Digital phonocardiographic experiments and signal processing in multidisciplinary fields of university education

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Abstract. Modern measurement of physical signals is based on the use of sensors, electronic signal conditioning, analogue-to-digital conversion and digital signal processing carried out by a dedicated software. The same signal chain is used in many devices like home appliances, automotive electronics, medical instruments and smart phones. Teaching the theoretical, experimental and signal processing background must be an essential part of improving the standards of higher education and it fits well to the increasingly multidisciplinary nature of physics and engineering too. In this paper we show how digital phonocardiography can be used in university education as a universal, highly scalable, exciting and inspiring laboratory practice and as a demonstration at various levels and complexity. We have developed open-source software templates in modern programming languages to support immediate use and to serve as a basis of further modifications using personal computers, tablets and smartphones.

1 Introduction

Modern measurements and signal processing are essential subjects of higher education in the field of physics, informatics, engineering and even in other disciplines. Since more and more sensors are becoming affordable and available, the students of the mentioned areas will probably meet these during their future work. Interfacing sensors to computers, tablets or smart phones are also possible via the analogue and digital inputs of these devices. The only widely available analogue interface of computers is the sound card, therefore, various measurement applications can be found targeting education [1-4]. Since the sound card is not designed as an instrument, proper usage and application limitations must be considered carefully.

The disciplines that were separated in the past now show a trend of conversion and forming multidisciplinary areas along the borders. It is confirmed by numerous multidisciplinary university programs, and also by the fact that most of the open-access journals' scope are multidisciplinary. Due to these trends it is reasonable to include physiological measurements and signal processing in the higher education curriculum of scientists and engineers [5,6].

A simple, low-cost and widely available electronic stethoscope that is easy to assemble and that is based on a computer sound card or smartphone makes it easy to measure and analyze the heart sounds [7,8]. Similar solutions, like Steth IO and StethoCloud using smartphones developed by students are already on the market, which clearly shows how such knowledge can be exploited by young experts [9,10]. A comprehensive review of similar products, applications and signal processing details can be found in the literature [11]. These solutions make the so-called phonocardiography experiments highly scalable: laboratory practice exercises can be based on it either for undergraduates at a basic level or at an advanced level for graduate students. They can serve as student projects during the semester or they can be used for demonstrational purposes during lecture presentations, even in high school classes. In this paper our goal was to support the application of the easy-to-assemble electronic stethoscope in various fields of university education. Note that a recent paper published in a leading journal regarding the teaching of physics in schools presents the smart phone phonocardiography principle briefly and demonstrates preparation of simple home-made stethoscopes [12].

Our aim was to make this measurement method open, as transparent as possible, and reproducible to support its educational applications. Although the presented device is simple and low-cost, it still provides phonocardiographic signals good enough to show their most important features, to detect heart beats, and to evaluate the heart rate for educational purposes. Since the overall cost of the acceptable quality components needed to the phonocardiographic device can be as low as about €20 and it can be assembled easily, it is possible that even all of the students can get one device at a laboratory practice. The recorded signal can be processed by one of our open-source software that can serve as a basis for further modifications or for new programs written by the students themselves. A measurement setup like this can be used to teach electronics, measurements of physical signals, digital signal processing and related programming in higher education. Moreover, due to the low price it can be used to gather high volume phonocardiographic data for the purposes of multidisciplinary research related to signal analysis and its optimization, software defined instrumentation, signal processing and data acquisition to support medical research. It is important to note that it can also help young students to be involved in research projects.

2 Digital phonocardiography

In this section we present a brief overview of the background and the main principles of measurement and processing. The heart rate and heart rate variability are commonly used indices in diagnostics, these values can be used as early indicators of diseases. The heart rate is measured using a number of methods either in clinical practice or at home, and it is typically expressed in beats per minute (BPM). It can also be measured by e. g. blood pressure monitors, ECG monitors, photoplethysmography, cardiotocography (CTG, based on ultrasound Doppler-effect to monitor fetuses), and phonocardiography [13,14].

Phonocardiography is based on the measurement of heart sounds. Listening to heart sounds is the earliest method to monitor the cardiac function. In medical practice the most common way to listen to these sounds is supported by stethoscopes.

Heart sounds have a complex structure due to different processes. In every cardiac cycle a first heart sound (S_1) can be heard at the beginning of the “systole” (when the heart contracts), caused by the closure of atrioventricular valves. A second heart sound (S_2) appears at the beginning of the “diastole” (when the heart is refilled with blood after contraction), caused by the closure of the semilunar valves and some additional components can be heard as well [15]. The beat-to-beat heart rate is measurable using these sounds, furthermore, murmurs and other changes of this specific structure can be used to diagnose a number of diseases too.

Heart sounds can be recorded using a digital stethoscope. These recordings are called phonocardiograms (see Figure 1). Phonocardiography is a diagnostic technique on the detection and characterization of the heart sound and its components. However, the beat-to-beat heart rate can be measured by this method very accurately. It is a non-invasive, passive method, and do not have any harmful effect, so it is securely applicable, which is beneficial e. g. in case of monitoring even fetal cardiac function.

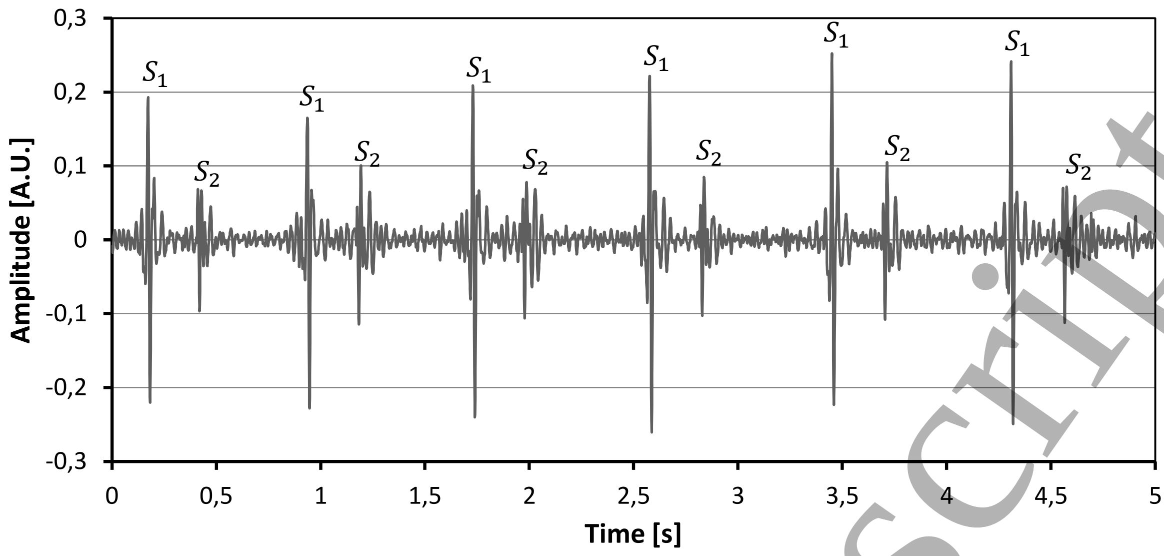

Figure 1: A typical phonocardiogram measured by our system described in Section 3. The first heart sounds are marked by $\boldsymbol{S_1}$, while the second heart sounds are labelled with $\boldsymbol{S_2}$.

Due to the simple, safe, and easily reproducible hardware of the measurement, which is described below, phonocardiographic experiments are able to support education.

3 Experimental set-up

While digital stethoscopes are commercially available, they are designed for clinical use, so their price can be rather high. Furthermore, their supplementary software cannot be modified in accordance with the needs of education and development, since it is required to implement own algorithms and signal processing [16]. In order to overcome these limitations a simple and low-cost, still accurate digital stethoscope can be assembled to support educational phonocardiographic experiments [7,17]. The device consists of a stethoscope chestpiece and a small-size microphone, which is connected to a computer sound card (see Figure 2). Note here that stethoscope acoustics are discussed briefly in [12].

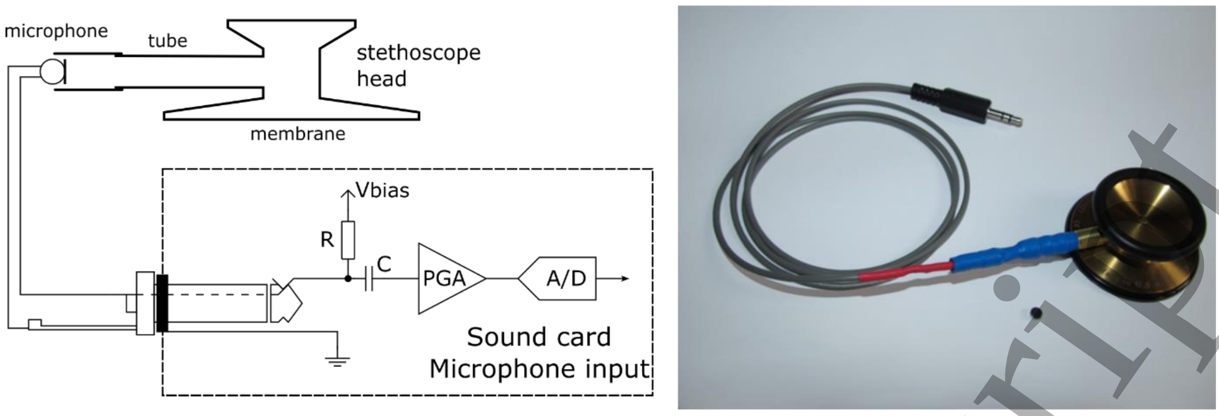

Figure 2: The schematic of a simple phonocardiographic set-up (left) and a photo of the assembled stethoscope (right), which can be used to carry out phonocardiographic measurements. A separate, small-size microphone can also be seen on the photo below the stethoscope to illustrate the type of the microphone built into the device and fastened by heat shrink tube.

A microphone with a size of about 4-6 mm, is small enough to place into the stem of the stethoscope chestpiece or to mount it outside the stem as shown in Figure 2 using e. g. heat shrink tube. The microphone can be directly connected to the microphone input of the sound card with a 3.5 mm jack plug. Since the sound card provides the required bias voltage for the microphone, the AC coupling via a capacitor, a programmable gain amplifier (PGA), and an analogue-to-digital converter; no further analogue signal conditioning is required. It is important to note that although a cheaper stethoscope chestpiece might satisfy the purpose of these measurements, the usage of a higher quality one results in cleaner phonocardiographic records. Furthermore, placing the stethoscope on different points of the chest wall also affects the amplitude and the shape of the recorded signal [15].

Typical sound cards are able to record signals in the frequency range of 20 Hz to 20 kHz. Although the heart sounds contain frequency components below 20 Hz, a significant portion of the power is located between 20 and 50 Hz [18,19], thus the high-pass filtering character of the sound card does not affect the accuracy of detecting heart beats. Both internal and external computer sound cards are suitable for these measurements, but their different transfer characteristics may slightly affect the shape of the recorded signals. Note that fairly accurate detection of the heart beat time instants is still unaffected.

4 Measurement software

In order to measure phonocardiographic signals, the audio signal digitized by the sound card can be exported typically into a wav file. This can be performed by several free sound recording software (like Audacity), and a special software can also be written for such purpose rather easily in high-level programing languages, such as LabVIEW, MATLAB, or Java. Students can learn simply how to handle the sound card, audio signals and audio file formats programatically by writing such software in the mentioned programming environments.

We have implemented the signal recording and all further analysis reported in Section 5 in LabVIEW programming environment. Students can use this software without modification or they can use the parts of the package to develop their own program.

We have developed a Java and an Android software too (for a photo and a screenshot see Figure 3 and Figure 4). Their usage is simple and the applications contain the basic functions described in Section 5. These software applications are mainly devoted to visualize the phonocardiographic signal, to perform some basic analysis or just to demonstrate the experiment. Both programs are able to detect the heart beats in the phonocardiogram and both can calculate the heart rate indicators defined in Section 5.2. The applications are fully open-source and can be downloaded for free [20-22].

Our Java software is able to record the heart sound and perform the above-mentioned analysis in real-time (a sample screenshot is shown in Figure 3). It can save the recorded signal into a wav file, moreover, it can load and analyse a previously recorded heart sound signal.

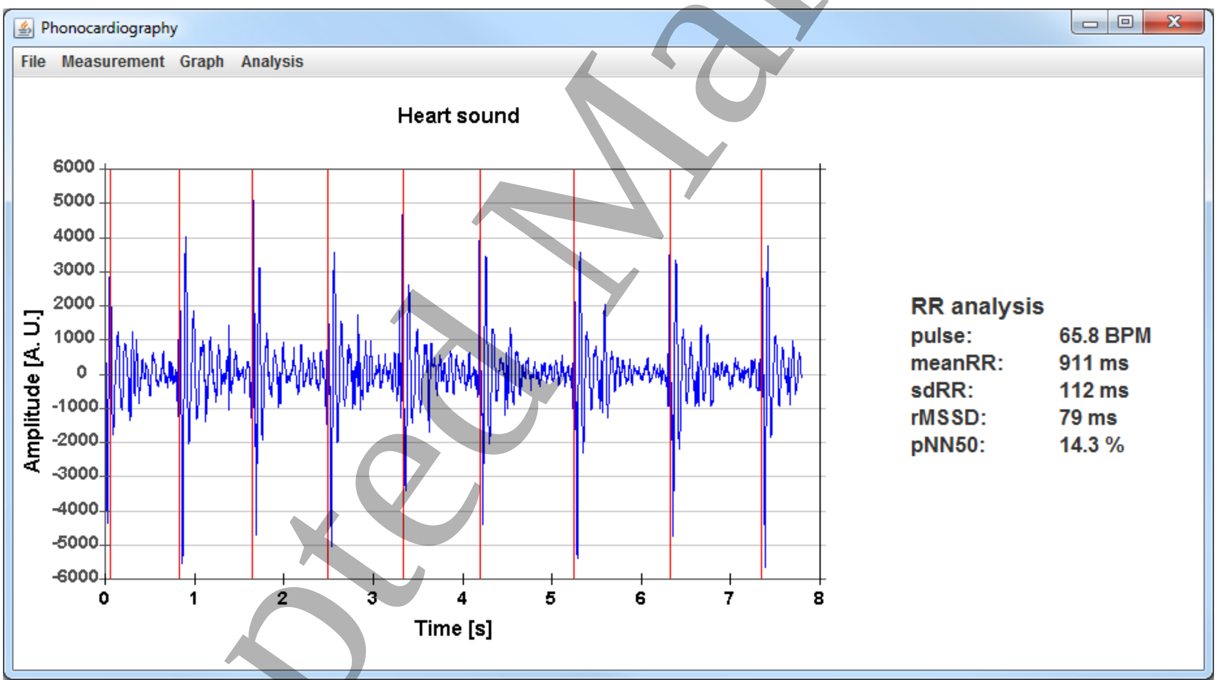

Figure 3: The Java software with a phonocardiographic record. The detected heart beats are signed with vertical red lines. On the right side the calculated indices of heart rate are displayed (see 5.2 for details).

The Android application developed by us cannot be used to record heart sound and perform real-time analysis, but it is able to perform the visualization and the offline analysis of a previously recorded heart sound (see Figure 4). For this purpose the heart sound can be recorded by the Android device using any sound recording software. The only restriction is that the recording must be saved as a wav file.

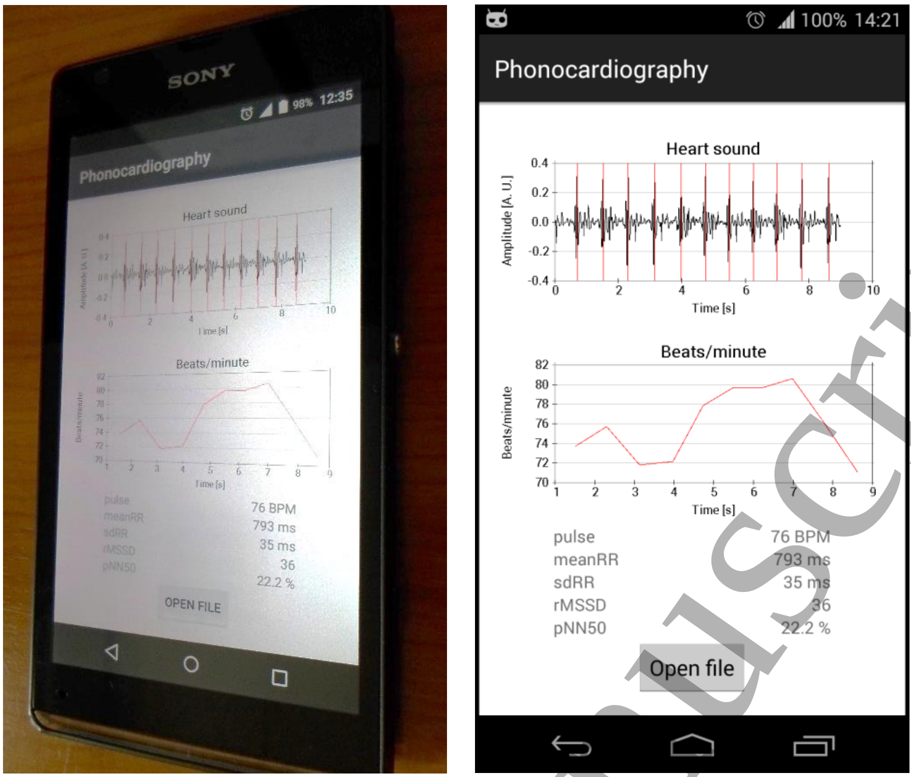

Figure 4: A photo with a smartphone running the Android application and a screenshot of the Android application with a phonocardiogram loaded from a file. The heart sound and the detected heart beats (marked with vertical red lines) can be seen on the upper plot, while the instantaneous heart rate plot can be seen below. At the bottom the calculated indicators of heart rate are displayed (see 5.2 for details).

5 Analysis of the heart sounds

Heart sound measurements can be widely used in higher education, because they can cover a wide range of complexities and applications. They can support demonstrations (e. g. using the mentioned Java software), simple programming, complex signal processing exercises and related analysis. Furthermore, the students are likely to find the measurement and processing of their own heart sound very interesting and spectacular.

In the following the measurement and processing of phonocardiographic signals in LabVIEW environment is presented, which could be a topic of university laboratory practices. The LabVIEW environment is very useful in such tasks, since the data acquisition, signal processing and visualization can be implemented in a very short time even for beginners. This allows the students to focus on the more important part of processing. Note that the presented methods can be implemented in many other high-level programming languages too.

5.1 Recording the phonocardiographic signal

The phonocardiographic signal can be loaded from the previously recorded sound file or it can be streamed directly from the sound card. This allows the students to learn how to process sound files or how to use the sound card programatically. The benefit of the latter is that it also makes possible to perform further analysis in real-time. A raw phonocardiogram and an example for the solution in LabVIEW can be seen in Figure 5.

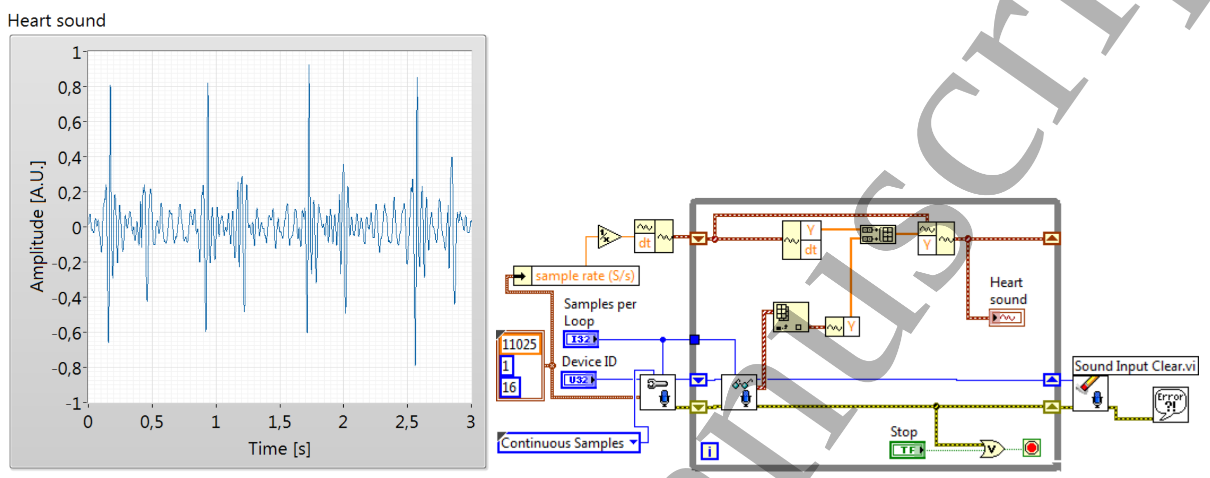

Figure 5: A raw phonocardiographic record (left) and a LabVIEW block diagram, which reads the data from the sound card and displays the phonocardiographic signal (right).

If an audio signal has been sampled at a high rate, like 44.1 kHz, the high amount of data can slow down the signal analysis and visualization. Since the high frequency components are meaningless in these measurements, the sound card can be set to a lower sample rate. The sound card can be used with 11.025 kHz sampling frequency, that is more than adequate to provide the good enough performace for the signal processing software.

Since no analogue signal conditioning is used, the measured signals can contain different kinds of noise, e. g. the 50 Hz electrical noise, or the lung sound. However, their level is typically low enough compared to the amplitude of the heart sound signal, thus, no digital filtering is necessary.

5.2 Heart beat detection

Beat-to-beat heart rate information can be gained from the phonocardiograms by the detection of specific patterns, e. g. the first heart sounds. Many advanced techniques can be found in the literature to detect heart beats more accurately, e. g. methods based on neural networks or wavelet transform [23-26]. Most of these methods are pretty complex, therefore, they are less suitable for education in most of the cases.

Since the sound card suppresses the low frequency components, the recorded phonocardiogram has a stable DC level, unlike in the case of ECG or photoplethysmographic signals, where DC level may shift slowly over the measurement [5,27]. Thus, for educational use, simple amplitude and time threshold based methods are applicable for reliable detection of heart beats, even in real-time. Due to the simplicity of these methods students can easily implement such algorithms in a short time, e. g. during laboratory practices. Two recommended algorithms are presented below, one uses only the built in functions of LabVIEW (so-called virtual instruments, VIs), while the other uses a more specific technique to enhance reliability.

Probably the easiest method is the application of the built in Peak Detector function of LabVIEW, which is based on the quadratic least squares fitting. This function makes it possible to detect the peaks in real time too, since it can collect the signal inside a loop, block by block. The Peak Detector finds the peaks in a signal using a threshold and a width parameter. The width specifies the number of consecutive data points in the mentioned fitting, and the threshold is used to ignore peaks with too small amplitude. This method can be adapted to the current signal by setting the threshold to the global maximum of the signal multiplied by a constant. The best value of this constant is found to be in the range from 0.55 to 0.65, while the width should be around 20 samples assuming the use of the mentioned sample rate. This method is less reliable due its simplicity, however, it works properly on clean enough signals. The offline peak detection capability of this VI is illustrated in Figure 6.

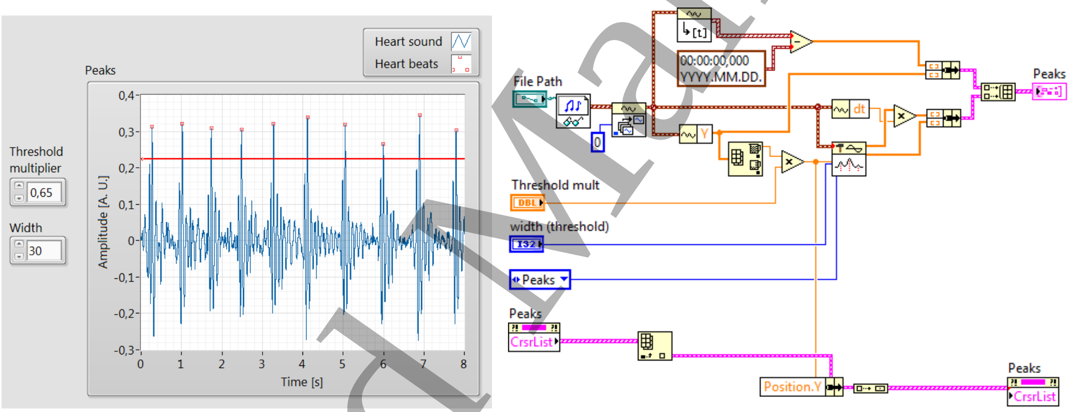

Figure 6: The offline heart beat detector VI uses the LabVIEW built-in Peak Detect function.

We have also implemented a more special algorithm for heart beat detection, which is based on level crossing detection and worked more accurately in this case. For this level crossing algorithm an adaptive threshold was used, the value of which was chosen as the half of the global maximum of the signal. After each detected level crossing, a maximum searching algorithm was used to find the highest peak in the heart sound pattern within a given time interval (100 ms). The position in time of the found peak was stored as a heart beat time instant. In order to avoid false detections (including the detection of the second heart sound), each level crossing were ignored within a certain time interval (400 ms) following a detected heart beat. This algorithm is illustrated in Figure 7, and its result is shown in Figure 8. Designing a simple threshold-based detecting algorithm and setting the best parameters experimentally can be an exciting exercise in the laboratory practice.

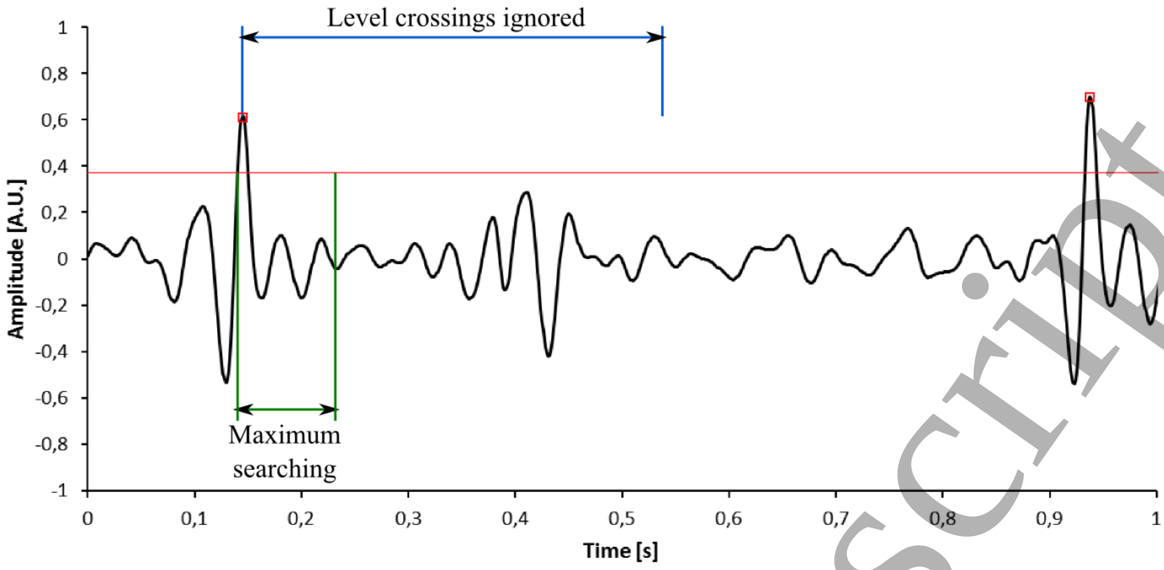

Figure 7: Heart beat detection method based on level crossing.

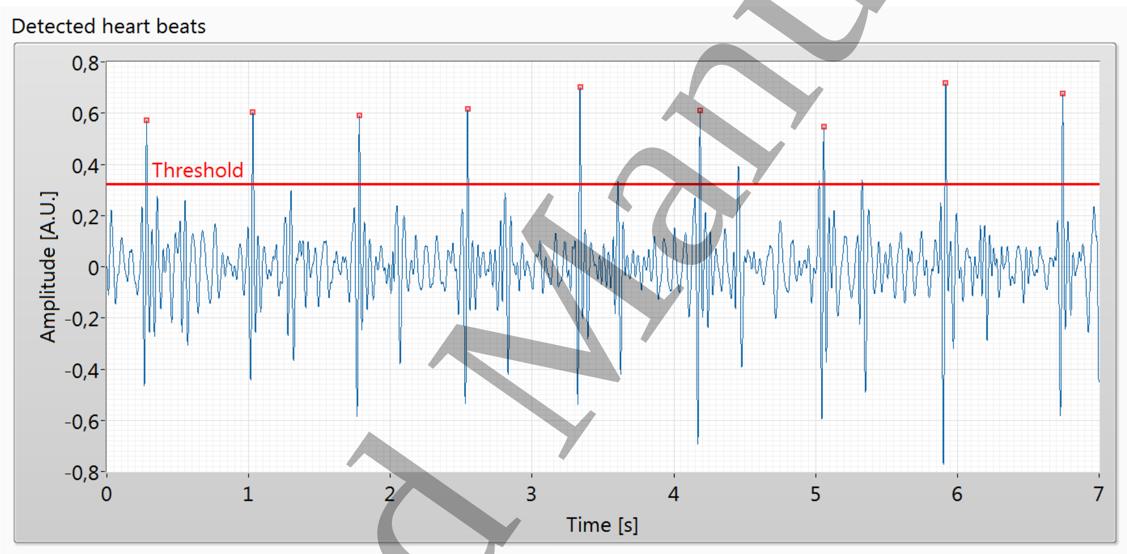

Figure 8: A phonocardiographic record with detected heart beats marked by rectangles.

Additionally, more advanced detecting algorithms like spectral or auto/cross correlation based ones can serve as bases for undergraduate projects. Related fundamental methods are commonly taught in the topic of measurement, data acquisition, or signal processing.

5.3 Further analysis of the processed data

Students can calculate the time differences between heart beats, so they can get the so-called RR-intervals after they have performed the heart beat detection of a phonocardiographic signals. RR-intervals, or the reciprocal of it, the beat-to-beat heart rate can also be plotted on a graph (see Figure 9). In addition, if the heart beats are detected in real-time, then a numeric heart rate display can be added, which shows the mean of the last 3-5 heart rate values, just like in the case of clinical ECG-devices.

Using RR-intervals (note, that false heart beat detections should be excluded) heart rate variability (HRV) indicators can also be calculated (see Figure 9). These indicators are commonly used in clinical diagnostics, since they can be used as indicators of diseases. Studies have shown that the mortality of post myocardial infarction patients is correlated with their HRV indices [28,29]. Surprisingly enough healthy heart can exhibit quite high RR interval fluctuations, even above 100ms. The mechanism behind this is rather complex, but a simplified explanation can be given as follows. The cardiac regulatory system must respond to external and internal impacts that can occur unpredictably. Consequently, the heart rate is modulated by these events resulting in a considerable, somewhat random fluctuations in the signal. Further exercises are possible on the calculation of these indicators, like the mean and the standard deviation of the RR-intervals (Mean RR, sdRR). Additional indicators include the proportion of successive normal-to-normal intervals which differ by more than 50 ms (pNN50), and the root mean square successive difference of the RR intervals (rMSSD). The formula of rMSSD is shown below (RR_i is the *i*-th RR interval and n is the number of RR intervals) [30-32]:

$$rMSSD = \sqrt{\frac{1}{n}\sum_{i=1}^{n-1}(RR_i - RR_{i-1})^2} \tag{1}$$

Beyond the presented time-domain analysis, examining the spectrum of this periodic signal can be instructive for students, and it can be easily calculated in the LabVIEW environment by built-in functions. Furthermore, spectral analysis of the heart sounds are widely used in diagnostics too, which can also be implemented in undergraduate projects as well [33].

Note that many kinds of students can use these methods in different ways. Students of physics can measure the related physical quantities by a modern method; they can make and/or use software defined instruments; they can learn about the use of modern virtual instrumentation techniques and about the statistical and spectral evaluation of measured data. In engineering the students can learn about the hardware and software requirements and they can practice the implementation of algorithms to process signals and data. They can also use or even implement digital spectral analysis and peak detection algorithms. Medical students can learn about measurements of heart sounds, can assess their own heart rate during a laboratory practice, can measure and understand heart rate indicators. They learn about paced breathing and Valsalva maneuver techniques and see the signals in real time during such experiments. For all disciplines it is very important to see the multidisciplinary character and the importance of modern measurements and information processing.

6 Experiments

The calculated indicators (e. g. the heart rate) can be forced to change in a controlled manner. This way students can experience how the physical actions performed by themselves affects the actual measured values, which they can find exciting and which can provide them the joy of discovery. The signals and figures shown below are recorded in normal conditions, so the students should be able to reproduce the results in the classroom.

In the following experiments different patterns of breathing were applied, which can function as the easiest ways to affect the calculated values due to the so called respiratory sinus arrhythmia [34]. The rhythm of breathing affects the heart rate, which is clearly demonstrated by these experiments. In this way the students will learn about an exciting control mechanism governed by the human nervous system in a real-time fashion.

6.1 Spontaneous breathing

In clinical practice heart rate variability is often measured during spontaneous breathing. For example, the so-called Holter monitors are widely used to record long term heart rate behavior in order to examine the association between heart rate variability and sudden cardiac death [28,35]. At the first time, when students successfully calculate the heart rate and visualize it on a graph, they will see a heart rate pattern similar to the one shown in Figure 9, since they will probably breathe spontaneously. It can be seen on the plot that the heart rate is even fluctuating at rest. This fluctuation is caused by many physiological effects, including breathing.

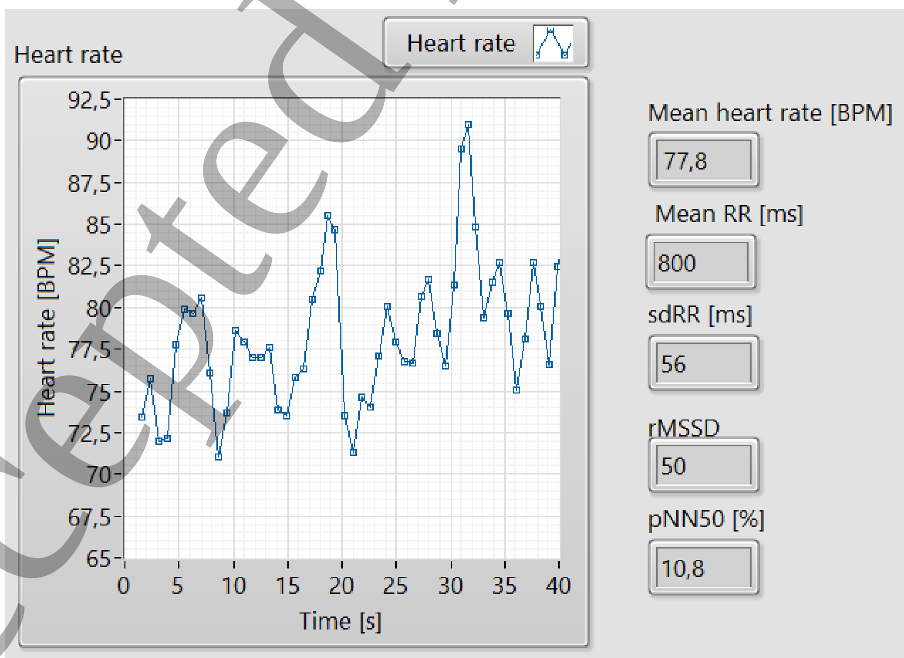

Figure 9: Heart rate plot and the calculated heart rate variability indices during spontaneous breathing. Healthy heart can exhibit rather high heart rate fluctuations.

Students can find some periodicity in the resulting heart rate signals, which is synchronous to their breathing. In order to study this periodicity, the spectrum of the heart rate should be calculated. Since the heart rate signal is unevenly spaced in time, its spectrum cannot be calculated by a simple Fast Fourier Transform (FFT). LabVIEW has a built-in function for this purpose called “Unevenly Sampled Signal Spectrum” which is based on a method of least squares fitting of sinusoids, on the so called Lomb periodogram [36]. In clinical practice the heart rate spectrum is often calculated by averaging the spectra of several 120 seconds long measurements in order to reduce short term variations [31,32]. Figure 10 shows such a spectrum, which is the average of the spectra obtained using 5 successive 120 seconds long measurements. A peak can be found around the breathing frequency, which shows that the heart rate fluctuates fairly periodically due to breathing. In the spectrum shown in Figure 10 the peak belonging to breathing can be found at about 0.32 Hz (19.2/min), which is a common respiratory frequency. Note that since spontaneous breathing is not perfectly periodic, the peak has a considerable width.

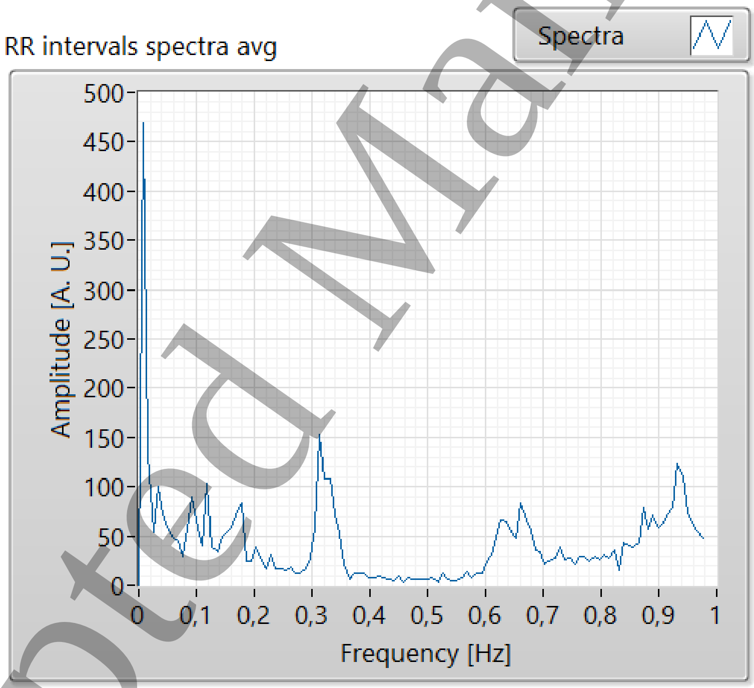

Figure 10: Average of spectra of 5 successive 120 seconds long series of RR intervals during spontaneous breathing. The peak belongs to breathing is at about 0.32 Hz (19.2/min).

6.2 Paced breathing

In order to measure the heart rate during paced breathing a timer is needed to ensure the required rhythm of inhalation and expiration. For that purpose a simple clock can be used, but the students can also modify their program to pace their breathing (e. g. by blinking an indicator on the screen periodically). Furthermore, it lets them generate and plot an approximate respiratory signal on the heart rate graph as shown in Figure 11. This figure shows also that during paced breathing the heart rate fluctuation is closely periodic and synchronous to the respiration. When the students see the results of this experiment it will be credible for them that the measurements reflect their physical actions.

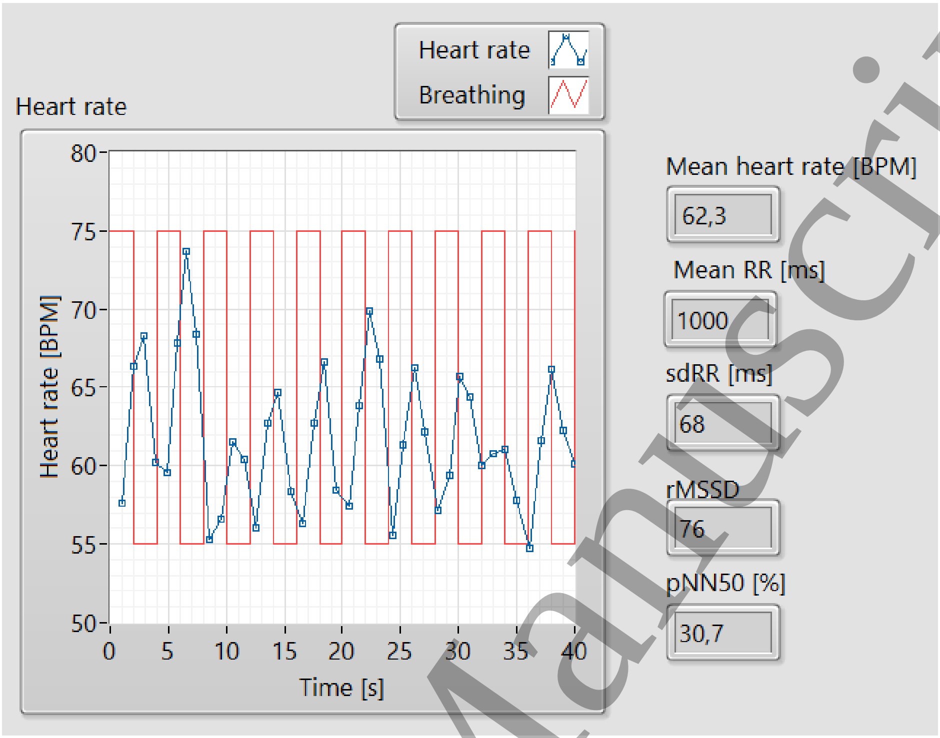

Figure 11: Heart rate plot and the calculated heart rate variability indices during paced breathing (breathing frequency: 15/min). The exhalations and inhalations are illustrated by the red rectangular signal, where inhalations and exhalations are represented by higher and lower values, respectively.

In the spectrum of the heart rate (calculated by the same way as presented above) a much higher and cleaner peak can be seen (see Figure 12), than that of the one found in the spontaneous breathing experiment. This is due to the significantly more periodic character of the breathing. In this way the effect of breathing can be very clearly visualized. Note that although the magnitude of the peak is much higher, the width of it is much smaller, therefore the magnitude of the heart rate modulation by the breathing is similar to the one observed during spontaneous breathing. Furthermore, in the figure below this peak is at 0.25 Hz (15/min), which was precisely the rhythm of paced breathing in our experiment. This method can also be useful to teach the students the usage of time and frequency domain analysis.

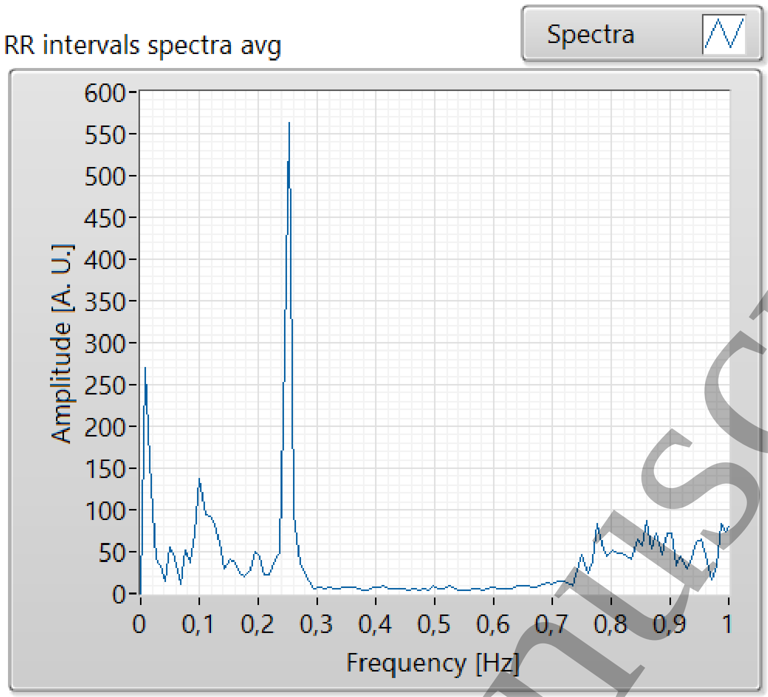

Figure 12: Average of the spectra of 5 successive 120 seconds long series of RR intervals measured during paced breathing (breathing frequency: 15/min =0.25 Hz).

6.3 The Valsalva maneuver

The physiological control of heart rate can also be examined by doing the so-called Valsalva maneuver that can be another exciting experiment during the studies. The Valsalva maneuver is basically a forced exhalation attempt lasts for a given amount of time, when the airway remains closed. In this case the pressure in the chest is elevated, therefore the veins returning to the heart get under a higher pressure. Consequently, the returning blood flow (the preload of the heart) drops, the heart ejects less blood therefore the blood pressure decreases. In order to maintain the proper perfusion of tissues the heart rate is raised under the control of the nervous system. When the subject opens the airway and returns to normal breathing, the blood pressure suddenly gets high due to the elevated heart rate and increased preload of the heart. As a reaction the heart rate falls quickly even below the mean value observed before the experiment. The Valsalva maneuver is one of the simplest methods to generate a significant change in the heart rate [37]. It is used in clinical practice to diagnose a number of cardiac malfunctions, e. g. aortic and mitral valve diseases [38].

In order to perform this experiment, the timing can also be done by using a clock, or students can modify their program to conduct timing too. In the latter case the timing of the maneuver can also be plotted on the heart rate graph as shown in Figure 13. As it can be seen, the heart rate starts rising almost immediately at the beginning of the experiment and starts falling quickly after the end of the pressing.

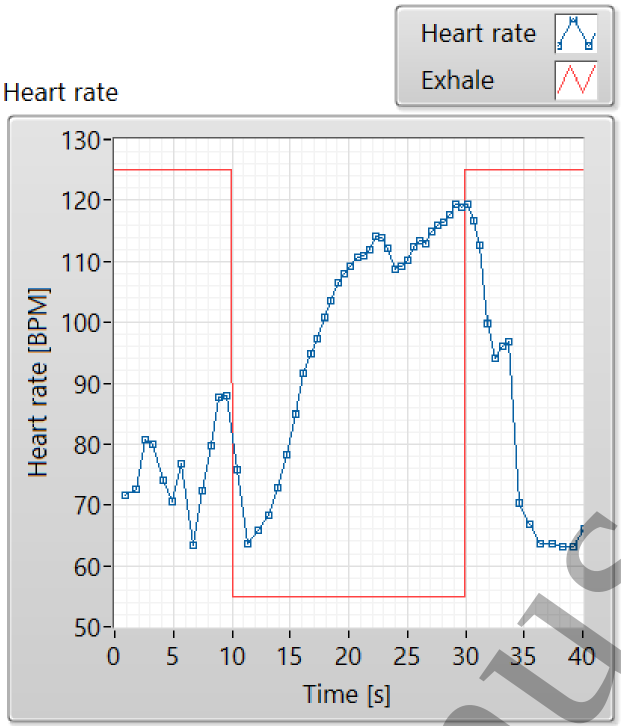

Figure 13: Heart rate graph and the calculated heart rate variability indices during Valsalva maneuver. The pressing is visualized by the red curve and corresponds to the lower value. The small dip around 24 s is due to the temporary reduction of the pressure applied by the subject.

7 Conclusions

In this paper we have shown phonocardiographic experiments, related signal processing and applications using an easy-to-assemble digital stethoscope that can be widely applicable in higher education. Our aim was to make this technology and measurement method as transparent as possible, to provide the possibility of gaining a comprehensive knowledge on the methods and to make it available for anybody. An instrument like this can be assembled using components that costs even less than about €20, which is a good alternative for the commercially available products like Steth IO and StethoCloud developed by young entrepreneurs [9,10] and many other solutions [11]. We have developed software application frameworks in LabVIEW, Java and Android platforms for phonocardiographic measurements, which are fully open-source and can be downloaded for free to support immediate experimentation and usage by students and lecturers. These tools also demonstrate how phonocardiograms can be processed to gain medical information and what kind of experiments can make lessons on heart rate and signal processing more spectacular .

These measurements can be used in the education in a highly scalable way. The method can be used for demonstrational purposes during lectures using one of our open-source software, which can also be modified according to the current purpose. Moreover, a number of related exercises of different difficulties can be given to the students on laboratory practices shown in Sections 5 and 6. Finally even student projects and theses can be based on the presented heart sound measurement methods and related tools.

By performing the experiments shown in this paper, students and lecturers can both gain knowledge of physics, informatics, engineering and medicine. They can learn about sampled measurements, digitizing, physiological signals and control mechanisms, spectral analysis, calculation of medical indicators and development of applications in various programming environments. Additionally, students usually find learning by experimenting and solving practical problems more exciting and inspiring. Such heart sound measurements in the curriculum of teachers, physicists, engineers and computer scientists help them to improve multidisciplinary knowledge and broadens their education, which is especially important today due to the dynamic changes in modern technology.

8 Acknowledgments

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