Oscillogram processing algorithm when monitoring cardiac patients’ conditions

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Abstract. The development of hospital information system requires the improvement of diagnostic and monitoring tools. The tools should provide extensive diagnostics and automatic data processing. In that respect volumetric compression oscillometry is considered a promising technique. However, at present diagnostic findings need to be adjusted by qualified healthcare professionals. The article deals with a process model when measuring arterial blood pressure, compares experimental findings and presents a blood pressure measurement algorithm. The devices designed on the algorithm will allow to conduct an advanced monitoring of patients’ conditions without healthcare professionals directly involved. Implementing algorithm-based devices into hospital system will allow to respond to change in patients’ conditions urgently.

1. Introduction

A hospital information system (HIS) is a basis for public health monitoring. It serves for multiple purposes i.e., collecting data, diagnostics, patient monitoring, medical consult, providing healthcare services. One of the ways to increase the efficiency of such systems is to improve patient-diagnostic and monitoring tools. Getting accurate information on the course of a disease helps a healthcare professional to quickly adjust treatment. It is especially vital when dealing with life threatening diseases. Cardiovascular diseases (CVDs) are the number 1 cause of death globally. One of the main factors when treating cardiovascular diseases is arterial blood pressure. Consequently, studies aimed at improvement of monitoring systems are of vital importance.

Nowadays Blood Pressure Cuff monitors based on Korotkoff sounds (K-Sounds) are used for blood pressure measuring. Korotkoff sounds are high-frequency vibrations of artery walls and surrounding tissues. They occur when the vessel restores after being occluded by outer pressure of the cuffs [1-3]. The sounds are defined by the properties of the artery walls and surrounding tissues. As the measurement is indirect it is believed that properties of artery walls and surrounding tissues are the same for all patients. Appearance of the vibrations is caused solely by the change of blood pressure and doesn’t depend on other factors, i.e., special features of a human body are not considered. However special features of a human body affect
measurement results. There are cases such as "infinite Korotkoff sounds" or an auscultatory gap, which make it impossible to use this method for blood pressure measurement.

The oscillometric method is an alternative technique for blood pressure measurement. Over the last years there appeared an industry of automatic and semi-automatic blood pressure monitors which are based on oscillometric method. The oscillometric method involves the observation of pulsations (oscillations) in the sphygmomanometer cuff pressure (waveform view is shown in figure 1). It occurs when comparing the level of this pressure against the level of arterial blood pressure. It is believed that appearance of the oscillations is not directly connected with equality of values of cuff and arterial blood pressure. It results in searching for correlation dependence between the oscillations and BP levels and finally according to the correlation estimating the systolic and diastolic BP [4, 5].

![Waveform view](image.png)

**Figure 1.** Waveform view.

Volumetric compression oscillometry (VCO) is a variation of the oscillometric method. It deals with oscillographic curves integration (view of the curve using the VCO method is shown in figure 2). The method provides more accurate way of BP diagnostics and is based on the studies of BP measurement when the cuff pressure is inflated and deflated [6]. However current BP measuring algorithms have substantial inaccuracy and need to be adjusted by qualified healthcare professionals.
Therefore, it is vital to design an algorithm for automatic BP measurement based on the analysis of the main processes which take place in cardio-vascular system and operating algorithms for measurement systems. The most preferable algorithms are the ones which can be implemented without complex algorithmic and mathematical solutions. It will allow to produce relatively inexpensive yet convenient BP measurement devices to monitor patients’ conditions and consider patients’ special features. The algorithm is designed on the basis of mathematical model of BP measurement processes.

2. Materials and methods

2.1 Mathematical model of BP measurement processes

When analyzing BP measurement processes it is important to note that circulatory system has complex closed structure (figure 3). The measurement is performed when one of the large arteries (brachial artery) is compressed, which can affect the entire system. Pressure change to be analyzed is based on the cuff pressure.

The main interacting elements are the brachial artery and the cuff. The brachial artery has two relevant areas – up to the spot occluded by the cuff (cross-section of an artery doesn’t change when measured) and a spot where the artery is occluded (figure 4). The cuff pressures the brachial artery narrowing the cross-section of an artery. When the cross-section changes, the artery reacts to the cuff causing pressure fluctuations in the cuff. It is recorded and processed by a measuring device, which operating model needs to be designed.
The modelling has been done on a variety of assumptions used in hemodynamic processes modelling [7-10], i.e., the motion is considered one-dimensional, the fluid (blood) is considered incompressible, arteries are vessels with elastic walls, blood flow is laminar. Aortic pressure changes from diastolic to systolic, whereas cuff pressure increases linearly. It also has been assumed that under compression only cross-sections of an artery change. Other elements are incompressible. Thus, when the upper arm is compressed, all vessels reduce their cross section. While the cuff pressure is below minimum level (diastolic pressure) each vessel is completely open, but when the pressure rises above minimum level, the vessel is partially or completely occluded. When the pressure in the cuff exceeds the maximum level, the vessel is completely occluded. The BP pressure change in the vessels is presented as following:

\[ P_a = \sum_{i=1}^{N} (a_n \sin(\omega_i t) + \varphi_i), \]

where \( a_n, \omega_i, \varphi_i \) — parameters of arterial pressure fluctuations.

Since only maximum (systolic) and minimum (diastolic) pressure are relevant for estimating blood pressure, only the frequency of the 1st mode (the fundamental frequency) is used in the calculations.

In the simplest case, the processes of hemodynamics can be described by simultaneous solution of the equation of incompressible fluid and the equation of dynamics of the elastic shell of the vessel [5]:

![Figure 3. Elements of BP measurement system.](image3)

![Figure 4. Design pattern.](image4)
\[
\begin{aligned}
\frac{\partial s}{\partial t} + \frac{\partial (us)}{\partial x} &= 0 \\
\frac{\partial u}{\partial t} + \frac{\partial}{\partial x} \left( \frac{u^2}{2} + \frac{p}{\rho} \right) &= F_e 
\end{aligned}
\]  

(2)

where \( t \) – time, \( x \) – longitudinal axis, \( s \) – cross-section of an artery area, \( u \) – average cross-section blood velocity, \( \rho \) – blood density (constant quantity), \( F_e \) - applied force. Viscous forces are neglected.

To close a system (2) linear approximation \( s = s(p) \) is used [7].

At the second stage outer force effects on brachial artery are in focus [7]:

\[
\begin{aligned}
\frac{\partial^2 s}{\partial t^2} &= \frac{s_{\text{min}} - s_{\text{max}}}{p_{\text{max}} - p_{\text{min}}} (p - p_{\text{ext}} - p_{\text{min}}), p_{\text{min}} < p < p_{\text{max}} \\
&= s_{\text{min}}, p < p_{\text{min}} \\
&= s_{\text{max}}, p_{\text{max}} < p
\end{aligned}
\]

(3)

where \( p_{\text{ext}} \) – applied pressure, \( s_{\text{min}}, s_{\text{max}}, p_{\text{min}}, p_{\text{max}} \) – artery characteristics.

The ideal gas law is applied to estimate the cuff pressure:

\[
p = \frac{m R T}{V_u},
\]

(4)

where \( m \) – cuff air mass, \( R \) – the ideal, (gas constant), \( T \) – cuff air temperature, \( M \) – molar mass, \( V_u \) – cuff volume. When the brachial artery is compressed by the cuff, volume changes to occluded artery volume. A pressure monitor will record the fluctuation. The change in pressure will look as following (figure 5).

![Figure 5. Pressure change at the second stage.](image)

After the cuff pressure exceeds diastolic pressure \( P_m = P_d \) point will have fluctuations increasing their range. After the cuff pressure exceeds average value \( P_m \), fluctuation range will go down.
3. Results and discussion

3.1. Designing blood pressure measurement algorithm. The volumetric compression oscilometry method.

The main problem the algorithm must solve is to find points $P_m = P_d$ and $P_m = P_s$ on the oscillogram. Actual curves can differ significantly from the ones shown in figure 2, 5. (see figure 6)

See below the following blood pressure measurement algorithm (figure 7) [11]:

1. Find bottom cuff oscillation value when measuring BP;
2. The obtained data is approximated by the analytical dependence in the decreased area;
3. Find the curve inflection point (If there are a few of them, chose the closest to minimum)
4. Draw a tangent line at the inflection point
5. Draw two horizontal lines. The first line is drawn according to the average value in the area corresponding to the cuff pressure of 20-40 mmHg. The second line is drawn according to minimum oscillation value in the area to the right from the inflection point;
6. The abscissa of the point of intersection between a tangent line and the first line sets diastolic pressure $P_d$;
7. The abscissa of the point of intersection between a tangent line and the second line sets average pressure $P_{sr}$;
8. Systolic pressure $P_s$ is calculated by the formula: $P_s = P_d + 2(P_{sr} - P_d)$.

3.2. Performance evaluation of the algorithm

The model representation makes it possible to evaluate the performance of the algorithm. For this matter processes which have the greatest influence on the shape curve are reviewed. These are other vessels’ influence and shear stress. The mathematical model allows to isolate the artery walls vibrations from other
factors.

When the upper arm is compressed, not only the brachial artery but also the smaller vessels (arterioles, metarterioles, etc.) are occluded. To assess the effect of the vessels on the oscillogram, a study similar to the process in the brachial artery has been carried out. They have lower pressure, therefore, on the left side of the graph, there are oscillations of lower amplitude and lower pressure.

The analyses of the results demonstrate relative goodness of fit in the area corresponding to BP measurement. Thus, the modal curve (full line) and the results of the measurement (dashed line) for patients who do not have cardiovascular conditions (figure 7) are quite similar and BP measurement margin doesn’t exceed 10 mmHg.

Figure 7. Model-based oscillogram and experimental oscillogram of a patient in good health (Korotkoff pressure 114/72, model pressure: 110/65).

The algorithm allows to distinguish three areas on the graph. Oscillations on the right are caused by other blood vessels and do not affect brachial artery pressure. This area is highlighted by drawing a tangent line at the inflection point. The second area is important for algorithm-based BP estimation. The third area is a result of effects neglected in this model (shear stress syndrome). Such effects are determined by vessel properties (e.g., vascular stiffness) and do not describe BP.

For people with cardiovascular conditions (figure 8) the first area of the model corresponds with the second quite well, whereas the first and the second areas differ significantly from the third one. Preliminary evaluation explains this as a consequence of a shear stress when the brachial artery is compressed rapidly. Such conditions are characterized by increasing vascular stiffness and as a result increasing pulse-wave velocity. It can lead to rise of pressure in occluded area of an artery by dozens of mmHg.
Figure 8. Model-based oscillogram and experimental oscillogram of a patient diagnosed with ischemic heart disease, stable angina pectoris (Korotkov pressure: 148/79, model pressure: 120/63).

4. Conclusions
The studies show that the algorithm can be taken as the basis of the algorithm for cardiovascular monitoring devices when measuring BP. Proposed methods make it possible to study the measurement process. This would enable to increase the accuracy of BP measurement. Healthcare professionals will get additional characteristics of cardiovascular system, which are calculated on the basis of the received data. As a result, the accuracy of diagnosing of cardiovascular diseases will increase and the risk of taking wrong treatment choices will be reduced. Devices built on the basis of the algorithm will allow to conduct advanced monitoring of the patient's condition without actual participation of healthcare professionals. Implementing algorithm-based devices into hospital system will allow to respond to change in patients’ conditions urgently.

References
[1] Grigoryan S S; Saakyan Yu Z and Tsaturyan A K 1980 On the generation mechanism of Korotkov sound Dokl Acad Nauk USSR 3 pp 570-579 (in Russian)
[2] Simakov S S 2018 Modern methods of mathematical modeling of blood flow using reduced order methods. Computer Research and Modeling 10 5 pp 581–604 (in Russian)
[3] Kositsky G I 1959 Sound method of research of arterial pressure Medgiz Moscow (in Russian)
[4] Romanovskaya A M and Romanovskiy V F 2018 Physical and metrological aspects of methods for measuring blood pressure using compression cuff Measurements World 2 pp 32-43 (in Russian)
[5] Romanovskaya A M 1987 Method of indirect measurement of arterial tension and a device for wave registration US Patent 4653506
[6] Degtyarev V A 2008 New non-invasive method of blood pressure measurement Functional Diagnostics 1 pp 95-101 (in Russian)

[7] Astrakhantseva E V, Gidaspov V Yu and Reviznikov D L 2005 Mathematical modelling of hemodynamics of large blood vessels Mathematical Modeling 8 pp 61-80 (in Russian)

[8] Abakumov M V, Esikova N B, Mukhin S I, Sosnin N V, Tishkin V F and Favorskii A P 1998 A difference scheme for solving problems of hemodynamics on a graph Preprint Dialog-MGU Moscow (in Russian)

[9] Biyue Liu and Dalin Tang 2000 A numerical simulation of viscous flows in collapsible tubes with stenoses Applied Numerical Mathematics 32 pp 87-101

[10] Astrakhantseva E V, Gidaspov V Yu, Pirumov U G and Reviznikov D L 2006 Numerical simulation of hemodynamics in arterial tree Investigation of vessel compression influence on flow parameters Mathematical Modeling 8 pp 25-36. (in Russian)

[11] Abramov G V, Abramov D G and Degtyarev V A 2020 Techniques of blood pressure measurement Patent № 2736690 (in Russian)