EPJ Web of Conferences **213**, 02099 (2019) https://doi.org/10.1051/epjconf/201921302099
EFM 2018

Blood flow in the brachial artery compressed by a cuff

Barbara Wilk*, *Robert* Hanus

Rzeszów University of Technology, Faculty of Electrical and Computer Engineering, Rzeszów, Poland

Abstract. Most non-invasive blood pressure measurements are based on the blood flow during the arm cuff deflation. In this paper, the measurement system for an investigation of a blood flow in the partially occluded brachial artery is presented. It allows us to record simultaneously the cuff pressure, Korotkoff sounds and the blood flow during the arm cuff deflation. The algorithms developed for digital processing of the recorded signals are described in detail. The results of analysis obtained for healthy subjects are presented and discussed.

1 Introduction

Human blood is an example of a non ideal fluid. The concentration of erythrocytes has a strong influence on blood viscosity. The walls of the arteries differ in stiffness, e.i., the lager arteries are more elastic.

The main purpose of the human arterial system is to provide oxygenated blood to the tissues by converting the pulsatile arterial blood flow into a continuous capillary flow. Generally, the blood flow in a vessel is determined by the pressure difference between the two ends of the vessel and the vascular resistance.

Arterial pressure is defined as a force applied to artery walls. The pressure wave in the aorta and the large arteries (as shown in Fig.1) is generated by the pumping action of the heart left ventricle ejecting blood in each systole.

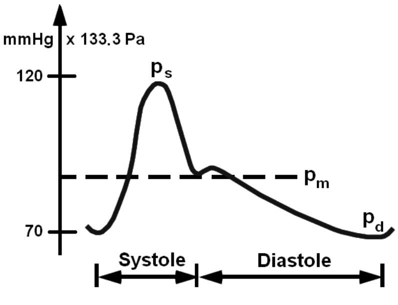


Fig. 1. A typical blood pressure waveform in the brachial artery.

The peak of a blood pressure waveform is determined by the stroke volume, the velocity of ejection, the distensibility of the proximal arterial system, and also the timing and amplitude of the reflected pressure wave. In clinical practice, this pressure peak is called systolic arterial blood pressure (p_s in Fig. 1). The walls of the large arteries are less elastic with age. A stiff arterial system results in faster transmission and reflection of the pressure wave. In this condition, the value of systolic arterial blood pressure is higher.

The minimum of a blood pressure waveform reached during ventricular relaxation is called diastolic arterial blood pressure (p_d in Fig.1). This value varies depending on the state of the peripheral resistance. The mean pressure (p_m in Fig.1) is calculated by integrating a pressure waveform over a period of a cardiac cycle. The pulse pressure, defined as the difference between the systolic and the diastolic pressure, reflects the stroke volume and the state of the peripheral resistance.

It is also worth remembering that the pressure wave varies as it moves through the arterial tree. The changes in its shape are mainly caused by a reflection of the pressure wave and the tapering down of the arteries towards the periphery. It is well known that the systolic pressure increases in more distal arteries, whereas the diastolic pressure decreases. Systolic and diastolic pressure values are varying in each cardiac cycle under the influence of many factors. such as respiratory, body position, exercise, pain, temperature, emotions, meals, and drugs.

Most non-invasive blood pressure measurements are based on the auscultatory or the oscillometric method [1, 2, 3]. Both techniques use an inflatable cuff and measure signals during a cuff pressure deflation.

The aim of this study is to get more information about blood flow in the brachial artery compressed by a standard arm cuff, especially about Korotkoff sounds. The exact mechanism of origin of Korotkoff sounds is not completely established [1]. In this paper, the measurement system for recording and off-line analysis of the signals representing the blood flow in the brachial artery compressed by the cuff is described.

2 Measurement system

Fig. 2 presents the PC computer based measurement system designed for data acquisition during the cuff deflation.

The pressure in a standard occlusive arm cuff was recorded using a piezoresistive silicon pressure sensor.

---

* Corresponding author: bmwilk@prz.edu.pl

Korotkoff sounds were detected by means a stethoscope with a build-in microphone. Ultrasound Doppler flow meter (5 MHz) was applied to record the blood flow in the brachial artery below the arm cuff.

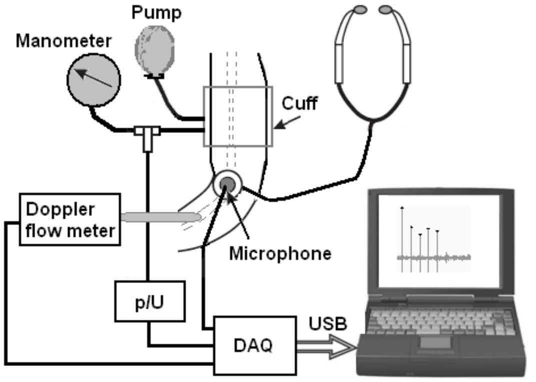


Fig. 2. The measurement system for data acquisition.

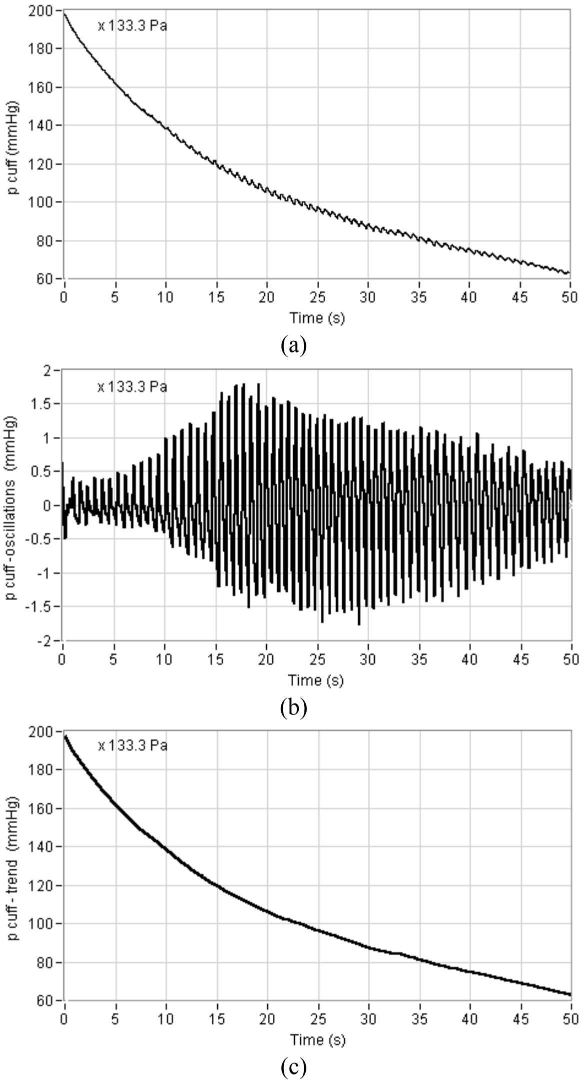
All the analog signals were digitized by the DAQ module with an ADC (16-bit accuracy) and transferred to the computer file for storage. The cuff pressure and Korotkoff sounds recorded simultaneously during the cuff deflation were sampled at 1 kHz. The sampling frequency was chosen at this high level to guarantee a good reconstruction of each Korotkoff sound. The acoustic output signal from the ultrasound Doppler flow meter was acquired at a higher sampling frequency (11 kHz) using a microphone. The stethoscope was placed over the brachial artery and a manometer was applied to determine both systolic and diastolic pressure by the auscultation of the first and the last Korotkoff sounds during the cuff deflation.

All the experiments were carried out with a group of 26 healthy volunteers (14 males and 12 females), age 22 to 55. The subjects were seated in a chair in a comfortable position with both arms supported on the desk at heart level. Measurements were taken for 60 seconds. A standard cuff wrapped around the left arm was inflated to a pressure above what is expected to be the systolic pressure. The cuff deflation was continuous and similar to that which occurs in the manual Riva-Rocci procedure.

3 Data processing

Fig. 3a illustrates an example of the pressure recorded in the arm cuff during the deflation.

This signal consists of two main components, namely the non-linear trend dependent on the deflation process, and the pulsatile oscillations (often called the oscillometric oscillations or pulses). The mentioned components were extracted from the recorded pressure signal using the Discrete Wavelet Transform (DWT), i.e., the original pressure signal was decomposed by the orthonormal wavelet (db10) according to the Mallat algorithm. As was reported in [4], the DWT gives a useful tool to select and de-noise the pressure oscillations (Fig. 3b) as well as it provides a very good approximation of the pressure trend (Fig. 3c). The pressure trend allows us to obtain the exact values of pressure during the cuff deflation.



(a)

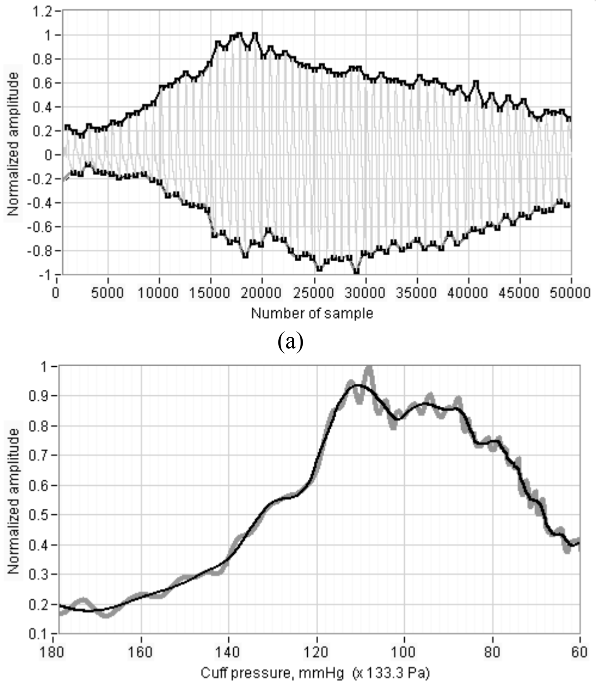
(b)

(c)

Fig. 3. The cuff pressure recorded during the deflation (a) and its components extracted by the DWT, i.e., the oscillometric oscillations (b) and the nonlinear trend (c).

Next, all local extremes of the oscillometric oscillations were detected by the peak detector to measure the peak-to-peak amplitude of each oscillometric pulse (Fig. 4a). The peak detector uses a quadratic fit to find the location and amplitude of peaks and valleys. In order to eliminate false extremes, all found local maxima and minima were verified by the algorithm based on the so-called refractory period. Next, the envelope of the pressure oscillations (so-called the oscillometric curve) was determined by adding an upper and a lower envelope estimate. An upper envelope was created by a cubic spline interpolation of the local maxima. However, a lower envelope is created by interpolation of the local minima. Figure 4b illustrates the oscillometric curve before and after smoothing by means of the moving average filter. This curve is usually normalized according to its maximum. It is generally accepted that the mentioned maximum corresponds to the mean arterial blood pressure [5].

To sum up, the amplitude of pressure pulse in the occlusive arm cuff varies when a cuff pressure is progressively reduced from above systolic to below diastolic values. This oscillation pattern is characterised by an increase in cuff perturbations up to a maximum level and then by a slower decrease. The shape of the oscillometric curve reflects the arterial compliance-pressure curve of the brachial artery.



(a)

(b)

Fig. 4. The upper and lower envelopes of the extracted oscillometric oscillations created by a cubic spline interpolation (a), and the smoothed envelope with respect to cuff pressure (b).

The signal representing Korotkoff sounds is usually noisy as is shown in Fig. 5. To eliminate noise the soft thresholding method based on wavelet analysis was applied.

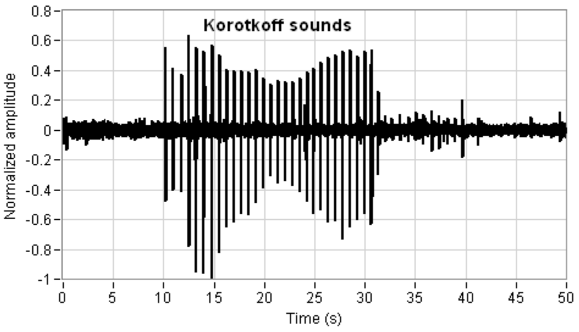
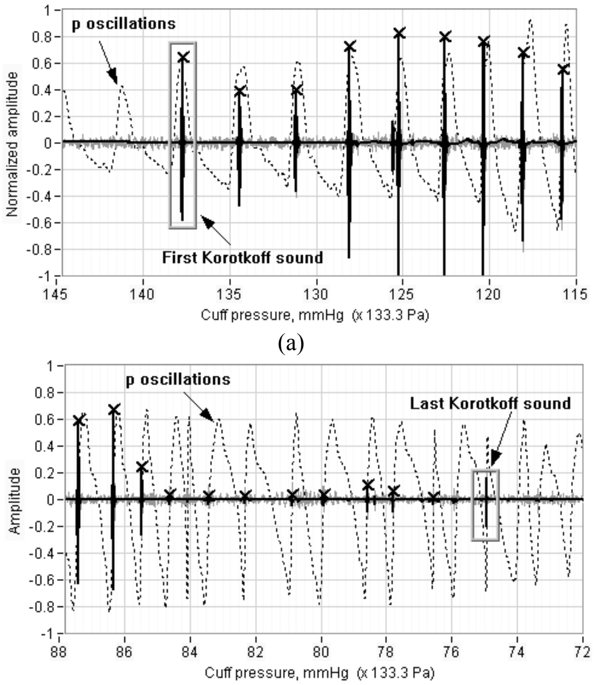


Fig. 5. Korotkoff sounds recorded by a microphone during the cuff deflation.

The Korotkoff sound appears in each cardiac cycle when cuff pressures are between the systolic and diastolic arterial blood pressures. All Korotkoff sounds are detected as the local maxima occurred in the denoised signal by means of the peak detector described above.

To verify the results of peak detection, each sound location in a time domain is compared to a location of the uprising slope extracted from the oscillometric oscillations (Fig. 6).

The systolic arterial blood pressure is identified as the cuff pressure associated with the onset of Korotkoff sounds during the cuff deflation (Fig. 6a). To determine the diastolic pressure value the last Korotkoff sound should be found (Fig. 6b).



(a)

(b)

Fig. 6. Detection of the first and last Korotkoff sounds.

The denoised Korotkoff sound is a typical transient signal similar to a damped sinusoidal wave and it is characterized by short time duration (Fig. 7).

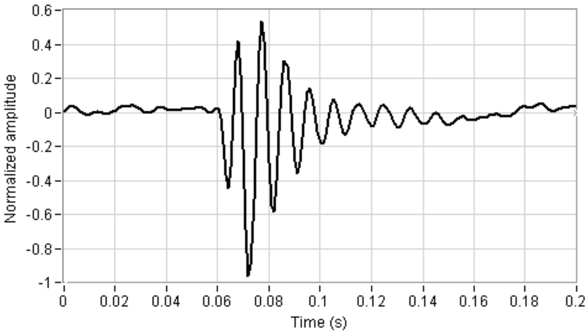


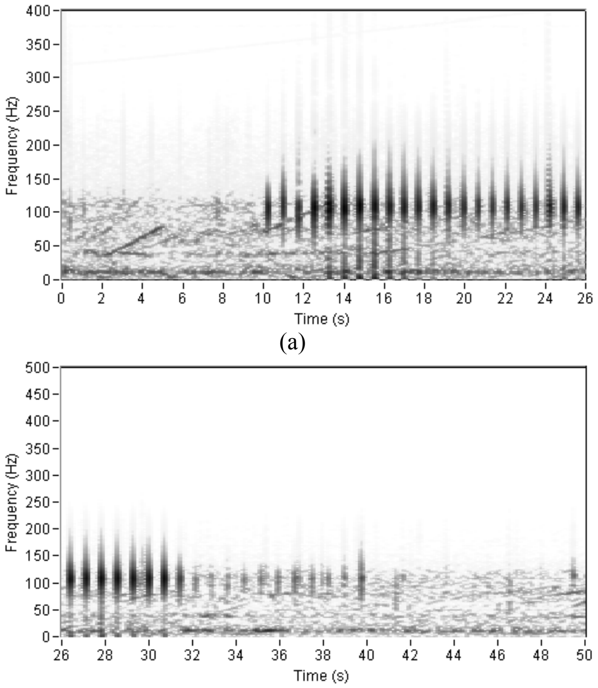
Fig. 7. An example of Korotkoff sound.

The spectrogram of the signal representing Korotkoff sounds is presented in Fig. 8a, b. This spectrogram was obtained by the STFT method. The frequency components of the first and last Korotkoff sounds are in the almost identical frequency range. Some sounds between the first and last Korotkoff sounds have frequency components below 50 Hz. It is worth noting that the automatic detection of Korotkoff sounds makes it possible to detect the sound which is sometimes not audible because of the high noise level.

Fig. 9 illustrates the pulsatile blood flow and its spectrogram for the brachial artery in a normal condition (i.e., before a cuff inflation).

The blood flows in the opposite direction under the influence of the reflected pressure wave. This flow is characterized by significantly lower amplitude and low frequency components.

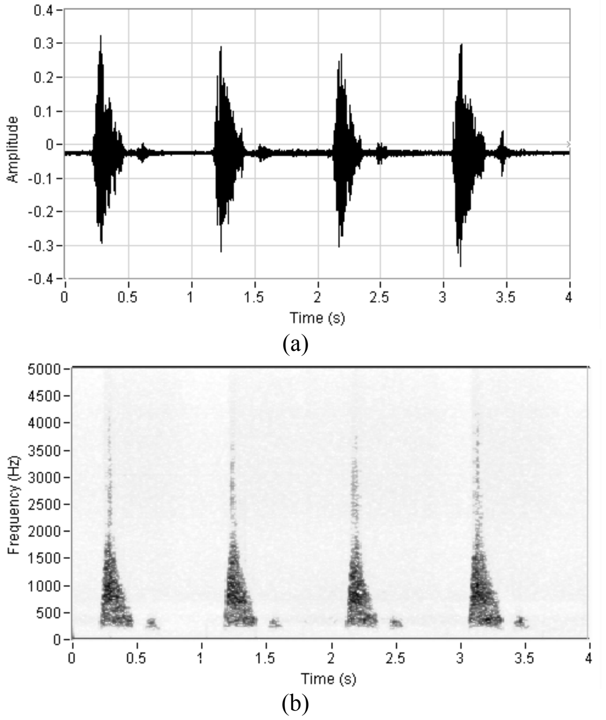
The blood flow and its spectrogram for the partially occluded brachial artery during the cuff deflation are presented in Fig. 10. The spectrogram of the blood flow can be applied to detection of the first Korotkoff and the last Korotkoff sounds.



(a)

(b)

Fig. 8. The spectrogram of the recorded Korotkoff sounds.



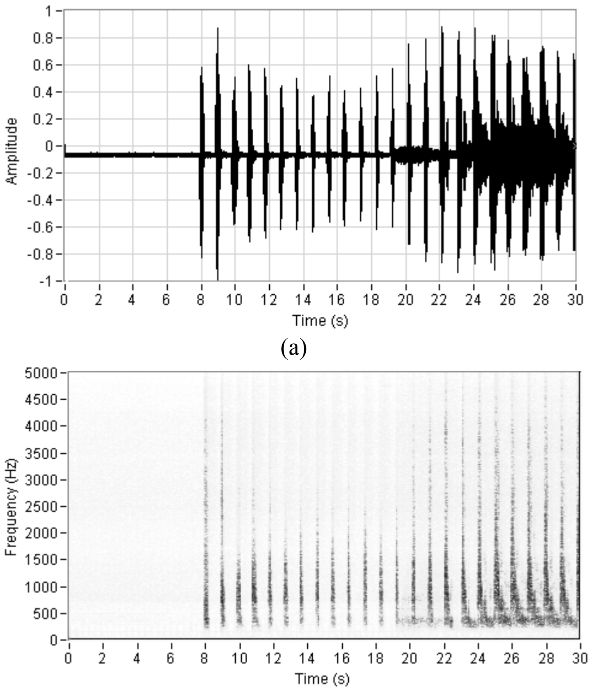
(a)

(b)

Fig. 9. An example of blood flow (a) and its spectrogram (b) for the brachial artery in a normal condition.

4. Conclusion

When cuff pressures are between systolic and diastolic blood pressure the brachial artery compressed by a cuff is collapsing completely and then reopening in each cardiac cycle. This artery opens because a cuff pressure is less than systolic pressure and then it collapses because a cuff pressure exceeds diastolic pressure.



(a)

(b)

Fig. 10. An example of blood flow (a) and its spectrogram (b) for the brachial artery during the cuff deflation.

However, when a cuff pressure falls below the diastolic blood pressure, the Korotkoff sounds disappear because the brachial artery wall no longer collapses. Korotkoff sound reflects the sudden deceleration of the rapidly opening arterial walls. The results presented in Fig. 6 prove that Korotkoff sound occurs in each cardiac cycle at the time when the gradient of pressure oscillation in a cuff reaches its maximum. Korotkoff sounds can be considered to be produced and modified by the self-excited oscillation of a collapsed artery.

This work is financed by Polish Ministry of Science and Higher Education under the program "Regional Initiative of Excellence" in 2019 – 2022. Project number 027/RID/2018/19, funding amount 11 999 900 PLN.

References

1. G. Drzewiecki, Noninvasive assessment of arterial blood pressure and mechanics, in J. D. Bronzino (Ed): *The Biomedical Engineering Handbook* (Boca Raton, CRC, 1995) 1196-1211
2. M. Nitzan, IEEE Instru. Meas. Mag. **14**(2), 32–37 (2011)
3. M. Forouzanfar, et al., IEEE Rev. Biomed. Eng. **8**, 44–63 (2015)
4. B. Wilk, Using wavelet analysis for oscillometric determination of arterial blood pressure, *Proc. of the IFMBE EMBEC'02 - 2-nd European Med. & Biol. Eng. Conf. Vienna*, 504-505 (2002)
5. M. Ursino, C. Cristalli, IEEE Trans. on Biomed. Eng. **43**, 761-778 (1996)