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THE SOURCE OF ERRORS IN THE OSCILLOMETRIC BLOOD PRESSURE MEASUREMENTS

This report presents an analysis of the source of errors in the blood pressure measurements which use the oscillometric method. The basis of this method are the blood pressure oscillations in the occluding cuff which are used to evaluate systolic and diastolic pressures. They are found during calculations with the use of fixed constants. These numbers, having a statistical meaning, are the main source of a measuring error. The respective theoretical considerations are presented. Here they have been confirmed by the example of comparison of the measuring results obtained from two different blood pressure devices. During tests the instruments were connected together to the same occluding cuff. A statistical method was used for evaluation of the results: the coefficient of variation and the reliability coefficient.

Keywords: blood pressure measurement, pressure oscillations, measuring error.

1. INTRODUCTION

A non-invasive blood pressure measurement plays an important role in the patient's diagnosis. It gives information not only about the heart state but also about the arteries. During this measurement two pressures are defined: P_s – systolic, which corresponds with a cramp of the left heart ventricle, P_d – diastolic, which presents a de-cramp of the same ventricle.

There exist two non-invasive methods for identification of both pressures: the first – auscultatory – known as the Korotkov method (or Riva Rocci), the second – the oscillometric one. In both cases a cuff, put on the patient's upper arm, is air pumped „to stop" blood flow in the hand arteries. After that the pressure in the cuff diminishes. The appearing blood flow causes the generation of sounds or blood volume oscillations in the tested arteries, according to the heart rate.

The oscillometric method is the most popular nowadays. The blood volume oscillations cause air pressure oscillations in the cuff tightly occluding the arm. They can

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be identified automatically and for this reason a stethoscope is unnecessary. The use of this method really does not need any instructions for the user, because the measuring procedure is realized automatically: cuff pumping, air deflation from it, identification of the pressure oscillations in the cuff. Finally, the values of systolic/diastolic pressures are defined during respective calculations made by the instrument which executes a calculating algorithm. The respective values of the pressure oscillations show the pressure values in the cuff which respond to the systolic and diastolic pressures. This is an easy and quick method in use and it can be applied individually by the patient and for this reason it is willingly used by him.

Although a great number o instruments exists on the market, they are still tested by their users and the measuring results are compared (e.g. [1]). The main reason is that during blood pressure measurement the instruments can present different results. The interesting thing what the source of the readouts' discrepancies is. One should know that the basis of the oscillometric method are the numbers (unfairly called „the constants") defined during population tests of a group of healthy patients and they are of a statistical character. For this reason we can expect that they may be a substantial source of an error which considerably surpasses the others (pressure sensor's and conditioner's errors).

2. THE GENERAL STRUCTURE OF AN OSCILLOMETRIC BLOOD PRESSURE METER

This instrument is built of two main blocks (Fig. 1): the occlusive cuff and the block which identifies the pressure in the cuff in a respective moment.

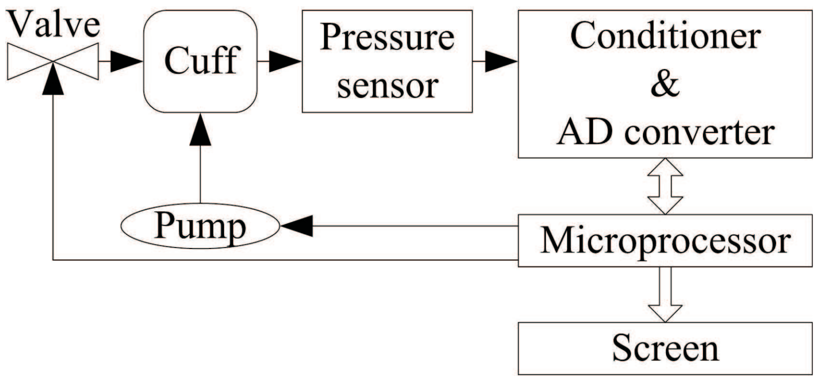

Fig. 1. Block diagram of an oscillometric blood pressure meter.

The oscillometric non-invasive pressure monitors estimate the blood pressure in the cuff that can be placed around: the upper arm, the wrist or the finger (thumb). The cuff is inflated and deflated by the user or automatically. During pulsatory blood flow the volume changes in the tested arm (or wrist or finger) transfer to the cuff which manifests in the cuff's pressure oscillations which are around a few mm Hg. The device designed for the blood pressure measurement on the wrist may be inaccurate (for the self-measurement, when the instructions saying that the wrist should be at heart level during measurement will not be strictly followed). The devices that measure the blood pressure on the finger are not recommended because the arteries vasoconstriction can introduce substantial errors [2].

The pressure signal from the sensor passes through the pass filters: the first (low pass filter) exposes the slowly changing pressure in the cuff (a large value), the second (high pass filter) catches the pressure oscillations appearing in the occluding cuff according to the flowing blood (a small value). Next both signals are sampled at a rather low frequency 100-400 Hz and AD-converted with a resolution of 10-12 bits. The microprocessor works as a control block and as a calculator, performing many tasks and in particular:

– collects and stores the cuff's pressure samples $P(t_i)$ in time t_i,
– collects and stores amplitude values of the pressure oscillations$P_o(t_i)$ in time t_i,
– finds the maximum amplitude of the oscillations$P_o(t_i) = \max = P_{o\max}$,
– calculates the respective values of these oscillations which are the basis for further findings and indirectly – the moments t_m, t_n ($P_o(t_m) = A_s\ P_{o\max}$, $P_o(t_n) = B_d\ P_{o\max}$, where A_s, B_d are respective coefficients necessary for the systolic and the diastolic pressure calculations),
– finds in the pressure samples the values of: $P(t_m) = P_s$ and $P(t_n) = P_d$.

3. TWO COEFFICIENTS USED DURING CALCULATIONS

In the oscillometric method the artery is observed during cuff's deflation and the phenomenon accompanying it. When the artery is closed and then slowly unblocked, the blood, pumped cyclically by the heart, squeezes the easier through this artery the smaller the pressure is. At this moment the blood volume oscillations appear and subsequently they are transmitted to the air oscillations in the occluding cuff. The pressure oscillations appear and they are recorded by the transducer monitoring the cuff's pressure. Right after starting cuff deflation the amplitude of these oscillations is very small. As the cuff pressure keeps lowering, the oscillations increase until a maximum amplitude is reached and then they decrease until the cuff is completely deflated and the blood flow returns to normal. The oscillations grow to a maximum and then they diminish. The cuff pressure at the moment of the maximum oscillation amplitude corresponds to the mean arterial pressure. The maximum value of the pressure oscillations is the basis for definition of both systolic and diastolic pressures. The point above the mean pressure at which the amplitude oscillations starts to increase rapidly corresponds to the systolic pressure. The point at which this variation in the oscillations decreases abruptly corresponds to the diastolic pressure (Fig. 2).

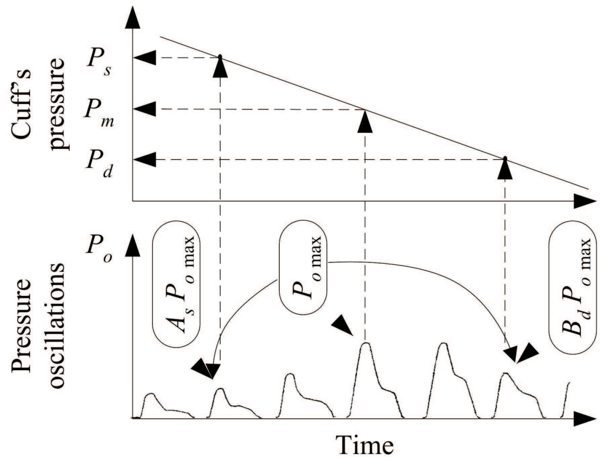

Fig. 2. The pressure oscillations being the basis for systolic P_s and diastolic P_d pressure definition, where P_o – amplitude of the pressure oscillations, A_s, B_d – coefficients. The maximum oscillation $P_{o\max}$ shows the mean arterial pressure P_m.

In the oscillometric method the systolic and diastolic pressure is determined by using a calculating algorithm in which standard values of coefficients A_s, B_d are used. The definition of these coefficients does not base either on physical or physiological grounds. They are derived empirically during tests on chosen control groups. Their values are differing, depending upon the author who proposes them (Fig. 3). Both coefficients vary in a wide range: A_s = 0.25-0.64 and B_d = 0.50-0.89. In the consequence of such big changes blood pressures are imprecisely defined and one may question which factors decide about A_s, B_d coefficient values.

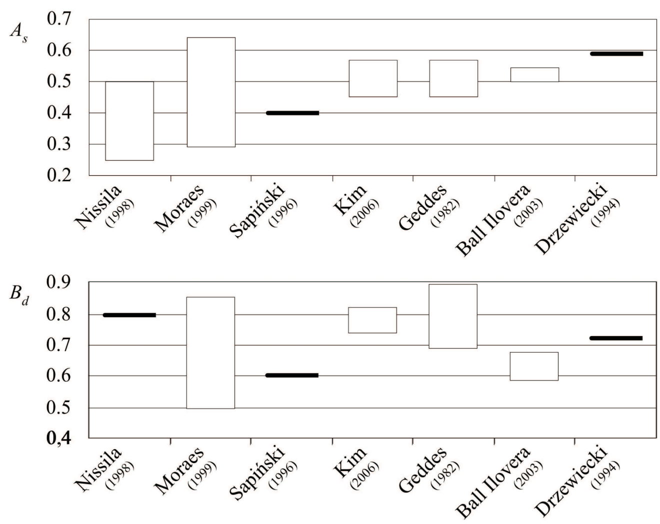

Fig. 3. Coefficients A_s, B_d used for defining systolic and diastolic pressures, the examples [3].

4. SOME FACTORS DECIDING ABOUT A_s AND B_d COEFFICIENTS' VALUES

The oscillometric method is an indirect method. In fact a dynamic object such as blood flow, pulsating in arteries, is tested. The elastic arteries are naturally surrounded by muscles and other soft tissues. During the blood pressure measurement they are tightly surrounded by the elastic rubber cuff affecting them. The pressure oscillations show the moment in which the pressure in the cuff should be measured. The amplitude of each pressure oscillation is affected by many natural factors such as the heart rate, mean intra-arterial pressure, the arterial elasticity and others.

The arterial $P-V$ relationship has a nonlinear character. The important presumption is that the cuff pressure P_c is transmitted to the arteries without attenuation. It counteracts intra-arterial pressure P_a. The resultant pressure P_{trans} is the difference:

$$P_{trans} = P_a - P_c \tag{1}$$

The pressure slowly diminishing in the cuff, unblocks the arteries and blood starts to flow, being pumped by the heart in cycles. However, each blood portion differs (comp. Fig. 2). This is the result of arteries' elasticity. Blood volume V exists there at pressure P_{trans}, according to the formula [4]:

$$V = \begin{cases} V_0 \cdot \exp\left(\dfrac{C_{\max}}{V_0} \cdot P_{trans}\right) & \text{for } P_{trans} < 0 \\ V_{\max} - (V_{\max} - V_0) \cdot \exp\left(-\dfrac{C_{\max}}{V_{\max} - V_0} \cdot P_{trans}\right) & \text{for } P_{trans} \geq 0 \end{cases} \tag{2}$$

where: V_0 – the arterial volume at $P_{trans} = 0$, $V_{\max}$ – blood volume in arteries when it is maximal extended, $C_{\max}$ – maximal arterial compliance at ($P_{trans} = 0$).

Blood pulses in arteries with V_{pulse} volume correspond with the pressure oscillations P_o in the cuff. Pressure P_c counteracts the free pulsations and the artery's compliance becomes more significant. Maximum compliance ($C_{\max}$) is for $P_{trans} = 0$, i.e. when $P_a = P_c$ (Fig. 4).

These relations can change in case of different arterial parameters: the arterial volume V_0, blood volume in arteries when they are maximally extended $V_{\max}$, and maximal arterial compliance $C_{\max}$.

Using formula (2) we can answer how big the arterial blood volume will be at every transmural pressure change, during the occluding cuff deflation with defined velocity. The heart pumps the blood cyclically. Simultaneously the cuff pressure diminishes with recommended velocity of 2-6 mm Hg/s (e.g. [5]). The results of respective simulations are presented below (Fig. 5). It means that when the same values of A_s, B_d are used for all patients, those with pathologically changed arteries will have erroneous P_s, P_d pressure readouts. An example of these considerations is presented in Fig. 6.

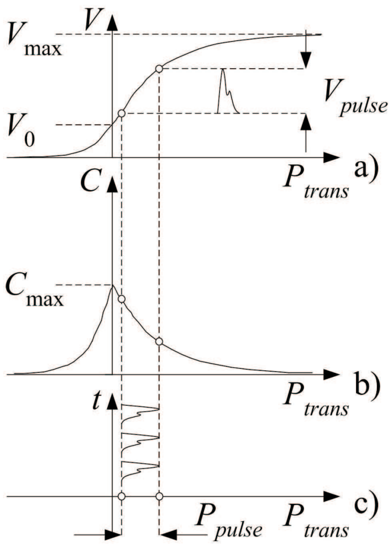

Fig. 4. a) Exponential model of arterial pressure-volume relationship, b) arterial compliance as a function of transmural pressure, c) the example of pulse signal.

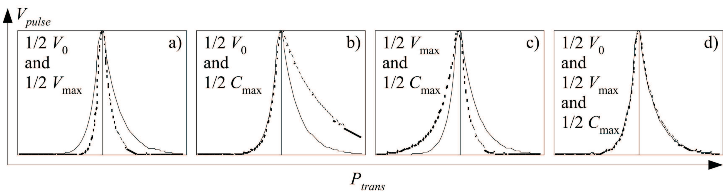

Fig. 5. The relation between V_{pulse} and P_{trans} for different parameters of the arteries: V_0, V_{max}, C_{max} (broken line). The normal state of the arteries is presented by the solid line.

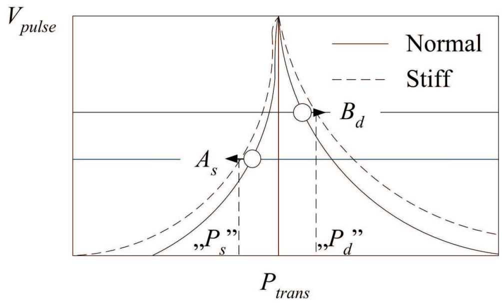

Fig. 6. The blood volume changes (the relative values) at every pressure change for two types of arteries: normal and pathologically changed (in this case more stiff). The rings show A_s, B_d values while the arrows show the tendency of the pressure readings for defected arteries. Both pressures are defined as higher „P_s” and lower „P_d”.

The cuff as an extra, auxiliary, external element affects through its compliance as well. It was tested theoretically how the object's features can influence A_s, B_d coefficient values. Table 1 presents only approximate values of the influencing factors which were calculated on the basis of the charts shown in [6]. The biggest influence in finding the systolic pressure by A_s value shows the heart rate, the arterial pulse amplitude (this influence is confirmed in [7] too), the wall viscosity and the wall stiffness. The diastolic pressure seems to be defined more reliably. These natural factors finally influence significantly even 15-20% in the computation of both pressures as the authors [6] say.

Table 1. Natural factors affecting A_s, B_d coefficients values.

Factor	Range	A_s			B_d		
		Range	*MV*	*D*, %	Range	*MV*	*D*, %
Heart rate	48-120 beats/min	0.45-0.47	0.46	2	0.60-0.76	0,68	12
Arterial pulse amplitude	20-100 mm Hg	0.45-0.69	0.57	21	0.60-0.84	0.72	17
Wall viscosity	0-0.4 N s/cm^2	0.36-0.56	0.46	22	0.73-0.76	0.74	2
Wall stiffening – Young modulus	3-18 N/cm^2	0.54-0.84	0.69	22	0.71-0.76	0.74	4
Mean arterial pressure	60-160 mm Hg	0.47-0.56	0.52	9	0.69-0.71	0.70	1
MV – mean value, *D* – dispersion							

What wide influence on the real tests can the mean arterial pressure have was shown by Moraes J.C. et. al. [8] testing a group of 85 individuals. A_s differs in range 0.29-0.64 and B_d – 0.50-0.85 (Fig. 7).

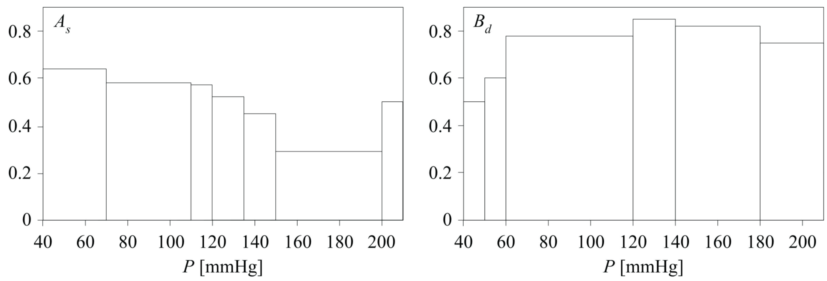

Fig. 7. Coefficients A_s and B_d, as a function of mean arterial blood pressure found during the experiments presented in [8].

In the same range of mean arterial blood pressure, as theoretically presented in [6], the patients' tests give a wider range for A_s and a little higher value for B_d. For mean arterial blood pressure 60-160 mm Hg both groups of investigators suggest:

– Ursino [6]: A_s 0.47-0.56, B_d 0.69-0.71,
– Moraes [8]: A_s 0.29-0.64, B_d 0.78-0.79.

Sapinski A., Swidzinska S., Sapinski F. [9] suggest using one A_s = 0.40 and one B_d = 0.60, if the heart rate is in the range of 60-130 beats/min. If there is bradycardia

(< 60 beats/min) A_s should be less than 0.3 and if it is tachycardia B_d should be greater than 0.50. It is better to define both coefficients individually for each patient.

Ursino M., Cristalli C. [6] have theoretically tested the changeability of cuff's compliance (which depends on many factors e.g. the elastance coefficient of the cuff external and internal wall, the collapse pressures for the cuff external and internal wall) which gives rather negligible changes of A_s and B_d.

Improper P_s, P_d identification can be the result of incorrect oscillation conformity with measured pressure value. The problem appears in searching the oscillation pulse with the calculated amplitude $P_{o\,\max}\ A_s$ (or $P_{o\,\max}\ B_d$). It can happen that an oscillation pulse with the proper value of the amplitude can even not exist. In this case P_s and P_d is only approximated.

5. A SHORT EXPERIMENT WITH THREE BLOOD PRESSURE METERS

Three blood pressure meters were tested (market sign): CT2000 (KaJaK – Poland), MF39 (Mark Fitness – Japan) and DS115 (Nissei – Japan). Their particular parameters are presented in Table 2. The standard instrument was the spring blood pressure meter CMmD (Varimex – Poland), where the Korotkov sounds were identified by one, the same person, by using a stethoscope.

Table 2. The technical parameters of used blood pressure meters.

No	Meter	Method of the blood pressure identification	Kind of pressure sensor	Readout	Remarks	Guaranteed accuracy
1.	CMmD	Korotkov sounds	Spring	Analog	Auscultatory method of sounds identification	2.5 mm Hg
2.	CT2000			Analog	Korotkov sounds identified with using a microphone, light and sound signaling	5 mm Hg
3.	MF39	Oscillometric	Semiconductor	Digital	Automatic control blood pressure oscillations	3 mm Hg
4.	DS115					

An interesting thing was if these two, using the oscillometric method, show the same blood pressure values for a group of healthy patients. 235 (41 + 194) patients were tested. Each of them had only one occluding cuff put on his arm. The cuff was connected **simultaneously** to two or three meters in such a way that each of them could control the same pressure changes. For such connection the other patients' features (e.g. arteries tiredness) do not play any substantial role. In the first part of the experiment two devices were connected: the standard CMmD and the tested CT2000. 41 readouts were taken. In the second part of the experiment three instruments were connected together: the standard CMmD and two tested MF39 and DS115. 194 readouts were registered.

Next, the statistical parameters [10] are defined (Table 3): the coefficient of variation CV and the reliability coefficient G:

$$CV = \sqrt{\frac{1}{n}\sum_{i=1}^{n} Q_i^2}. \tag{3}$$

where

$$Q_i = \sqrt{2}\,\frac{x_{ni} - x_{si}}{x_{ni} + x_{si}}. \tag{4}$$

x_n – the result obtained the from tested instrument (CT2000, MF39 and DS115), x_s – the result obtained from standard instrument (CMmD), i – the measurement number, and:

$$G = \frac{s_M^2 - \dfrac{s_{\Delta D}^2}{4}}{s_M^2 + \dfrac{s_{\Delta D}^2}{4}}. \tag{5}$$

s_M^2 – the variance calculated for the averages $((x_t + x_s)/2)$, $s_{\Delta D}^2$ – the variance calculated for the differences $(x_t - x_s)$.

Table 3. Statistical parameters for evaluation of the tested instruments in relation to CMmD meter.

Instrument	CT2000		MF39		DS115	
Pressure	P_s	P_d	P_s	P_d	P_s	P_d
CV	0.0256	0.0293	0.0432	0.0524	0.0773	0.1010
G	0.6800	0.6577	0.7025	0.5187	0.6256	0.5917

The CMmD meter chosen as the standard may be questionable. The result of this choice was the fact that this kind of blood pressure meter is still the most popular in medical practice as a standard. Calculated coefficients CV (small value) and G (big value) show that the best measuring results can be obtained from the CT2000 blood pressure meter. It defines the pressures on the basis of Korotkov sounds.

The coefficients of variation for these meters using the oscillatory method are substantially bigger for both defined pressures. The reliability coefficients are smaller for diastolic pressures and for the two devices. It is similar with diastolic pressure defined by DS115. Although the reliability coefficient is the biggest for MF39 meter and for systolic pressure, its value is comparable with this calculated for CT2000. The source of big differences (Fig. 8) for both instruments MF39 and DS115 can result from two patients' features (comp. Table 1): the heart rate (mean value more than

18%) and the arterial pulse amplitude (mean value more than 47%; the arterial pulse amplitude is the difference between P_s and P_d).

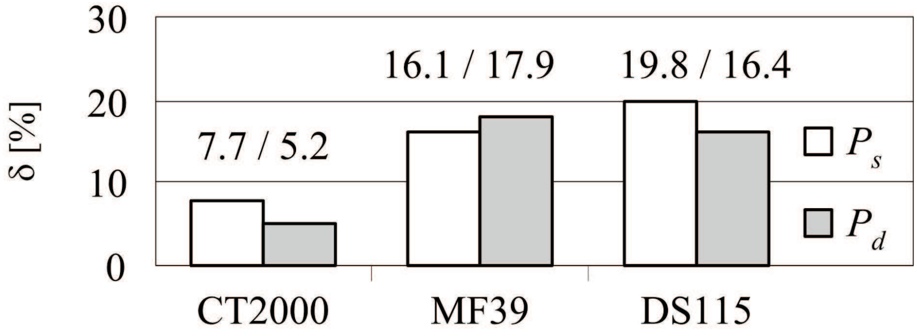

Fig. 8. The results of the comparative tests of the blood pressure meters. The values of relative differences are given above.

6. CONCLUSIONS

The oscillometric method is an indirect means of measuring blood pressure basing on the occlusion of blood vessels by a cuff. Its accuracy may be adversely affected by certain factors which have a metrological and non-metrological nature (e.g. "white coat" syndrome). All electric blocks being component parts of the blood pressure monitor decide the final instrumental accuracy: pressure transducer, amplifier (conditioner) AD converter.

However, the definitions of systolic and diastolic pressures base on a special calculating algorithm in which the standard values of A_s, B_d coefficients (for P_s and P_d pressures, respectively) are used. The definition of these coefficients has neither physical nor physiological bases. They are derived empirically during tests of chosen control group patients. These coefficients, having a statistical character, are presented in ranges A_s = 0.25-0.64, B_d = 0.50-0.89. This is the reason why in different blood pressure devices, in calculating procedures, different values of A_s, B_d can be used.

As was theoretically shown that the arteries' features can influence both these coefficient values: arterial blood volume, arterial compliance, arterial pulse amplitude, heart rate, wall viscosity and stiffening, mean arterial pressure. All these features have an individual meaning for each patient. This fact is particularly important for the patients with stiffer arteries (e.g. suffering from diabetes). The mathematical model presented by Raamat R. et al. [4] is very useful for confirmation of such considerations. It means that A_s, B_d coefficients (being even inadequate for a patient) are the main source of error in the oscillometric blood pressure measurements. The consequence of such consistence is that the blood pressure is imprecisely defined.

The way of finding the more accurate blood pressure monitor is the comparison of measurement results. The best solution is simultaneous connection of two compared meters to one occluding cuff put on the patient's arm. It gives the possibility to avoid an uncontrolled interaction the patient and the instrument. Two statistical parameters proposed by Wise R.A. et al. [10], the coefficient of variation *CV* and the reliability coefficient *G*, can be a very useful measure in this case. The smaller the *CV* value and the bigger the *G* value are the more accurate the blood pressure measurement results are. The statistical parameters used in this work can help in choosing the best device.

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