two BCG channels, and one Flexiforce amplifier. The Flexiforce sensor can be added to the chair to measure the subject's weight, as the EMFi-sensor is unable to measure this kind of information. The system has a 16 bit analogue-to-digital converter which is controlled by the microcontroller on the separate radio frequency board via an optically isolated serial link cable. The data are transmitted wirelessly to a receiving unit, which is connected to a PC via the serial port.

Pre-processing methods of the BCG signal are needed because the recorded BCG-signal contains different kinds of artifacts. The largest artifacts appear when the subject being measured moves on the chair. The movements cause a significant increase in the power of the signal achieved from the EMFi sensors and in most cases the actual BCG signal will be useless. The method to detect movements was therefore developed. It is based on the calculation of the power of the signal in a suitable time window. If the power is greater than a threshold value, the part of the signal is marked as an artifact, and no further analyses are made. The same method was also used to detect if a patient was sitting on the chair. The parts of the signal in which the power of the signal is not high enough are also not processed further.

To detect the different signal components of the BCG signal correctly, there is a need to use the ECG signal as a reference signal first. When the BCG analysis works well on its own, ECG is not always needed anymore. There are several known useful QRS detection methods available but we chose to use our own very simple method. First, we high pass filter the ECG signal to remove the low frequency baseline drift and the ECG amplitude modulation with respiration. This also attenuates the P and T waveforms, and leaves the amplitude of the QRS complexes unchanged. We then filter the output of the highpass filter with a maximum filter and compare the result with the output of the highpass filter. If the output of the highpass filter is greater than a threshold value multiplied with the output of the maximum filter, the indexes are stored. The R spike is then detected from the original ECG signal as the maximum value within the indexes. The noise sensitivity of this method has not been studied yet, but until now it is good enough for the signals recorded in the ProHeMon project.

From the heart-originated part of the BCG signal we try to detect different peaks, labeled from "G" to "N" by The American Heart Association's Committee on Ballistocardiographic Terminology. The "H" peak is the first headward deflection after the ECG R wave on the acceleration (force) BCG. The next peak is labeled as "I", and the next one as "J".

The main frequency band of the heart-originated BCG signal is from 1.5 Hz to 20 Hz. Therefore, first step in the analysis of this signal is the band-pass filtering. After band-pass filtering, the signal is segmented with the help of the R-spike detection achieved from the ECG-signal analysis. These segments are then classified into the different classes. The classification is based on the correlation of the segments, and in the each classes, the correlation between any two segments will be greater than threshold value.

After the classification, the actual BCG waveforms are detected. Because the correlation inside each class is high, the mean of each segment inside one class gives us a good estimate of the location of the different waves. The first wave which we try to detect is the mean I-wave which is most likely the minimum of the signal between 0.1 to 0.25 seconds after the R-spike detected. Then we can detect the mean J-wave, most likely the maximum value of the signal within the time window length of the 0.2 second after the I-wave. The mean H-wave is detected as the maximum of the signal between 0.05 second after R-spike and detected I-wave. After we have found the mean waves, we will find the actual waves from each of the segments. If the correlation threshold value was set to high enough, the actual waves should be found from each segment when we investigate the segments in the short time windows around the detected mean wave locations. After the detection of the different waves, we can calculate the different parameters, like I-J amplitude etc.

The respiratory signal is separated from the EMFi sensor signal by a bandpass filter (lower cut-off frequency about 0.1 Hz, upper cut-off frequency about 0.5 Hz). As the order of such a bandpass filter will be remarkably high, we first perform decimation. The maximum decimation factor can be as high as 100 (if the original sampling rate is 200 Hz), but optimization can be used to minimize the number of operations needed for the filtering. The zero-crossings of the signal (from negative to positive) were then marked as the beginning of each respiratory cycle.

In the supervised classification part of this project we used well known artificial neural networks such as multilayer perceptrons (MLP) and radial basis functions (RBF) which need training using small part of recorded BCG data and a strong feature extraction tool called wavelet transform ,specially compactly supported kinds, to classify and evaluate recorded BCG data of several subjects [Akh05c]. Also, we developed a new feature extraction method so-called time-

frequency moments singular value decomposition (TFM-SVD) [Akh05b] which gives us almost the same result as wavelet gives us. To find performance of the combined approach, several test subjects from three groups were used: two healthy young persons, two healthy old men and two old men with a past infarct in their heart. The results showed that our developed methods have higher performance than other existing methods, but the issues of learning speed and computational load are still not solved. To solve these two remaining problems, we applied our newly developed neural network called Supervised Fuzzy Adaptive Resonance Theory (SF-ART) [Akh05a] and wavelet transform to classify the BCG cycles with very high learning speed and low computational load (need less than ten learning cycle and few seconds to learn BCG patterns). The patients and subjects we used for both training and testing these methods are the three groups including, young healthy students, old healthy men and old men with a history of myocardial infarct.

Results

Medical results

BCG and hemodynamic recordings were in 159 subjects, in 22 subjects twice. Recordings of 30 persons were left outside of the analysis, because they had other disorders. Thus, a data set of recordings of 127 subjects was included in the study. This data set provided the means of approaching the signal analysis problem of the BCG for the technical subproject.

Using the current measurement setup BCG could be measured reliably at the same time with ICG and ECG. On visual analysis we didn't find any direct relationship between the decrease in cardiac pump function, blood pressure or age and Starr classes (Table 1.).

Table 1. Starr classification and hemodynamic data of all recordings. Values are Mean ± SD.

Group	Age (years)	Systolic blood pressure (mmHg)	Stroke index (ml/m²)	Heart rate (beats/min)	Starr class I	Starr class II	Starr class III	Starr class IV
Healthy (n = 72)	32 ± 14	119 ± 9	34 ± 4	66 ± 11	28	12	31	1
Hypertension (n = 14)	57 ± 3	141 ± 10	36 ± 4	62 ± 9	2	2	9	1
Infarct (n = 18)	61 ± 6	127 ± 17	35 ± 4	52 ± 9	5	3	10	-
Dialysis treatment (n = 14)	54 ± 12	138 ± 20	32 ±6	67 ± 5	1	1	11	1
Asthma (n = 9)	64 ± 4	134 ± 22	34 ± 4	79 ± 14	-	-	8	1

We also compared the results of Starr classification between sitting and supine positions (Figure 1). In the majority of the subjects the Starr class moved either to a higher or a lower class. In most cases the Starr class was better in supine position. Most probably, the reasons for that phenomenon are the damping properties of the body mass.

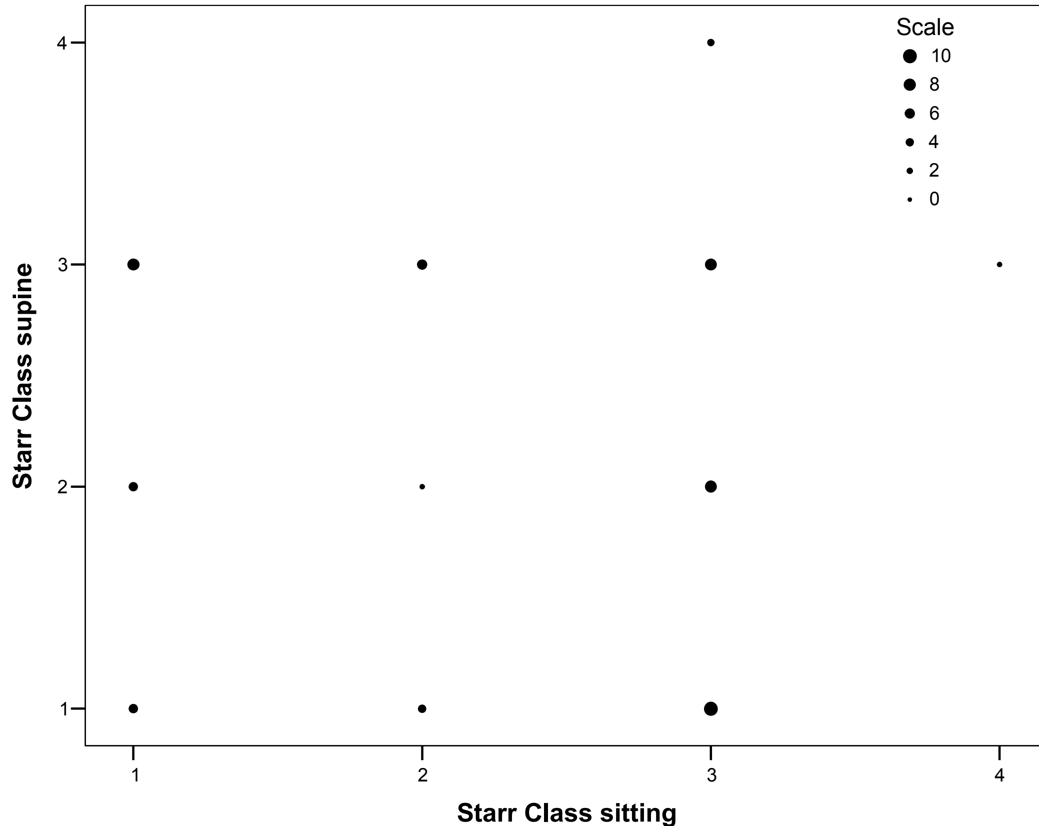

Figure 1. Comparison between Starr classes in supine and in sitting position (n = 59). The bullets denote the change in Starr classification from supine position to sitting position. The line from (1,1) to (4,4) shows the number of subjects in whom the Starr classification remains the same.

Technical results

Most of the results of the project have been presented in publications (listed partly in references, years 2003-2005). The developed 12 lead ECG & three channel EMFi sensor amplifier and the two-channel battery powered charge amplifier unit were accepted for medical use (see Figure 2). The latter was used to perform all the patient recordings done in the project and the former to make other studies with EMFi sensors [Ala05a, Ala05b]. The two-channel charge amplifier was used for two years in Tampere University Hospital with the same set of batteries. Relating mostly to the larger device a program was developed to record the signals directly to the popular European Data Format [Kem92]. The program displays the recorded signals during the recording so that their quality can be observed. It runs on Microsoft Windows XP and can make use of two different data acquisition cards: DAQP-16 (PCMCIA) from SuperLogics and NI-6036E (PCMCIA) from National Instruments

The final wireless chair has been tested, and it produces good quality BCG, data transmission works, and ECG recorded from the armrest is easily good enough for R-spike detection. Contrary to normal ECG devices which require a minimum of two ECG electrodes and a reference electrode, our ECG amplifier requires only the two ECG electrodes. The chair (without the armrest electrodes) was demonstrated at the ProAct program final seminar, see Figure 3.

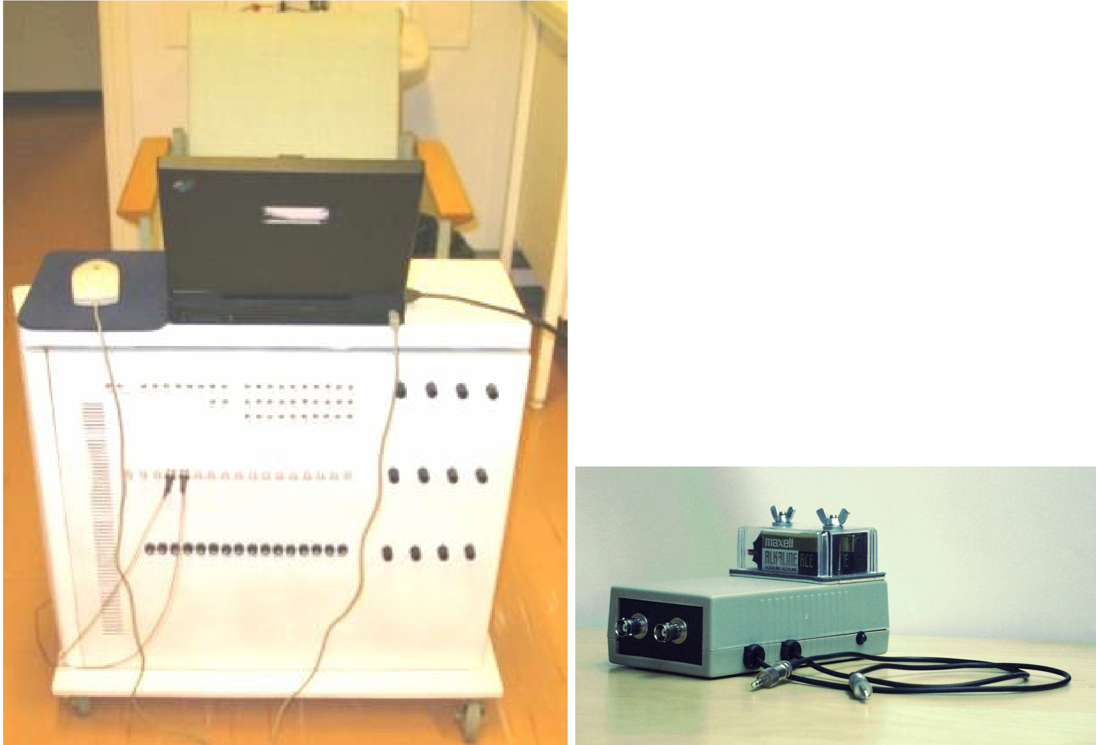

Figure 2. The 12 lead ECG & 3 channel EMFi amplifier (left) and the two-channel EMFi amplifier (right).

Signal analysis development produced good results, too. As an example of the detection of a person sitting on the chair Figure 4 shows the logarithm of the signal power during one recording (1 second window is used). From time 0 to 320 s, the patient was not sitting on the chair. The increase in the power between 320 s and 360 s indicates that patient was sitting down, and large artifacts appeared. There is also a smaller increase before the time 400 s, and it was due to the patient's movements. After the time 400 s, the patient has been sitting without any movements and the level of the power remains almost constant. The analysis methods are able to detect the presence of a person on the chair based on these observations. The calculation of the pulse of the subject sitting on the chair is also possible [Bar05].

Figure 3. The finished prototype of the ProHeMon chair. The sensors are hidden in the upholstery of the chair and the amplifiers and wireless link electronics are in a box under the seat. The strips of copper on the arm rests serve as ECG electrodes.

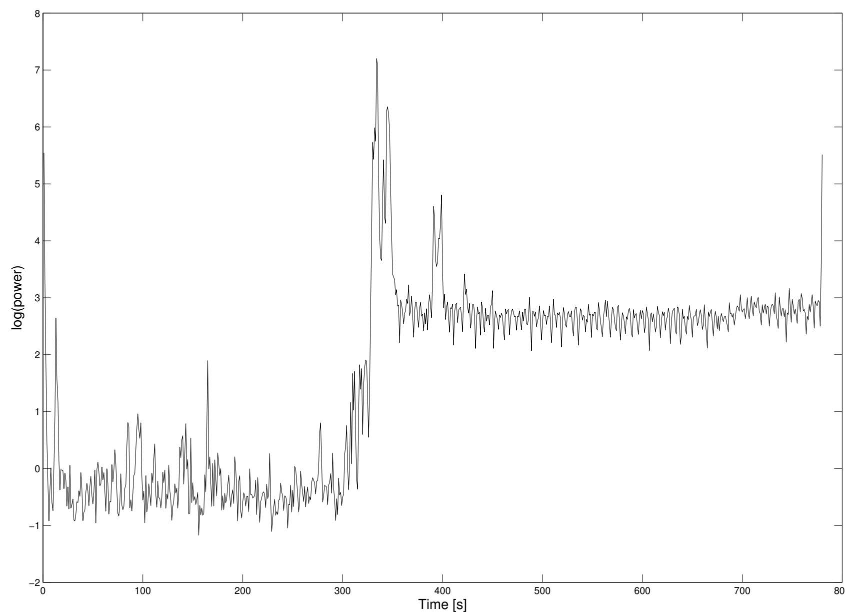

Figure 4. The logarithm of the signal power during one recording (1 second window is used). The presence of a person on the chair can be detected from these power values.

The separation of the respiratory component of the BCG signal succeeds very well as Figure 5 shows. When the respiratory component is subtracted from the original BCG signal, the heart originated BCG signal remains. Our studies suggest that when a high-pass filter is used to remove the respiratory components, the cut-off frequency of the filter should be 1.5 Hz.

Table 2 contains a sample set of time domain measures of the BCG signal. The analysis programs are able to determine these automatically. In a subject whose BCG is distorted due to decreased condition of the heart all these parameters are no longer obtainable from every BCG cycle, not even with visual analysis.

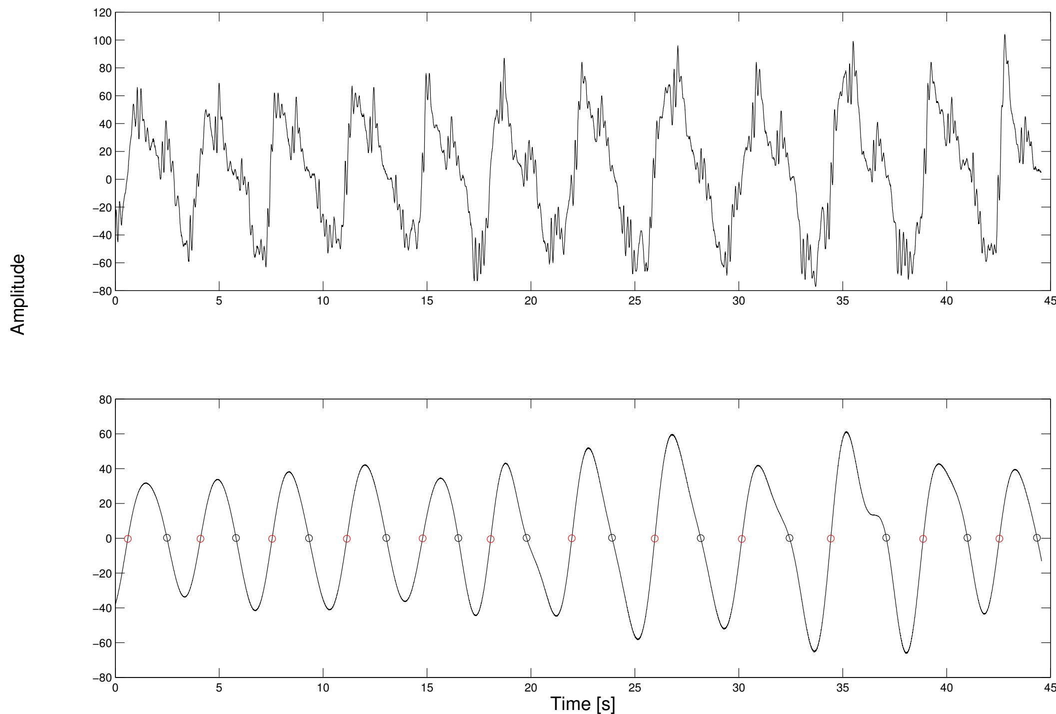

Figure 5. On top there is the original EMFi sensor signal which has a length of 45 seconds. The respiratory and the heart originated BCG signals can be seen easily. On the bottom, the respiratory signal after band pass filtering is shown. The beginnings of the respiratory cycles are marked with a circle.

Table 2. Automatically calculated time domain parameters of the BCG signals of one subject.

Patient A01	min	max	mean	std
I position	0.20 s	0.25 s	0.21 s	0.01 s
I value	-52.95	-10.27	-26.62	7.30
J position	0.32 s	0.34 s	0.33 s	0.01 s
J value	30.38	71.29	43.10	6.74
H position	0.13 s	0.17 s	0.15 s	0.01 s
H value	-5.01	22.43	7.89	5.20
I-J diff	45.96	108.60	69.72	11.91
H-I diff	14.79	63.00	34.50	8.74
I-J diff / H-I diff	1.36	4.04	2.10	0.43

The most advanced method of the time domain analysis of the signal in this project is based on the self-correlation of the BCG cycles of the subject. The Starr classification is based on the idea that the BCG of the normal heart is rather self-similar along the course of time whereas those with degraded heart condition have an irregular BCG waveform shape. Figure 5 shows the self-correlation image of a recording of a normal subject. The development of correct thresholds for the correlation class assignments is still in progress.

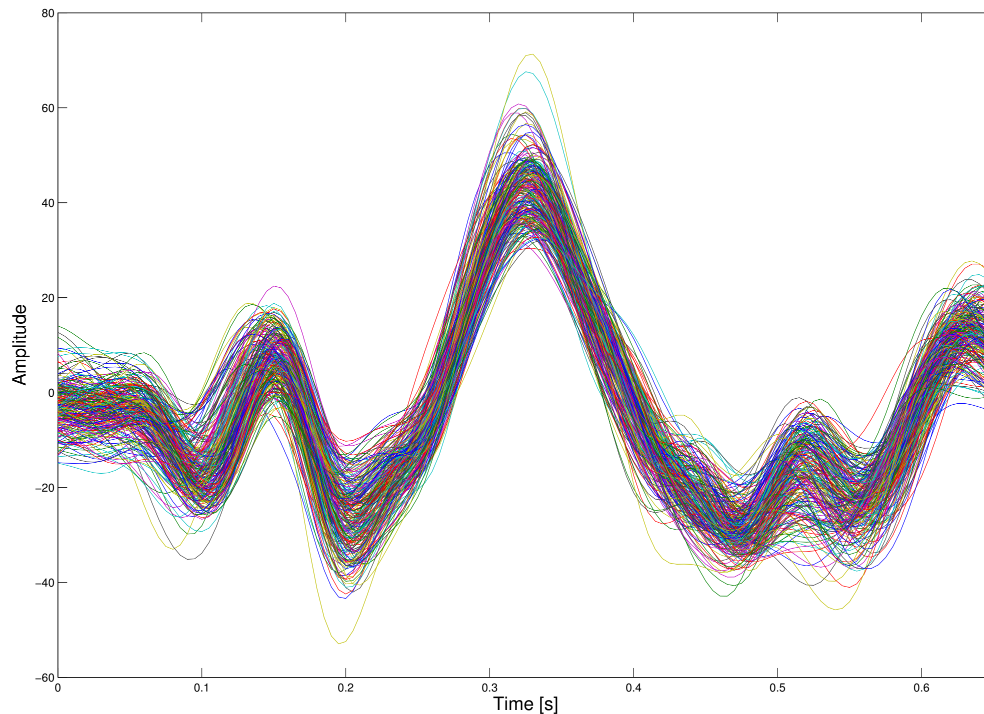

Figure 6. All the BCG segments fromone person in the group of normal young subjects. The correlation threshold value was 0.8. The BCG cycles are relatively self-similar indicating normality of the subject. The R spike of ECG was used to time align the BCG cycles. Time alignment with the I wave component of BCG (the deflection downwards before the largest deflection upwards in this waveform) is also possible but it changes the results of the correlation analysis somewhat.

In the supervised time-frequency feature based classification section of the project the evaluation of the recordings from certain representatives of the hypothetically typical categories as 'normal young', 'normal old', and 'abnormal old' indicated that our combined method was found to be reliable and of high performance, even with non-linear disturbance or latency in the BCG signals. The study showed also that the analysis of a BCG trace needs more than just a few BCG cycles in order to produce accurate results. The correct class of the BCG can be determined only by analysing the distribution of the BCG cycles in the feature space (see Figure 7).

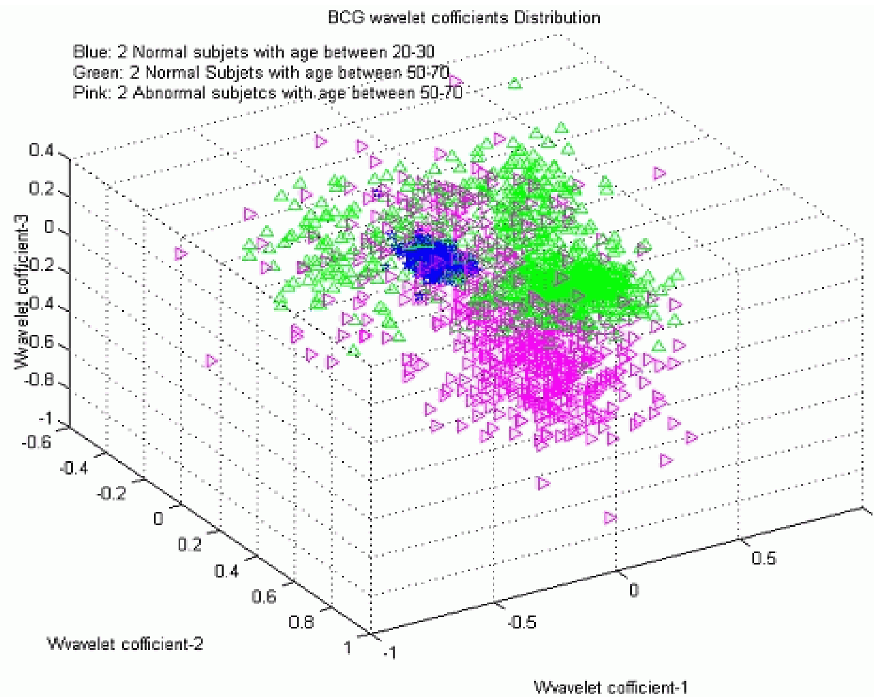

Figure 7. The distribution of BCG cycles in a three-dimensional wavelet-based feature space. The three different groups of subjects are indicated with different colours.

Evaluation

Medical subproject

The objective of the medical part of the project was collect hemodynamic data from healthy and diseased persons for evaluation of the ProHeMon chair. This task was fulfilled entirely allowing us to study the usefulness of method earlier used to describe BCG signal recorded with the ProHeMon chair. The results show that the ProHeMon chair can be used for BCG signal recording. However, the Starr classification of BCG did not turn out to correlate with cardiac pump function sufficiently which suggests that it cannot be recommended for this purpose. Based on the data collected we are currently working on other BCG based indicators which reflect the state of the heart better than the Starr classes.

A relatively large set of joint BCG, ECG and ICG recordings was produced [Koi05a, Koi05b]. This data set is a useful resource of further studies of the correlations between the three variables in the subject groups recorded. The measurement system with EMFi sensors produces sufficiently high quality BCG traces, which can be used for the medical examination of the BCG. In future, the medical use of the ProHeMon chair lies in its ease of use. The hemodynamic data collected with the chair might be used to follow circulatory disorders. For diagnostic purposes the BCG signal is perhaps not suitable.

Technical subproject

The main objective of the project was almost completely reached. It is now possible to measure BCG and ECG on the chair developed in the project, transmit the signals wirelessly to a nearby PC, obtain the heart rate of the person being measured and analyse the class of the recorded BCG to some extent with the methods developed in the project. The results of these achievements have been published in refereed conference papers and a few journal paper

manuscripts are currently in the review process. What is still missing is the integration of all the analysis and trace display components under a user-friendly interface which could be used by other people than the researchers of this project. This is, however, more conventional software engineering than theoretical scientific work.

The implemented small battery-powered charge-amplifier had very good electrical properties, and was very power efficient. The signals measured using it and the frequency response of the total system was more limited by the performance of the commercial CircMon medical data-acquisition unit, to which it was connected. The performance evaluation of the wireless chair is not yet complete, as the required software for PC end has not been available. Based on a visual analysis, the recorded signals look very good and they are similar to earlier recordings made in a clinical laboratory setting in the project. The wireless link is able to transfer the required amount of data, and does not seem to interfere with the recordings. Power consumption of the measurement electronics is low and the total power consumption is greatly determined by the power consumption of the RF transmitter, which again is quite fixed for different technologies and depends quite directly from the required bit rate in continuous data transfer applications.

The evaluation results of the supervised classification of thirty (ten normal young, ten normal old, and ten abnormal old) subjects we think that our approach is promising and justifies further investigations in which both the number of the representatives of the typical categories as well as the number and the definition of these categories can be altered.

Conclusion and open questions

A wireless BCG measurement chair was successfully implemented. The chair uses IEEE 802.15.4 standard for communication. The hardware works very well, and is quite power efficient. The user interface and signal analysis software for the PC end still needs more development, and the communication protocol between the chair and the PC can be much improved. The signal analysis methods have room for improvement and they are currently being investigated with other research funds. The recorded signal data base is a very good resource to bring this study further and it can also be used as a tool for the verification of the results in signal analysis development. The project has opened us possibilities to develop the chair concept also for home use in other projects. The machine intelligence algorithms developed in the project will find uses in other areas, too, and we plan to develop them even further.

From the medical point of view some open questions still remain. The equation which describes haemodynamic activity is

Blood pressure = Stroke volume x Heart rate x Systemic vascular resistance

If three out of the four variables above are known, the fourth can be determined. As the heart rate and blood pressure are easily obtainable, it would be interesting if the BCG measurement could help in the determination of the stroke volume. Based on the results obtained so far this question still remains open. As this problem has not been solved yet, the question to what extent the monitoring of the BCG is useful in the diagnosis and follow-up of the patients is also open. In order to study the effect of the different calculated parameters of the BCG conclusively, a more long-term follow-up study of the patients than the PROACT program allows would be necessary. We would still like to find out, what are the differences in the BCG between the different patient groups recorded. We plan also to study the relationships of the BCG and ICG signals in more detail in future.

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