Verification of the Assumptions of Volume-Clamp Method for Continuous Blood Pressure Measurement in a Silicone Phantom

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Abstract

The volume-clamp method allows continuous blood pressure monitoring with a finger cuff. During measurement, a constant volume of a finger is maintained. The changes in diameter are measured with a photodiode and infrared LED built-in cuff. Changes in volume caused by the change in finger artery blood pressure are compensated with changes in cuff pressure. At a valid set-point, blood pressure and cuff pressure equality are assumed during measurements. In this paper, we verified this assumption in the phantom experiment. The silicone cylindric phantom was used. For measurements of changes in diameter, we used a pulse oximeter sonde with a dedicated amplifier with analog voltage output. The finger cuff was placed over the phantom. We observed changes in voltage caused by applied pressure in two scenarios: first, when pressure was applied only to the inner cylinder, and second when the same pressure was applied to the inner cylinder and the cuff.

In both cases, the attenuation is a function of inner pressure. This observation is in contradiction to the assumption of the methods. The pressure in the cuff alters the nature of the phantom light attenuation function. To maintain the constant volume of the phantom, a different level of inner and outer pressure should be applied.

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1. Introduction

In 1967 Penaz patented the device for continuous non-invasive blood-pressure monitoring [1] and presented, a working device at a conference in Dresden[2]. For measurement, a finger cuff was used. During measurement, the device compensated for changes in finger volume through a shift in cuff pressure (the volume-clamp method). In this method, the equality of blood pressure and cuff pressure necessary for the volume clamp is assumed. Mechanical properties, especially the elasticity of a finger, are neglected since the volume does not change.

In this method, the volume of the finger is measure by photoplethysmography – as light absorption. Changes in the light absorption are assumed to be proportional to changes in finger volume. For measurement, an LED and phototransistor placed between finger and cuff are used [3]. Changes in volume caused by the change in finger artery blood pressure are compensated with changes in cuff pressure. At a valid set-point, blood pressure and cuff pressure equality are assumed during measurements.

The volume-clamp method is used in commercial devices: Finapres Nova (Finapres Medical Systems, Holland) and TaskForce monitor (CNSystems, Austria). The discussed method is empirical, and the method was validated with the gold standard techniques. Wesseling et al.[4] estimate the mean error of the measured blood pressure as 9-16% for the Korotkoff method and 6-7% for invasive measurements.

In this paper we verified assumption of volume-clamp method – if apply cuff pressure equal to artery pressure can maintain constant diameter of artery. We perform simulation of that condition for silicon cylinder phantom.

2. Method

As finger phantom we use silicon cylinder. With diameter of 1 cm, wall thickness of 2 mm and inner diameter of 6 mm. Height of the cylinder was 40 mm. During measurement cylinder was filed with dark blue water.

On the cylinder standard photoplethysmography finger clips was attached. IR diode, as source of light, was used during experiments. The transimpedance amplifier was used to amplifier current of photodiode. Schematic of the circuit was plot on figure 1.

On top of the phantom finger pressure cuff was attached (from Finapres Nova). To generate and measure pressure hand manometer with pomp was used. We observed relationship between changes of amplifier output voltage in function of pressure for two cases: first where pressure was applied only to the silicon cylinder and second when equal pressure was applied to cuff and inner of the cylinder.

In first case manometer and inner of the cylinder was connected, in second scenario also cuff was connected to manometer.

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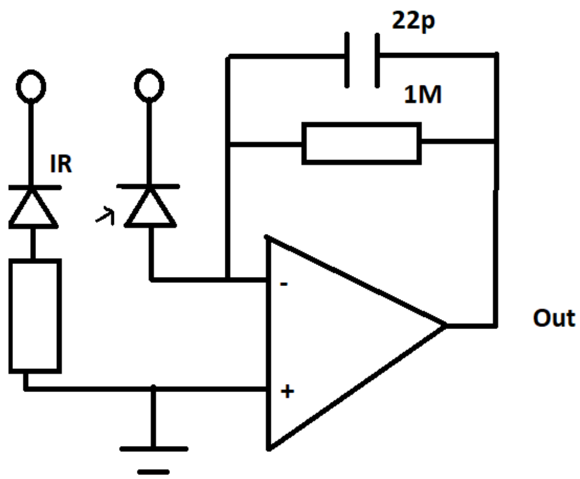

Figure 1. Electric schematic of photo-diode amplifier. IR diode from photoplethysmography sonde was used. Both diode was supply with 5V.

Figure 2. Photography of the silicon phantom with attached photoplethysmography sonde and pressure cuff. Silicon cylinder was filed with dark blue water.

3. Result

We recorded the relationship between amplifier output voltage and pressure in range from 0 to 200 mmHg, with step of 40 mmHg.

Result are summarized in table 1. Increases of voltage in each step was also calculated (ΔV). On figure 3 obtained changes in output voltages for both cases are plot.

Table 1. Changes in voltage measured on output of photodiode amplifier. Measurement are performed for two cases: when pressure was apply only to the cylinder and when equal pressure was apply to cuff and cylinder. ΔV mean changes of voltage related to previous measurement

PRESSURE [MMHG]	JUST INNER PRESSURE		INNER PRESSURE == CUFF PRESSURE	
	V[V]	ΔV[V]	V[V]	ΔV[V]
0	2,79		2,91	
40	2,75	0,03	2,96	-0,05
80	2,80	-0,04	3,01	-0,06
120	2,84	-0,04	3,08	-0,07
160	2,90	-0,07	3,09	-0,01
200	2,98	-0,07	3,04	0,05

4. Discussion

Imholz et al.[5] reviewed literature about NIBP. The authors summarize the results from 43 studies where Finapres was used. They determined method error as: for systolic pressure: -0,8 ± 11,7 mmHg, for diastolic pressure: -1,6 ± 7,7 mmHg, and mean pressure: -1,6 ± 8,5 mmHg. Wesseling et al. [4] state that the volume clamp method overestimates systolic pressure compared to Korotkoff, on average by six mmHg with a standard deviation at 20 mmHg. The method also underestimates diastolic pressure by three mmHg, and standard deviation at 11 mmHg. Wesseling et al. [4] estimate that the mean measurement error with the volume clamp method is 6-16% according to non-invasive measurements and 6-7% compared to invasive measurements. A significant standard deviation of measurement error was reported. This may indicate that the volume clamp method does not include same population variability.

We observed changes in voltage caused by applied pressure in two scenarios: first, when pressure was applied only to the inner cylinder, and second when the same pressure was applied to the inner cylinder and the cuff.

In the first scenario, for pressure greater than 40mmHg volume increases proportionally to the inner pressure increase. In second scenario when applying equal pressure to the cuff and inner of the cylinder, we measured increase in voltage for pressure below 120mmHg, stabilize in the range of 100-160mmHg, and for larger pressure, measured voltage decrees (Figure 3).

In both cases, the attenuation of light is a function of inner pressure. This observation is in contradiction to the assumption of the methods. The pressure in the cuff alters the nature of the phantom light attenuation function. To maintain the constant volume of the phantom, a different level of inner and outer pressure should be applied.

Cuff pressure does not unload the finger. Stress is a

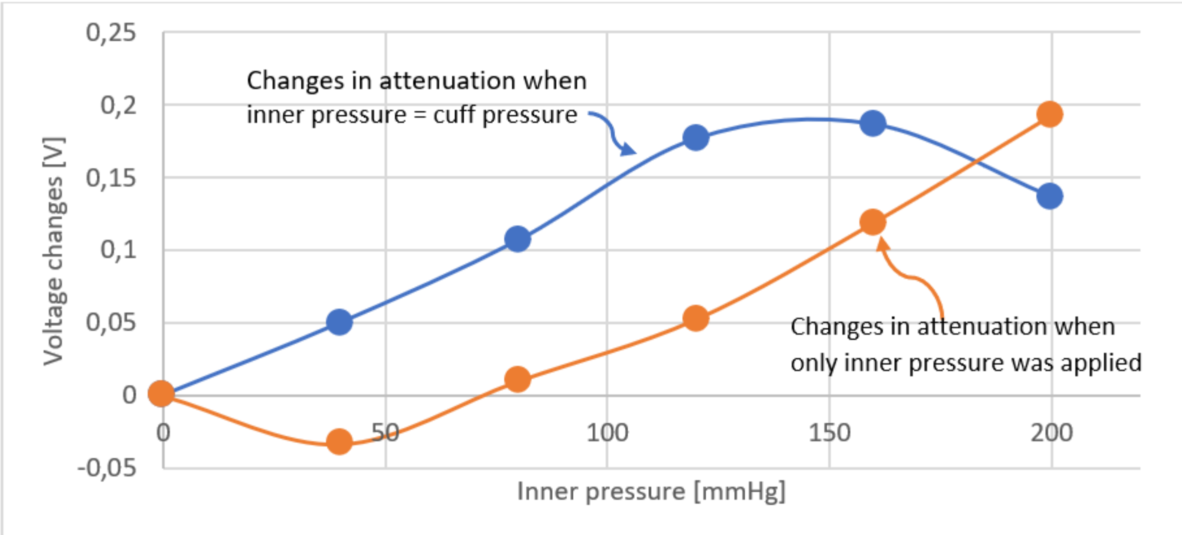

Figure 3. Plot of changes in voltage caused by applied pressure in two scenarios: first, when pressure was applied only to the inner cylinder, and second when the same pressure was applied to the inner cylinder and the cuff.

function of blood pressure during volume clamp measurements in the cylinder model. The load of the artery changes during the measurement, and it may implicate distortion of the wall – the elastic properties should be considered at least in the discussed model.

The limitations of the experiment with silicon cylinder phantom should be emphasized. The geometry used to describe the finger is a huge simplification. A finger is not a thick-walled cylinder. In reality, it is quite flattened. A finger is also not homogeneous tissue. There is a bone, muscle, skin, etc., and each element has a different Young's modulus. For example, the bone is inflexible does not change diameter as a result of the pressures applied. The phantom model is only an illustration. The results obtained cannot be directly transferred to actual conditions

Young's modulus, have a significant impact on the result of method measurements. Important here are the non-linear properties of the wall's Young's modulus affecting non-linear relation between measured and actual blood pressure.

Arteries are not static pipes, they are living tissues. They adapt to conditions: blood pressure and shear stress in the walls. An increase in blood pressure can result in remodeling. In a few days an artery's wall becomes thicker, which lowers the shear stress [6]. Arteries are built with elastic fibers (collagen) and smooth muscle, which allows fast changes in artery diameter. After exceeding a certain level of vessel stretching, muscles are activated, diameter drops, and stress is reduced in the artery wall. This phenomenon is called the Bayliss effect[7].

Dobrin and Rovick[8] study in the vitro impact of smooth muscle on the mechanical properties of the carotid artery. They found that the relation between the diameter of the vessel and transmural pressure is different for the artery after treatment with norepinephrine and after treatment with potassium cyanide. For the live artery, activation of smooth muscle decreases the elastic modulus when this was plotted as a function of pressure. For a poisoned artery, elastic properties of the artery were determined by collagen. The activation level of smooth muscle can change as a result of hypertension[9]. Activation of smooth muscle can change measurement conditions in the volume clamp method, which could result in a change in shape, amplitude, and level of systolic and diastolic pressure of recorded blood pressure curves.

Also, the temperature of the finger can affect measurements with the volume-clamp method. Tanaka and Thulesius[10] found that systolic blood pressure and finger temperature are inverse correlates. Heating reduces peripheral systolic pressure measured at the finger. Change of temperature did not affect mean or diastolic pressure. In the same case, low finger temperature and low blood perfusion may make it impossible to measure with the method[11]. Blood pressure measured on different fingers from one hand can be various[5]. During measurement with the volume clamp method, individual differences – perfusion in the fingers – can disturb measurement with the volume clamp method.

It is reasonable to look for better measurement algorithms for non-invasive cuff blood pressure measurements. It would appear useful to apply the recurrent neural network to upgrade the closed-loop algorithm in the volume-clamp method. Argha and Celler[12] use this algorithm to increase the accuracy of oscillometry technique. This approach can reduce the measurement error [13] and may be an effective technique to measure BP, which could be developed further to replace the current oscillometric-based automatic blood pressure measurement method.

The result presented in this paper may explain some blood pressure measurements with the volume-clamp method. Even when transmural pressure is 0, pressure in cuff equals artery pressure changes in artery volume can occurred. However, observations are limited to the limitation of the silicon cylinder phantom of a finger: the real finger is not homogeneous, so performance of a real finger may be significantly different from the values used in this paper.

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