OSCILLOMETRIC MEASUREMENT OF ARTERIAL BLOOD PRESSURE: ESTIMATION AND ANALYSIS OF THE ENVELOPE OF OSCILLATIONS

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Abstract: This paper deals with some problems of digital signal processing occurring during arterial blood pressure measurement using the oscillometric method. The discrete wavelet transform is applied to select the pressure oscillations from a cuff pressure signal recorded during a continuous deflation. The amplitude envelope of pressure oscillations is estimated by a polynomial or a spline interpolation. This envelope called oscillometric curve is used to determine the systolic and diastolic pressure values. Some results of the oscillometric curve analysis are presented.

Introduction

Arterial blood pressure is a good indicator for assessing the state of cardiovascular system. Despite of the fact, that the invasive methods are the most accurate methods and they make possible on-line monitoring of blood pressure, they are not as popular in the clinical practice as non-invasive methods. The main advantage of non-invasive methods is lack of drawbacks caused by an arterial catheter.

In recent years increasing attention has been put on to the oscillometric method, since it can be easily automated in commercially available devices and it does not require the presence of trained personnel [1]. This non-invasive method is based on the observation that the amplitude of pressure oscillation in the occlusive arm cuff varies when 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 mentioned variation in arm cuff is related to the arterial compliance-pressure curve of the brachial artery. It is now generally accepted that the maximum oscillations corresponding to cuff pressure equal to the mean arterial pressure (p_m) [2]. The systolic (p_s) and diastolic (p_d) pressure values are identified by the characteristic ratios (i.e. the proportionally factors between the cuff oscillation amplitude at systole and diastole and the maximum cuff oscillation amplitude), that have been determined empirically from a population of subjects. It is worth noting that the accuracy of blood pressure measurement has a significant implication for the clinical management of the patient during the treatment, the most important part of which is an appropriate diagnosis.

Materials and Methods

The pressure in a standard occlusive arm cuff was recorded using a piezoresistive silicon pressure sensor. The sensor output signal was amplified and then converted in the ADC (16-bit accuracy) with a sampling frequency of 1 kHz. The cuff deflation was continuous and similar to that which occurs in the manual Riva-Rocci procedure, with a deflation rate in the range of 2-10 mmHg/s. The pressure signal was acquired during about 50-60 s and stored as a raw data. Data was collected form 20 healthy subjects at rest.

Fig. 1 illustrates an example of the cuff pressure recorded during the deflation.

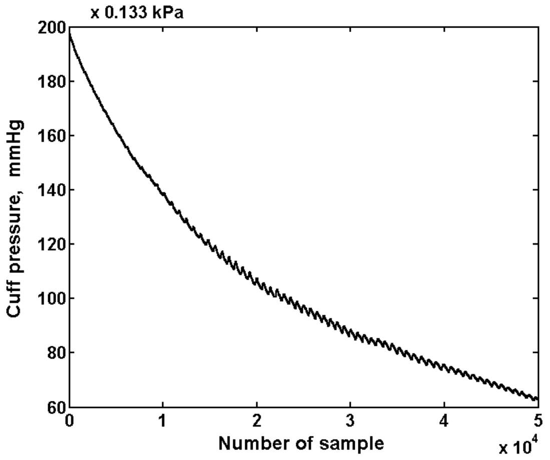

Figure 1: Sample recording of the cuff pressure during the deflation

The recorded pressure signal consists of two main components, namely the non-linear trend strongly depended on the deflation process, and the noisy pulsatile oscillations. The pressure trend allows to obtain the exact values of pressure during the cuff deflation. The envelope amplitude of pressure oscillations is used for estimation of systolic (p_s) and diastolic (p_d) pressure values. As was reported in [3], the discrete wavelet transform (DWT) gives a useful tool to select and de-noise the pressure oscillations, as well as it provides a very good approximation of the pressure trend during the deflation. The DWT was applied to decompose the recorded signal up to level nine using Daubechies' orthonormal wavelets (db10).

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These scales cover the main energy of the original signal sampled at 1 kHz, see Fig. 2. The approximation of the analyzed signal at level nine (A9) seems to be an acceptable estimate of the pressure trend. The details D1, D2 and D3 can be used to eliminate a large part of the noise. Fig. 3 illustrates the pressure oscillations before and after de-noising.

An example of the de-noised pressure oscillations in the arm cuff during the deflation is shown in Fig. 4. This signal has been used to measure the peak-to-peak amplitude of oscillations in each cardiac cycle.

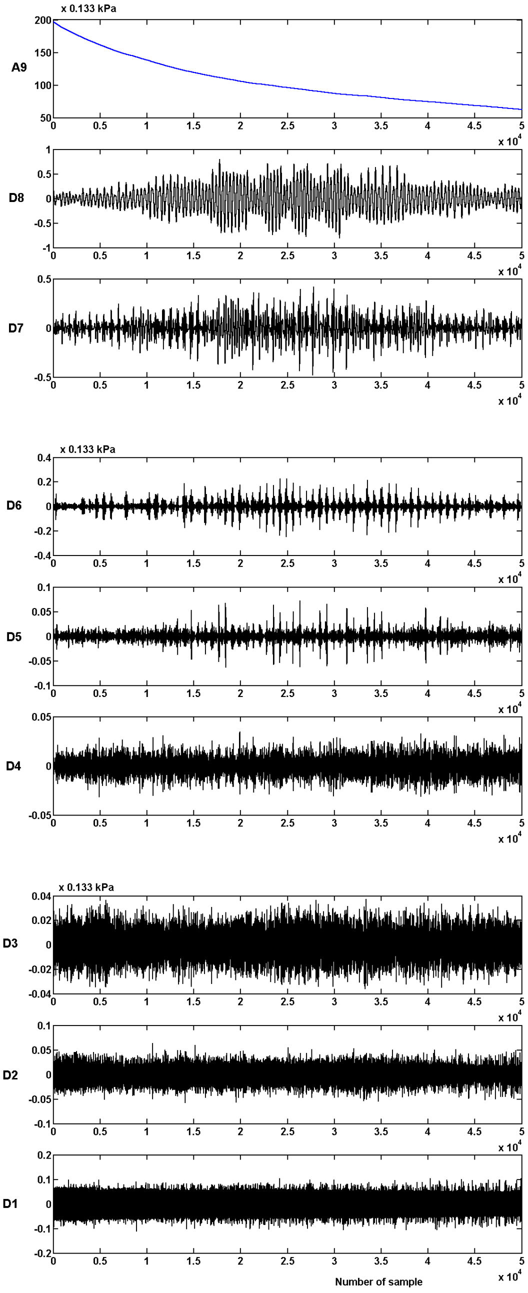

Figure 2: The multiresolution decomposition of the recorded cuff pressure signal, A9 - approximation, D1÷D8 - details

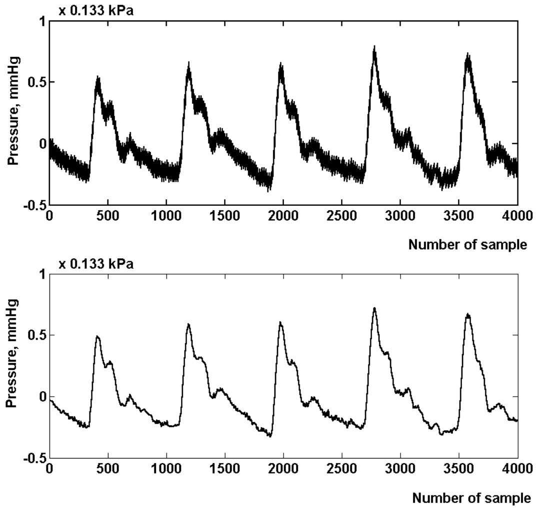

Figure 3: Oscillometric oscillations before (a) and after (b) de-noising

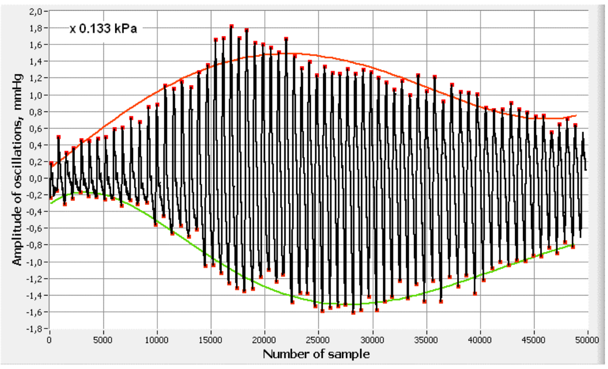

Figure 4: The pressure oscillations in the arm cuff and the results of a polynomial interpolation

The measurement method of the peak-to-peak amplitude is based on the identification of the extremes and on a procedure in which an upper envelope is created by a polynomial (or by a cubic spline) interpolation of the local maxima. A lower envelope is created by interpolation of the local minima. To detect all local extremes of the oscillometric oscillations the peak detector based on the 2-nd derivative was used. 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 algorithm based on the so-called refractory period. It is worth noting that noisy pressure oscillations have many false extremes.

Fig. 5 illustrates the steps of the envelope build-up by adding an upper and a lower envelope estimate.

A polynomial interpolation was carried out by using polynomials with different order. The experiments show that the upper and lower envelope require different polynomial order, see Fig. 5, Fig. 6 and Fig. 7.

The results of a cubic spline interpolation are presented in Fig. 8.

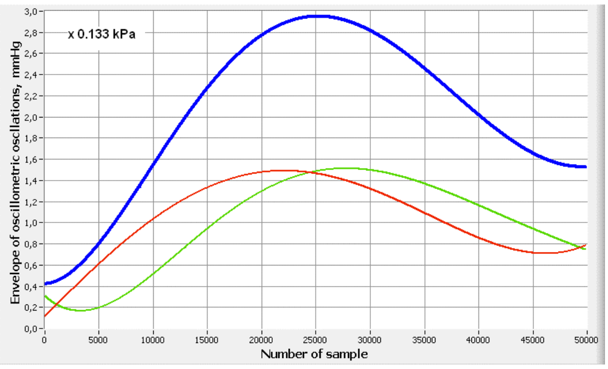

Figure 5: The envelope of oscillometric oscillations created by a polynomial interpolation (blue), where the red curve is an upper envelope (polynomial order: 4), and the green curve is a lower envelope (a polynomial order: 5)

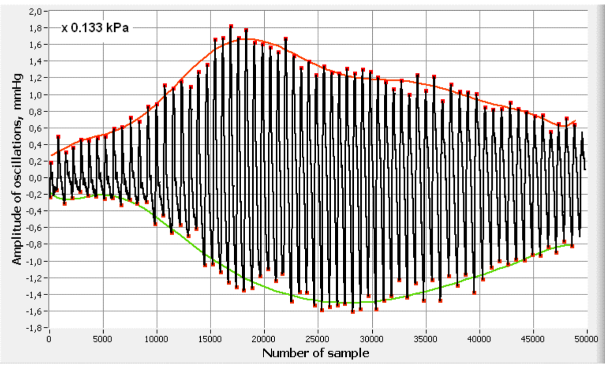

Figure 6: The pressure oscillations and the results of the interpolation by the best fitting polynomial

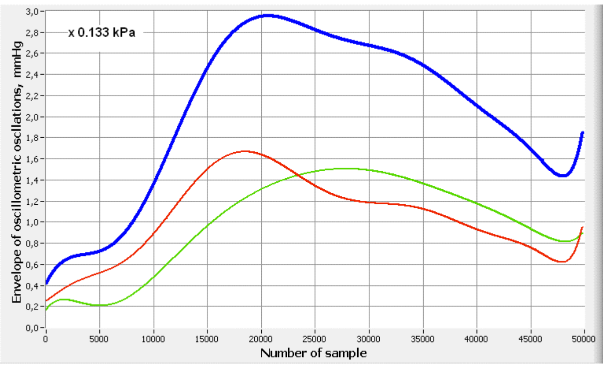

Figure 7: The envelope of oscillations created by the best fitting polynomial, where the 11-th and the 9-th order polynomial were applied to an upper and a lower envelope respectively

Sometimes it is very difficult to find a good estimate for pressure oscillations. Fig. 9 shows oscillometric oscillatons for one subject after exercising. Significant heart rate changes during measurement cause the rapid changes of pulse amplitude. In this case only a cubic spline interpolation provides a very good estimation for the characteristic pattern of the oscillometric pulse amplitude (see Fig. 10).

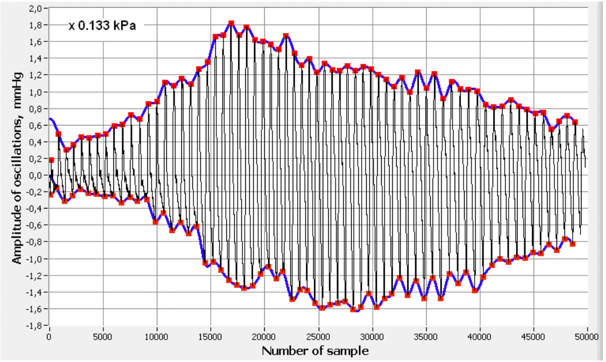

Figure 8: The oscillometric oscillations and the results of a cubic spline interpolation

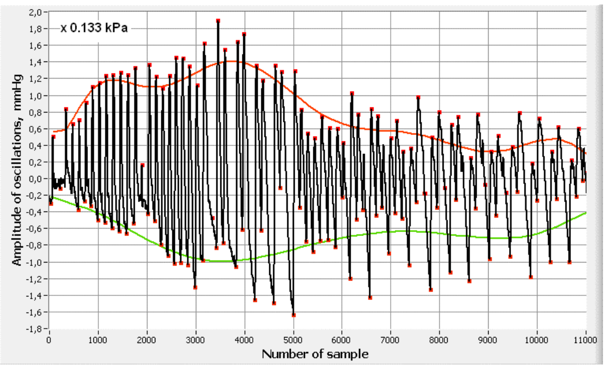

Figure 9: The oscillomertic pressure oscillations during heart rate changes and the results of envelope estimation by using the 11-th order polynomial

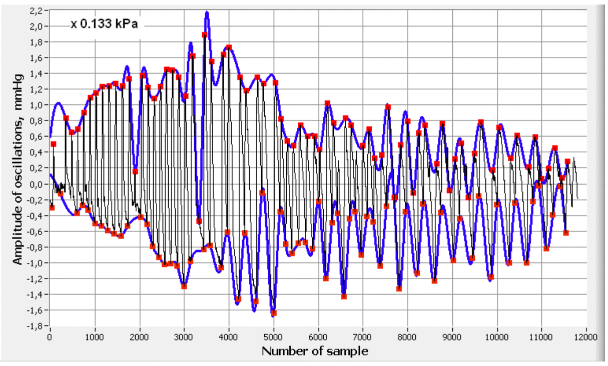

Figure 10: The oscillometric pressure oscillations during heart rate changes and the results of a cubic spline interpolation

The envelope of pressure oscillations is often called the oscillometric curve. As mentioned above, the maximum oscillation is related to the mean arterial pressure. The oscillometric curve is usually normalized according to this maximum, because it helps to identify the systolic (p_s) and diastolic (p_d) blood pressure values determined by an algorithmic interpretation of the shape of oscillometric amplitudes (i.e. by the characteristic ratios, see Table 1). Fig. 11 and Fig. 12 show the systolic and diastolic pressure identification by two fixed thresholds represented by dotted lines.

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Table 1: The characteristic ratios at systole and diastole applied for identification of p_s and p_d (where Δp is the peak-to-peak amplitude of oscillometric pulse) [2, 4, 5]

	$\Delta p_s / \Delta p_m$	$\Delta p_d / \Delta p_m$
(a) Geddes	0.55	0.82
(b) Drzewiecki	0.55	0.85
(c) Pałko	0.68	0.73
(d) Sapiński	0.40	0.60
(e) Ursino	0.52	0.70

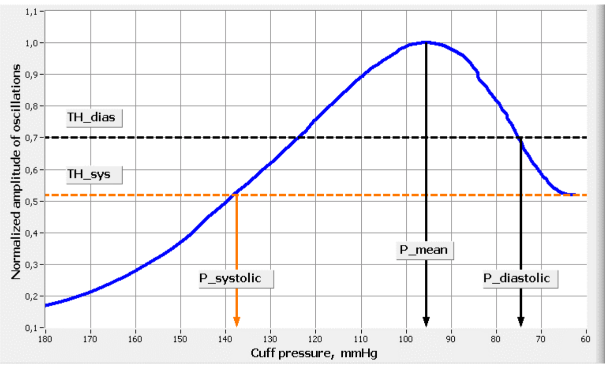

Figure 11: The envelope of oscillations created by a polynomial interpolation with respect to cuff pressure

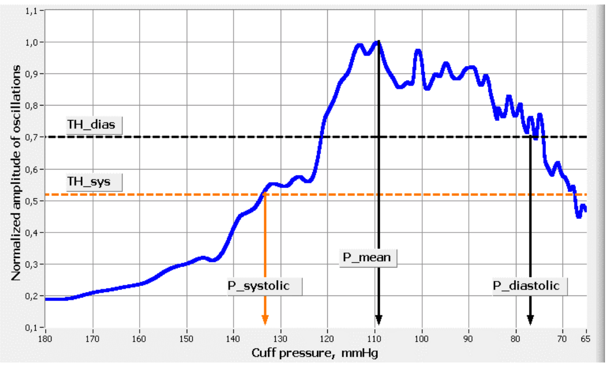

Figure 12: The envelope of oscillations created by a cubic spline interpolation with respect to cuff pressure

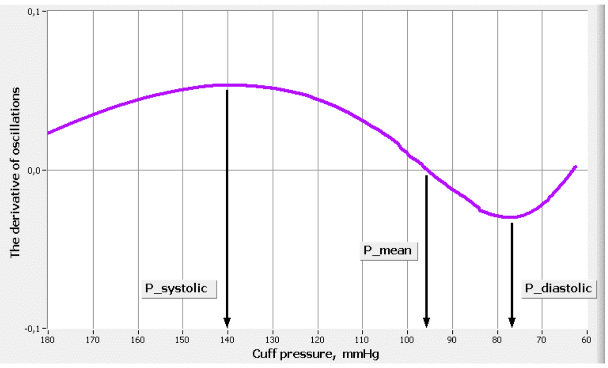

Figure 13: The derivative of oscillation amplitude curve with respect to cuff pressure

The values of systolic and diastolic pressures can be obtained by the derivative of the oscillation amplitude curve [2], see Fig.13. When the derivative is plotted against cuff pressure, the mean arterial blood pressure (p_m) can be easily identified as the point where the derivative is zero. The derivative reaches a maximum positive value at cuff pressure equal to systolic. The minimum negative value occurs at diastolic pressure.

Results

The values of systolic and diastolic pressure obtained from the data shown in Figure 1 are summarised in Table 2. The pressure values were determined by using different characteristic ratios shown in Table 1. To estimate the envelope of oscillometric oscillations two described estimation procedures were applied, i.e. a spline and a polynomial interpolation. A polynomial interpolation was carried out with polynomials of various orders. The results of using the 5-th order and the 11-th order polynomial are demonstrated in Table 2 (see Fig. 4 and Fig.6).

Table 2: The values of arterial blood pressure obtained from the data shown in Figure 1, and by using different characteristic ratios and two envelope estimation procedure (where * denotes the derivative method, and the symbol '?' means a problem of an accurate identification)

	p_m mmHg	**p_s mmHg**	**p_d mmHg**	
Ausculatory of Korotkoff sounds				
	-	**139**	**77**	
Oscillometric method				
Envelope estimation by a spline	109.6	132.5	85	(a)
		121.7	78	(c)
		140.5	73	(d)
		134	76	(e)
		?	?	*
Envelope estimation by the 5-th order polynomial	95.4	137	79	(a)
		125	75	(c)
		148	70	(d)
		139	74	(e)
		140	**77**	*
Envelope estimation by the 11-th order polynomial	104	132	79	(a)
		126	75	(c)
		141	70	(d)
		134	74	(e)
		130	77 ?	*

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In this study, the Korotkoff's method was used as a reference. The Korotkoff sounds were detected by a traditional stethoscope and recorded parallel with a cuff pressure by using a piezoelectric microphone.

Discussion

Table 2 shows different pressure values obtained by using the Korotkoff's method and the oscillometric method. No difference in systolic and diastolic blood pressure between the two measurement methods was found for the derivative method applied to oscillometric curve, which was estimated by a 5-th order polynomial.

The different pressure values at systole and diastole obtained from the same oscillomertic curve show the influence of the characteristic ratios. The characteristic ratios reported by Pałko [5] underestimated significantly the systolic pressure.

In all cases, the best fitting curve estimating the peak-to peak amplitude of pressure oscillations was created by a spline interpolation. The similar results can be achieved by using a high order polynomial interpolation. The major problem is to choose an appropriate polynomial order. The order of the best fitting polynomial was found to be equal 11. It provides the best envelope of pressure oscillations for all data collected form 20 subjects.

The method called derivative oscillometry allows to determine the systolic and diastolic pressure without referring to any characteristic ratios. This method is very sensitive to the shape of oscillometric curve. The preformed experiments showed that this method is not useful if the oscillometric curve has many extremes. In such cases, it is very difficult or even impossible to identify the systolic and diastolic pressure. The obtained results demonstrate that the derivative method works correctly when the oscillomertic curve is interpolated by the 5-th order polynomial. It is worth noting that the upper envelope has stronger influence on systolic pressure identification than the lower envelope.

As mentioned above, an upper and a lower envelope usually need different polynomial orders.

Conclusions

This preliminary study shows that the accuracy of arterial blood pressure determination in the oscillometric method depends on a proper estimation of the of oscillometric oscillations envelope.

The two estimation procedures (i.e. a spline and a polynomial interpolation) were proposed for creating the oscillometric curve.

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