A Model-Based Retrospective Analysis of the Fixed-Ratio Oscillometric Blood Pressure Measurement

Rein Raamat, Kersti Jagomägi, Jaak Talts, and Jana Kivastik

***Abstract*—Noninvasive systolic and diastolic blood pressures (P_{syst} and P_{diast}, respectively) are often measured by applying the fixed-ratio oscillometric method, which determines blood pressures using empirically estimated fractions of the oscillometric amplitude envelope. These fractions are known as characteristic ratios (k_{syst} and k_{diast}, respectively). A review of studies over a more than 20-years time course shows a noticeable variation of characteristic ratios estimated by different researchers. We compared the literature-based data with data obtained by modeling of the fixed-ratio oscillometric measurement. The results suggest that if the between-study variation of characteristic ratios is described as a change in the difference k_{diast} - k_{syst}, then the observed variation can be explained by differences in the symmetry of the arterial wall pressure/volume relationship of the studied groups, and also by differences in cuff handling. In contrast, if a parallel shift of k_{diast} and k_{syst} up or down exists, this refers to the different pulse pressure and/or different steepness of the pressure/volume relationship of the studied groups.**

I. INTRODUCTION

Blood pressure (BP) is an important parameter which reflects the state of the cardiovascular system. Noninvasive brachial or radial BP is very often measured by automated oscillometric monitors. These devices do not need special instructions for the user, since the measuring procedure is performed automatically: cuff pumping, cuff deflation, identification of oscillations in the cuff.

The earliest description of the oscillometric method was provided by Marey in the 1870s [1]. He noticed that when the pressure in the measuring chamber was increased, oscillations reached a maximum because of vascular unloading, and then decreased. Further studies proved this finding and specified that maximum oscillations occur when the mean cuff pressure is approximately equal to the mean arterial pressure (P_{mean}) [2]. A basic criterion which has been used to estimate systolic and diastolic blood pressures (P_{syst} and P_{diast}, respectively) is the amplitude-based methodology [3]. In the amplitude-based approach the systolic and diastolic pressures are determined using empirically found fractions of the maximum oscillation amplitude [4]. These fractions are known as characteristic ratios (k_{syst} and k_{diast}, respectively).

An experimental study by Geddes *et al*. in 1982 [4] was one of the first attempts to determine P_{syst} and P_{diast} by oscillometry. According to this work, P_{syst} corresponds to the point of 50% and P_{diast} corresponds to the point of 80% of maximum amplitude of the cuff oscillations. Later research has recommended a large variety of values for k_{syst} and k_{diast} (Table 1). A short review in Table 1, covering the time period from 1982 to 2009, demonstrates that the empirically estimated k_{syst} varied from 0.40 to 0.59, k_{diast} from 0.60 to 0.80 and the difference k_{diast} - k_{syst} from 0.13 to 0.35.

Several analytical studies have demonstrated that the accuracy of the fixed-ratio oscillometric BP measurement can be influenced by a number of affecting factors capable of modifying the shape of the oscillometric amplitude envelope (OAE) [9], [10], [12], [14]–[17]. As a result, it causes changes in corresponding characteristic ratios.

In this paper we make an attempt to determine factors which could cause a variation in the empirically estimated characteristic ratios as reported by authors during a long time course. A mathematical model of the fixed-ratio oscillometric BP measurement is used for this retrospective analysis.

II. METHODS

A. Descripton of the model

We applied the simulation technique to model oscillometric BP measurement similar to that used in our earlier studies [18], [16], [19]. The simulator contained a nonlinear pressure/volume (P/V) model with arterial pressure pulses as an input signal and cuff volume oscillations as an output signal. Considering the fact that in conventional oscillometric monitors, volume oscillations are measured from the occluding cuff rather than directly from the tissue, the model was extended to involve the cuff-related parameters as well (artery-to-cuff signal transfer and cuff mechanics). The developed artery–cuff P/V model allowed us to simulate the entire signal path from the brachial artery to an oscillometric device. On the basis of simulated cuff

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oscillations, the OAEs were drawn and k_{syst} and k_{diast} calculated.

There was a possibility to modify the shape of the asymmetric arctangent P/V relationship, and the amplitude and shape of the input pressure pulse. The shape of the artery–cuff P/V relationship was modified by two indices (Fig.1):

1) steepness index ($P_{0.5}$) – a half-maximum width of the pressure/compliance curve (P/C curve), indicating the rate of decrease of the maximum compliance (C_{max}) to its half value,

2) symmetry index (k_{PV}), indicating the contribution of the negative transmural pressure (P_{transm}) to the total volume change. This index can also be expressed using the $P_{0.5}$ portions for the negative and positive transmural pressure, P_n and P_p, respectively [18].

The transmural pressure is defined as $P_{transm} = P_{intr} - P_{cuff}$, where P_{intr} denotes the intra-arterial pressure and P_{cuff} denotes the cuff pressure.

The shape of the arterial pressure pulse was described by the pulse shape index, k_{pulse}, determined as $k_{pulse} = (P_{mean} - P_{diast}) / P_{pulse}$, where P_{pulse} denotes pulse pressure, defined as $P_{pulse} = P_{syst} - P_{diast}$.

B. Choice of model parameters

It was reported in the references [16], [18] that the shape of the arterial pressure pulse has no effect on results of the oscillometric P_{syst} and P_{diast} estimation and, subsequently, on k_{syst} and k_{diast}. At the same time, the shape of the artery-cuff P/V relationship and the amplitude of the arterial pressure pulse (P_{pulse}) can considerably affect the accuracy of the P_{syst} and P_{diast} measurement. Therefore, we aimed to study how the variation of 1) the artery-cuff P/V curve steepness index, 2) the artery-cuff P/V curve symmetry index, and 3) the arterial pulse pressure could influence the characteristic ratios as reported in the literature.

The influence of each affecting factor was studied separately by varying the factor in the range of ±30% of its basal value, while the other parameters were kept constant and equal to their basal values. We regarded the following arterial condition as basal: P_{pulse} = 50 mmHg, k_{pulse} = 0.35, k_{PV} = 0.35 and $P_{0.5}$ = 40 mmHg.

TABLE I
AMPLITUDE–BASED CHARACTERISTIC RATIOS

Source	k_{syst}	k_{diast}	$k_{diast} - k_{syst}$
Geddes *et al*. (1982) [4]	0.50	0.80	0.30
Sapinski *et al*. (1986 [5]	0.40	0.60	0.20
Ramsey *et al*. (1988) [6]	0.50	0.69	0.19
Miyawaki (1988) [7]	0.50	0.75	0.25
Dinamap [8]	0.50	0.63	0.13
Drzewiecki *et al*. (1994) [9]	0.59	0.72	0.13
Ursino and Cristalli (1996) [10]	0.52	0.70	0.13
Moraes *et al*. (1999) [11]	0.56	0.76	0.20
Amoore *et al*. (2007) [12]	0.49	0.72	0.23
Zheng *et al*. (2009) [13]	0.45	0.80	0.35
min	0.40	0.60	0.13
max	0.59	0.80	0.35

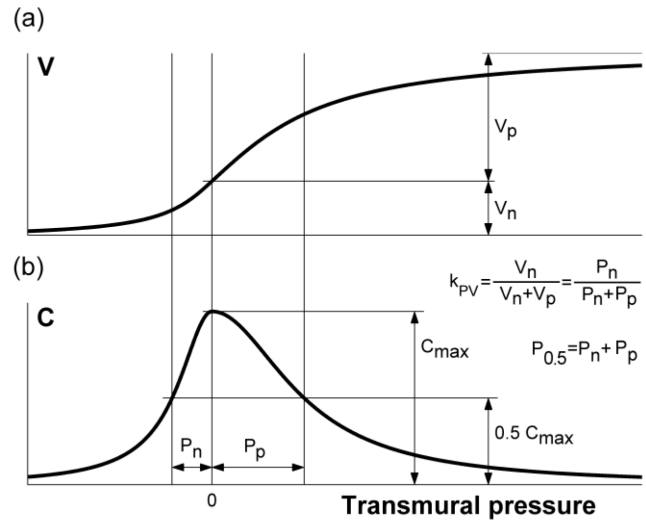

Fig. 1. Schematic diagrams of the artery–cuff pressure/volume relationship (a) and pressure/compliance relationship (b) used to model oscillometric BP measurement.

III. RESULTS

Results of modeling are presented in Fig.2–Fig.4.

Fig.2 demonstrates that both k_{diast} and k_{syst} decrease with increasing pulse pressure (P_{pulse}). At the same time the difference $k_{diast} - k_{syst}$ remains practically constant.

Fig.3 shows that k_{diast} as well as k_{syst} increase with increasing $P_{0.5}$ (i.e. with decreasing of the steepness of the P/V curve). The difference $k_{diast} - k_{syst}$ remains practically constant.

Fig.4 characterizes the behavior of k_{diast} and k_{syst} when the symmetry of the artery-cuff P/V relationship varies. As seen in the figure, k_{diast} decreases and k_{diast} increases with increasing k_{PV} (i.e. with the P/V relationship becoming more symmetrical). As a result, the difference $k_{diast} - k_{syst}$ decreases with increasing k_{PV}.

In order to better compare the results of modeling with the review data in Table 1, we presented the review data in descending sequence of the difference $k_{diast} - k_{syst}$ as shown in Fig.5.

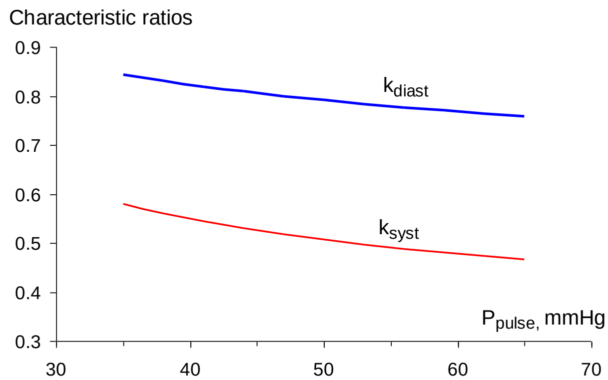

Fig. 2. Characteristic ratios as functions of the arterial pulse pressure (P_{pulse}).

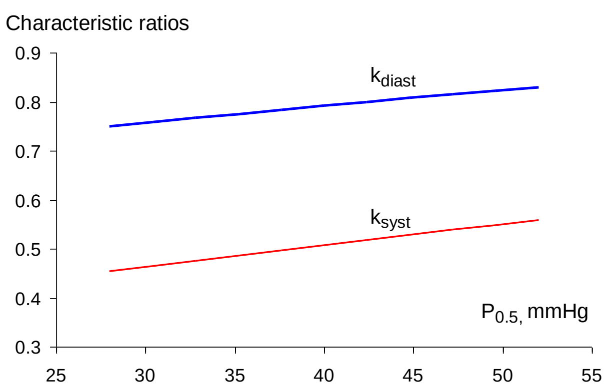

Fig. 3. Characteristic ratios as functions of the artery-cuff P/V curve steepness index ($P_{0.5}$).

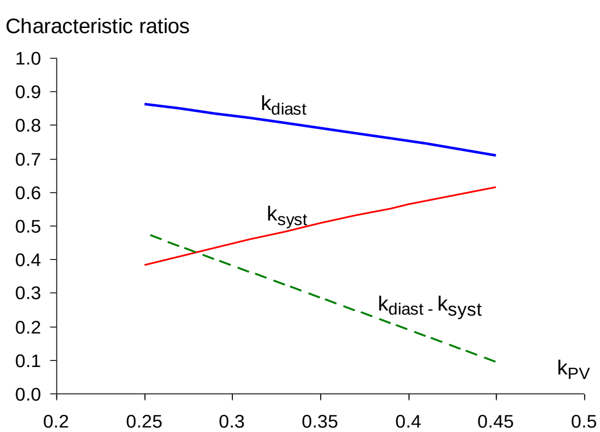

Fig. 4. Characteristic ratios as functions of the artery-cuff P/V curve symmetry index (k_{PV}).

IV. Discussion

Fig.2 and Fig.3 indicate that changes in the pulse pressure as well as in the steepness of the P/V relationship can move k_{diast} and k_{syst} up and down quite similarly, without changing the difference between them. Thus, when we compare the relatively low values of k_{syst} and k_{diast} reported by Sapinski *et al*. with corresponding data by Moraes *et al*. (Table 1), we can suggest that the values by Sapinski *et al*. were lower either because of the higher pulse pressure or because of the steeper P/V relationship (narrower P/C relationship) of the studied cohorts.

As shown above, the difference k_{diast} - k_{syst} is not influenced by factors P_{pulse} or $P_{0.5}$, remaining practically constant in the tested range of parameters. In contrast, changes in the symmetry of the P/V relationship strongly influence this difference (Fig.4). The smaller is the difference k_{diast} - k_{syst}, the closer is the P/V relationship (or the P/C relationship) to a symmetric curve. When analyzing the literature data in Fig.5, we can conclude that data on the right are associated with a more symmetric P/V curve than those on the left. For example, characteristic ratios suggested by Geddes *et al*. can refer to the symmetry index of 0.35, while those by Drzewiecki *et al*. to the index of 0.43.

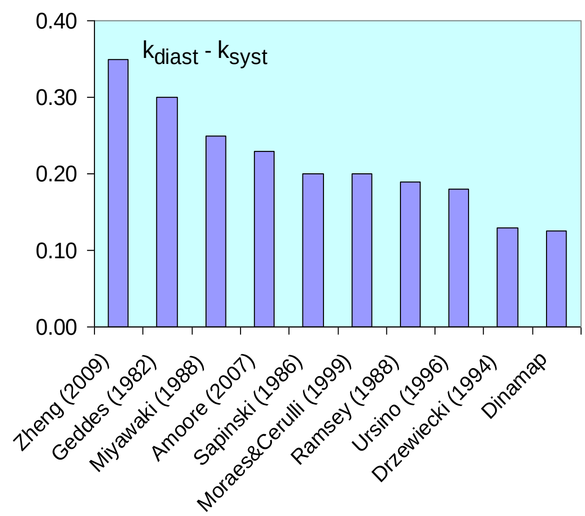

Fig. 5. The literature data presented in descending sequence of the difference k_{diast} - k_{syst}.

In more detail, the symmetry index of the artery-cuff P/V relationship (or the artery-cuff P/C relationship) describes, first of all, the symmetry of the arterial wall P/V relationship. However, as pointed out in the Methods section, k_{PV} also contains information on the cuff-related parameters. It is known that because of the nonlinear compliance of an air-filled cuff as a volume sensor, the pulsations are transferred from the cuff to an oscillometric monitor with a greater transfer factor at higher cuff pressures (i.e. at negative P_{transm}) [20]–[23]. This feature can slightly modify k_{PV}. The use of inappropriate cuff dimensions may have even a stronger effect on k_{PV}: undercuffing increases the contribution of the negative P_{transm} to the total volume change, increasing k_{PV}, while overcuffing reduces the edge effect of the occluding cuff in the region of negative P_{transm}, leading to a decrease in k_{PV} [19].

Concluding our retrospective analysis, we suggest that if the between-study variation of characteristic ratios is described as a change in the difference k_{diast} - k_{syst}, then the observed variation can mainly be explained by differences in the symmetry of the arterial wall P/V relationship of the studied groups, and also by differences in the cuff handling. In contrast, if a parallel shift of k_{diast} and k_{syst} up or down exists, this refers to the different pulse pressure and/or different steepness of the P/V relationship (narrower P/C relationship) of the studied groups.

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