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SIMPLIFIED DISTRIBUTED-PARAMETER MODEL OF BRACHIAL-RADIAL ARTERIES FOR NONINVASIVE DETERMINATION OF MECHANICAL CHARACTERISTICS OF VESSEL

A. S. Ferreira[1], J. Barbosa Filho[2], M. N. Souza[1,3], *IEEE Member*
[1]Biomedical Engineering Program, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil
[2]National Institute of Cardiology, Rio de Janeiro, Brazil
[3]Electronic Engineering Department E.E., Federal University of Rio de Janeiro, Rio de Janeiro, Brazil

Abstract—**This paper proposes a simplified distributed-parameter model of the brachial-radial arteries segment for the determination of mechanical parameters of these arteries and compares it with a four-element Windkessel model. The comparison is performed using data collected noninvasively of pressure pulse waveforms at two different locations of the arterial segment, under physiological (normotensive) and pathological (primary hypertension) conditions. The results show, by Akaike Information Criterion, that the proposed model fits the real pressure pulse waveform better than classical Windkessel model, and that also gives mechanical parameters coherent with the clinical condition.**

Keywords—**Windkessel model, transmission line, primary hypertension.**

I. INTRODUCTION

Determination of mechanical properties of arteries is of great interest in clinical cardiology [1-4]. Most of these studies are focused in the determination of the arterial compliance and/or Pulse Wave Velocity (PWV). These indices are used as prognostic ones, suggesting the existence of early signal of cardiovascular diseases, such as remodeling of blood vessels in primary Systemic Arterial Hypertension (SAH) [5-7].

To determine arterial compliance, several models have been proposed. The most used ones are the *Windkessel* (reduced) models, which has a variety of configurations, such as the three- and four-element models (Wk-3 and Wk-4, respectively) [1,3-4,6]. They were extensively used to derive total arterial compliance in health and disease, using the information of aortic blood flow and pressure acquired invasively [8]. We recently showed that the Wk-4 model has a better theoretical adjustment than Wk-3, and that it could be used to obtain segmental compliance from two pressure pulses waveforms acquired noninvasively over a peripheral artery segment (the brachial to radial arterial segment, [B-R]) [9,10]. Despite the great usage, *Windkssel* models are lumped-parameter models and do not deals with wave reflections, resulting in poor theoretical fit of the diastolic phase of the pulse wave. To overcome this fact distributed-parameter models based on Transmission Line (TL) theory are used to better deal with transmission and reflection waves [11].

The aim of the present paper is to propose a simplified distributed-parameter model of the B-R segment for the determination of arterial compliance. Such model was designed based on anatomic knowledge of the arterial segment and derives important parameters of the vessels, as its radius and compliance. Pressure waveforms acquired noninvasively from normotensive and hypertensive subjects are used to evaluate the clinical use of this approach.

II. METHODOLOGY

The well-know Wk-4 analog model contains parameters representing the vessel's resistance (*R*), inertance (*L*), capacitance (*C*) and peripheral resistance (Z_0) [4,8]. The transfer function (TF) of this model has been shown in a previous work [10] as:

$$H(s) = \frac{Z_0}{s^2(LZ_0C) + s(RZ_0C + L) + Z_0 + L}. \quad (1)$$

The B-R segment (Fig. 1) comprises the major arterial path to the hand through the forearm. The brachial artery branches right above the elbow to originate the radial and ulnar arteries. Both arteries follow the forearm bones until they reach the wrist, where they reconnect at the palmar arches. From there, many branches are derived until the capillary bed is generated. As the arterial pressure propagates through this system, the mean pressure decreases and the pressure pulse (systolic minus diastolic pressure) increase [11]. This pressure drop between the ascending aorta and the forearm is minimum, about 2-3 mmHg in supine position [15]. Therefore, these parameters can be assumed constant during the transmission over this segment.

The modeled arterial segment is assumed linear and time-invariant. From electrical analogy, we derived a distributed, three-section model (Fig. 1). The first section models the minor brachial segment, the second section represents all radial artery extension, and the last section accounts for the hand's arterial parameters (peripheral resistance and hand vessel's compliance).

The transfer function (TF) in the Laplace domain of the proposed distributed model is given by

$$H(s) = \frac{(K_1 s + K_2)(1 + K_3 s^4 + K_4 s^3 + K_5 s^2 + K_6 s)}{(K_7 s^5 + K_8 s^4 + K_9 s^3 + K_{10} s^2 + K_{11} s + K_{12})(1 + K_{13} s^2 + K_{14} s)} \quad (2)$$

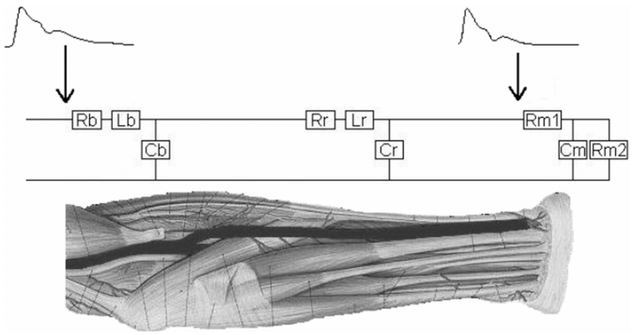

Fig. 1. Brachial-radial segment and its analog model. *Rb*, *Rr*, = brachial and radial vessel's resistances; *Lb*, *Lr* = brachial and radial vessel's inertance; *Cb*, *Cr* = brachial and radial arteries compliance; *Rm1*, *Rm2* and *Cm* = hand's Windkessel terminal.

where the terms K_1 to K_{14} are determined by the elements of the model (*Rb*, *Rr*, *Rm1*, *Rm2, Lb*, *Lr, Cb*, *Cr*, and *Cm*).

The distal pressure pulse wave can be interpreted as the output, being the proximal pressure pulse wave the input. If the proximal pulse wave is applied to the model, the model's parameters must determine the output pressure pulse wave.

With the TF in (1) and (2), and an experimental proximal pressure wave, a theoretical output wave (distal pulse wave) can be calculated from the multiplication of the Fourier transform of this proximal wave and *H(s)*. Applying the inverse Fourier transform to this product, the theoretical output wave can be compared with its experimental counterpart and, through an optimization algorithm, the model's parameters can be obtained. The first 10 harmonics were used to compute the FFT and IFFT, since after the 10th harmonic the residual energy of the signal can be neglected [11].

The implemented optimization algorithm was based on a steepest descend gradient method, being the initial guest values for the model's parameters:

$$Rb = \frac{8 \cdot \eta \cdot S_b}{\pi \cdot r_b^4},\ Rr = \frac{8 \cdot \eta \cdot S_r}{\pi \cdot r_r^4},\ \left(\frac{dyn \cdot s}{cm^5}\right), \quad (3)$$

$$Lb = c_u \frac{\rho \cdot S_b}{\pi \cdot r_b^2},\ Lr = c_u \frac{\rho \cdot S_r}{\pi \cdot r_r^2},\ \left(\frac{g}{cm^4}\right), \quad (4)$$

$$Cb = \frac{\pi \cdot r_b \cdot \Delta D_b \cdot S_b}{PP},\ Cr = \frac{\pi \cdot r_r \cdot \Delta D_r \cdot S_r}{PP},\ \left(\frac{cm^5}{dyn}\right), \quad (5)$$

$$Rm1 = 1.06e^4 dyn \cdot s / cm^5 \quad (6)$$

$$Rm2 = 4.22e^4 dyn \cdot s / cm^5, \quad (7)$$

$$Cm = 3.5e^{-6} cm^5 / dyn, \quad (8)$$

where η is the blood viscosity (0.035 dyn.s/cm^2 [12,13]), ρ is the blood density (1.056 g/cm^3 [11]), *PP* is the difference between systolic and diastolic pressures (dyn/cm^2), and c_u is a constant that accounts for the parabolic profile of the blood flow at the radial artery (4/3 [8]). The brachial and radial segments length, internal radius, and diameter change are represented by S_b, S_r, r_b, r_r, ΔD_b, ΔD_r, respectively.

Using the proposed model, the estimation of the parameters was performed for two groups of subjects. Because models with different number of parameters can not be compared directly, we used the Akaike Information Criterion (*AIC*) [8] to perform the comparison between the present model and the Wk-4 one. Such index is calculated as

$$AIC = N \cdot \ln\left(\sum_{i=1}^{N} \left(P_{Pi} - P_{mi}\right)^2\right) + 2P \quad (7)$$

where P_p and P_m are the predicted and measured pressure waveforms, *P* is the number of parameters, *N* the number of samples and *i* the index of the samples.

Values in tables are shown in the form mean ± standard deviation. The parameters values between groups were compared using independent samples Student's t-test (SPSS 10.0®). The significance level considered was p<0.05.

A. Subjects

Proximal and distal pressure waveforms were obtained in the B-R segment of two groups of volunteers: the control group (CG) and the systemic arterial hypertension group (SAHG). We chose the B-R segment because the pathologic alterations caused by SAH are diffuse, and it is one of the most superficial and linear arterial segment of the human body [11].

The experiments were performed in the Hypertension Division of the National Institute of Cardiology (RJ, Brazil), being the volunteers previously informed to the aim of the experiment and had given their written agreement. The CG was represented by 14 subjects (7 men) and the SAHG was compounded by 11 subjects (7 men). The values of age, systolic and diastolic blood pressures, and heart rate are summarized in Table I.

The inclusion criteria in the CG were normal ECG, arterial pressure lower than 130/80 mmHg and no risk factors for cardiovascular disease.

During the acquisition of the pressure pulse waveforms the subjects were in supine position, with the arms beside the thorax, being a rest time of 5.0 min always observed before the acquisition.

TABLE I
CLINICAL PARAMETERS OF THE CG AND SAHG

	CG	**SAHG**
Age (years)	33.8 ± 10.7	41.0 ± 8.3
SBP (mmHg)*	118.1 ± 9.3	179.6 ± 28.7
DBP (mmHg)*	70.6 ± 8.4	107.7 ± 19.8
HR (b/m)	68.9 ± 10.0	75.9 ± 11.4

*p<0.05

Proximal site to the acquisition was in the anterior region of the elbow over the brachial artery and the distal site in the anterior region of the wrist over the radial artery.

B. Data Acquisition

We have developed a system to acquire arterial pulses noninvasively and analyze these signals off-line. It has been validated in a previous work for two groups of volunteers [9]. Briefly, the system calculates PWV and determines arterial parameters of the Wk-3/Wk-4. The PWV and model's results are in accordance to the literature [5,7].

The acquisition of the pressure pulses waveforms was performed with piezoelectric transducers (HP 21050-A, bandwidth 0.01 Hz to 2 kHz) connected to preamplifiers specially developed for this study. The two pressure pulse waveforms signals were recorded with a resolution of 12 bits using an acquisition board, model AT-MIO 16 (National Instruments). The signals were acquired at a sample frequency of 1 kHz/channel to increase time resolution.

III. RESULTS

Representative pairs of experimental proximal-distal pressure waveforms of CG and SAHG is shown in Fig. 2.

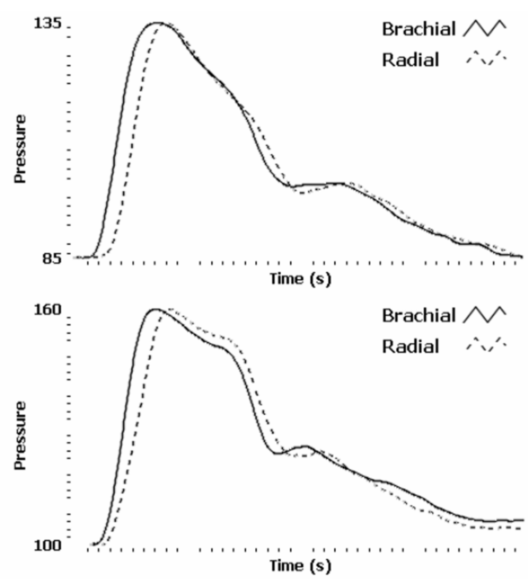

Fig. 2. Pairs of proximal (continuous line) and distal (dashed line) experimental pressure pulses of CG (top) and SAHG (bottom).

Table II shows the values of the radial artery parameters determined with the model for the two groups. Although compliance was not statistically different between groups, the estimated radius exhibited statistically significant difference ($p<0.05$).

The AIC for the two groups are represented as box-plots in Fig. 3 for comparison. The smaller the AIC, the better is the theoretical fit.

TABLE II
DETERMINED SEGMENTAL ARTERIAL PARAMETERS FROM THE RADIAL ARTERY FOR THE CG AND SAHG

	CG	**SAHG**
Radius (cm)*	0.2030±0.0243	0.1661±0.0404
Diameter change (cm)	0.0095±0.0023	0.0172±0.0188
Compliance (10^{-6} cm^5/dyn)	2.12±0.61	1.14±0.84
PWV (cm/s)*	830±210	1290±540

*$p<0.05$

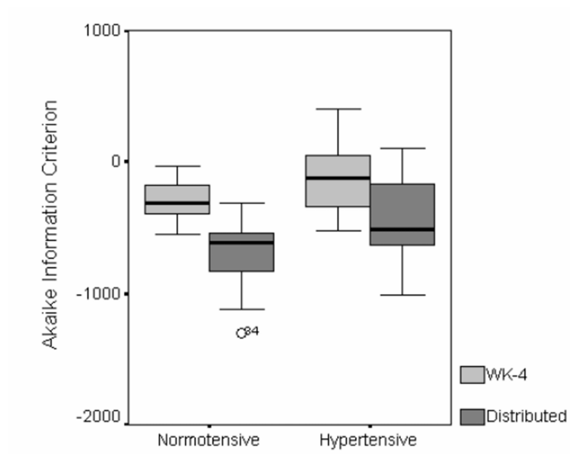

Fig. 3. Box-plot showing the Akaike Information Criterion for both Wk-4 and distributed models.

The AIC obtained showed that for both groups, the proposed model predicts the complete radial pressure pulse better than the Wk-4 does for the wavefront.

IV. DISCUSSION

Table II shows that the model's parameters can separate healthy subjects from those with clinical signs of hypertension-induced arterial adaptations, yielding statistically significant ($p<0.05$) reduced values for the radial artery radius. However, the compliance was not statistically different. This is in accordance to the literature [16] that showed normal or elevated arterial compliance of radial artery on hypertensive subjects.

Figure 3 shows the AIC for both models and groups. It can be seen that the distributed model fits a theoretical waveform better than Wk-4 model. Also, our method estimates geometrical parameters to fit hemodinamical aspects. This estimation gives more information about mechanics of the radial artery in hypertensive subjects, providing information about the remodeling process.

The pressure-induced arterial remodeling is a process that can occur in several ways. The most frequent is the reduced internal diameter (or radius), with respective increase in wall mass that can result in a normal or even elevated segmental compliance [16]. This is an important adaptation mechanism of muscular arteries, which accounts for the elevated pressure pulse that travels to the capillary bed and tries to reduce the high amplitude generated by the heart. The distributed model has the advantage, over the Wk-4, of providing such information.

V. CONCLUSION

This work presented a simplified distributed-parameter model of the brachial-radial arterial segment. This model yields parameters coherent with the clinical condition of individuals with SAH. Also, it has a better theoretical waveform than Wk-4, giving more reliable parameters.

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