Non-Invasive Blood Pressure Monitoring with Positionable Three-chamber Pneumatic Sensor

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Abstract: The main goal of the paper is to present a new type of a sensor for non-invasive continuous blood pressure measurements. The principle of such a sensor operation, based on local pressure compensation, is in the centre of discussion. The sensor presented has very small sensing pads (1 mm^2 or less) which permits accurate sensor positioning directly on the elastic surfaces such as the human skin. Thanks to that it is possible to provide a high quality of the blood pressure measurement, when keeping the continuity of the measurement parameters and minimizing the level of disturbances. For this reason, the paper focuses on a detailed discussion of the positioning problem and the results of developing approaches to its solving. As a promising method, a positioning based on the pulse wave controlling by a three-chamber pneumatic sensor is proposed.

1 INTRODUCTION

The invasive method for measuring arterial blood pressure (ABP) is direct and the most accurate. However, due to strict professional personnel requirements, it is used only in acute cases in a hospital, under the supervision of a qualified and certified medical personnel. This method does not allow to continuously monitor the patient's every day activities, to track objective hemodynamics and the state of the cardiovascular system outside the hospital.

Most of modern methods for non-invasive measurement of ABP are based on manipulation of counter-pressure in the cuff or the applicator, compressing the artery (usually together with the limb). The goal of these manipulations is to neutralize the possible additional pressure caused primarily by strained elastic artery walls (Settels, 2014). Oscillometric method and Korotkoff method are quantitatively dominant in ABP measurement, but they determine only two pressure levels - *systolic* and *diastolic*, along with pulse frequency, just enough for everyday use. These methods, however, do not present the shape of ABP pulse wave beat-to-beat. Moreover, continuous monitoring of ABP is impossible when the methods inherently intermittent are used. In further development of Marey's proceedings, dated 1860-80, new methods of arterial tonometry were proposed in 1960-70-s. For example, when monitoring BP using the Peňáz method, for these purposes, the principle of volume compensation is used, exploiting the idea of dynamic "unloading of vessel walls" (Peňáz, 1973). Pressman and Newgard proposed the idea of local compensation of an artery wall by a flat applicator with a plunger (rider) located in it (Pressman and Newgard, 1963). The plunger was provided by a tracking drive for mechanical push on the artery wall (through the skin) in counterphase with pressure in it. It was assumed that the force required to keep the plunger stationary (according to the displacement sensor) is proportional to the pressure in the arteries. Looking ahead, we note that the distribution of pressure on the applicator pad in the projection of the artery is very uneven, so at best this method could measure the change in average pressure at the plunger pad. High demands on the accuracy of manufacturing miniature mechanical

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assemblies and the presence of friction and backlash in moving parts are the additional disadvantages of this method.

The disadvantage of Peňáz method is that in order to avoid stagnation of blood in the limb, it is necessary to periodically relax the cuff, which breaks the continuous regime of ABP monitoring. To overcome this problem some new approach to a continuous, non-invasive and indirect measurement of ABP based on changes in pulse wave velocity (PWV) was proposed in (Gesche et al., 2012). PWV is the speed of the pressure pulse propagating along the arterial wall and it can easily be calculated from pulse transit time (PTT). The implementation of this approach, based on MEMS pressure sensors was reported in (Kaisti et al., 2017).

To avoid disturbances related to the inflation of the cuff and the alterations of the ABP caused by such disturbances, we also developed a new approach to continuous, non-invasive blood pressure measurement. But in contrast to PWV our method is based on the principle of local pressure compensation (Figure 1).

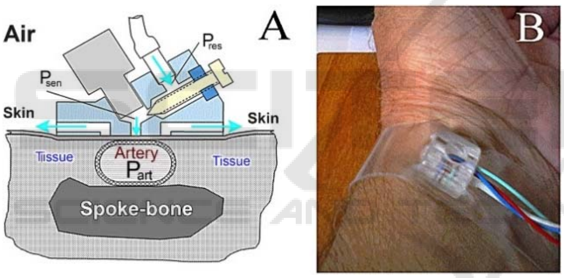

Figure 1: The measurement principle of blood pressure due to local pressure compensation in the artery Part by pressure in the measuring element Psen of the pneumatic sensor (A) and the appearance of the element applied to the patient's wrist (B).

Practical implementation of this method became possible by the previously developed unique technic of pressure compensating measurements on a very small working area (1 mm2 or less) (Antsiperov et al., 2016).

2 THE PRINCIPLE OF LOCAL PRESSURE COMPENSATION

When analyzing well–known methods of non–invasive continuous measurement of blood pressure, we can conclude that the best results of monitoring non–stationary dynamics of ABP are achieved by the so–called compensation methods or methods similar to them.

The compensation methods are used for measurement of various physical quantities and are based on the compensation of an unknown measured value by controlled counter value and nullification of their difference. The simplest example of the compensation method is the use of balance scales on which unknown mass is measured using a set of counter -weights. The predetermined position of the balance beam or the associated arrow serves as a null indicator of the balance scales.

The compensation methods as methods of high precision are used for electrical measurements, in embodiments having bridge and half-bridge circuits. Note that the compensation methods are usually used to measure the static variables, for example the constant unknown resistance in bridge circuits.

We consider the compensation method as the fundamental basis to measure the varying blood pressure. The application of this method for measuring the non–static dynamic quantity has become possible, for two reasons.

Firstly, the fact that blood pressure changes are not so fast, its rhythm is of the order of one beat per second, and its spectrum fits into the range of a few tens of Hz. Secondly, there are relatively cheap, high performance microcontrollers for which such a change in pressure is quasi-static.The idea of local compensation principle for measuring pressure in inaccessible volumes of gas or fluid is as follows: if the external force fails to make the shape of the surface bounding the volume of the elastic membrane locally flat, then the external pressure due to the lack of longitudinal elastic stresses in the shell will be equal to the internal. This principle is realized in the method of applanation tonometry to measure intraocular pressure (Goldmann and Schmidt, 1975). For non-invasive pressure measurement in the inaccessible volume of the artery this principle is illustrated in Figure 1. Namely, if at some initial moment the pressure in the measuring chamber of the sensor element P_{sen} is less than the pressure in the artery P_{art} then the tissue and the skin directly above the artery snug against the air channel of the sensor and lock it. Once P_{sen} reaches P_{art}, the channel outlet is opened, and the excess air goes under the flat surface of the measuring element being pressed against the skin. If the air flow into the chamber is chosen correctly (choice of pressure P_{res} in the receiver and the throttle position of the screw), the laminar flow of air from the chamber will keep the skin surface in a flat, minimally open state, automatically maintaining balance $P_{sen} \approx P_{art}$ (even with variable blood pressure).

In other words, we developed the pneumatic pressure sensor with local compensation principle, based on the idea of an automatic pressure relief valve in the working chamber with a constant flow of air from the outside (from the receiver).

3 POSITIONING PROBLEM

It turned out, however, that the advantages of locally-compensatory blood pressure measurement are not obtained free of charge, and they have to be paid for by the problems arising here with the positioning of the measuring sensor. Since the contact pad (outlet channel hole) of the measuring element has substantially smaller sizes than artery size, the in-sensor pressure coincides with P_{art} (see Figure 1) only when the sensor pad is located directly above the artery. Defacements of blood pressure measurement, associated with positioning of the sensing pads, are illustrated in Figure 2.

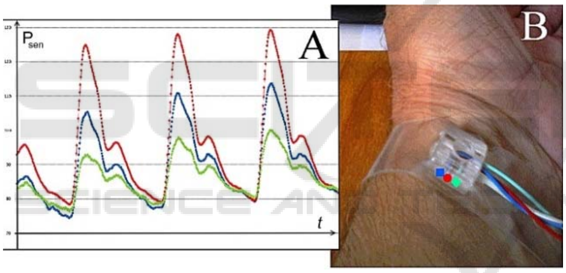

Figure 2: Distinguishing shape of pulse wave signal from sensor (A), depending on sensing pads position: ● — pad is directly over the artery, ■. ♦ — pad is shifted to the left, to the right from the centre of the radial artery.

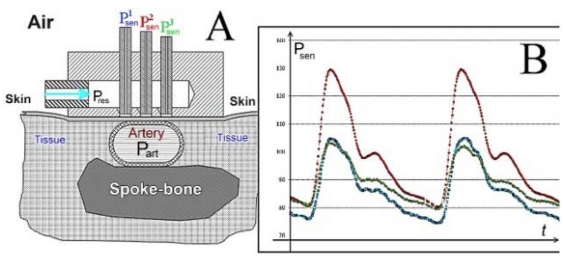

Figure 3: Sensor with three-chamber measuring element based on locally compensatory blood pressure measurement (A), implementing the three-channel synchronous measurement of the pulse wave (B).

A detailed study of the positioning problem revealed the following. In the position just above the artery the ABP signal has the greatest magnitude between the major maxima and minima and wherein the extrema are themselves more acute (see Figure 2).

As seen from Figure 3, the same symmetrical positions with respect to the artery occur when the pulse wave graphics substantially coincide.

4 SENSOR POSITIONING METHOD

These observations led us to design a pneumatic sensor for monitoring blood pressure comprising a measuring unit with three chambers for locally compensating pressure measurements (each with its own independent pressure meter), arranged in a row transversely to the direction of the artery. Thus, in certain positions of the measurement element the chamber pads are simultaneously over the artery. A schematic view of the sensor and the result of simultaneously measuring by the three-channel pulse wave at the proper position upon the artery are shown in Figure 3. Details of the technical implementation of the sensor are presented in the patent (Mansurov et al., 2018).

In the claimed design of three-chambered pneumatic blood pressure measuring sensor lateral chambers are used basically to control the positioning of the measuring element. Namely, the correct arrangement of the sensor corresponds to the maximum coincidence of signals from the lateral channels (see Figure 3). Thus, it is not essential that these channels cannot achieve complete "unloading" of the side walls of the artery and, therefore, ABP signals are significantly distorted. It is important that the coincidence of these signals ensures the central chamber to be located exactly above the artery normal and in this position an undistorted signal from central chamber replicates the pressure in the artery.

The methodology of measuring three-chambered pneumatic ABP sensor is closely associated with the described features of its construction. Namely, immediately before the measurement the artery location is estimated by means of palpation (feeling for the pulse) to the patient's wrist. Then the measuring element is applied so that the sensing pads were arranged in a row transversely to the direction of the artery (see Figures 2, 3). Further, moving the sensor in the direction transverse to the artery, such a position is sought in which the side channels signals would maximally coincide. After that, the sensor is pressed to the arm to make the contact of the central pad with artery wall (through skin) as flat as possible, without artery occlusion (applanation principle).

5 CONCLUSIONS

A new method of positioning the three-chamber pneumatic sensor for ABP measurement based on local pressure compensation is proposed in the paper. The main idea of local compensation is discussed in detail. It is shown that this idea is quite simple and in part resembles the principle of the relief valve. But to achieve the stability in ABP measuring it is necessary to provide very small sizes (tens of microns) for the outlet channel hole of the measuring element. While the sizes of a pads become smaller than the artery size, the in-sensor pressure coincides with ABP only when the sensor pad is located directly above the artery. So, the advantages of locally-compensatory blood pressure measurement are not obtained free of charge – they have to be paid for by the problems arising here with the positioning of the measuring sensor.

The features of the measuring element construction that we found made it possible to produce up to four or more working chambers with a linear step from one and a half mm to two mm in one block of the element. According to the results obtained the variant with three working chambers is optimal. We believe that this solution allows the implementation of a sensor option with the automatic positioning of the applicator over the artery, since manual positioning restricts the applicability of the sensor proposed.

In short, the test results of the three-chambered pneumatic sensor positioning and the developed calibration technique showed the following:

1) a significant improvement in the accuracy of measuring of systolic, diastolic blood pressure and pulse characteristics due to calibration and correct positioning of the measuring element;
2) the possibility of continuously measuring blood pressure beat-to-beat for a long time (many cycles);
3) the possibility for qualitative measurements of the patient’s hemodynamics in everyday life.

The most important task in prospect is to replace the manual positioning of the sensor by the automatic control of its position and to develop on this basis a mobile device for continuous monitoring of ABP parameters.

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