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Two-point Method for Arterial Local Pulse Wave Velocity Measurement by Means of Ultrasonic RF Signal Processing

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The aim of this paper is to describe a non-invasive method of examination of the local pulse wave velocity. The measurements were carried out in the model of the artery immersed in a water tank. Two synchronized ultrasonic apparatus VED with the ultrasonic radio frequency echoes acquisition system were used for evaluation of the arterial elasticity. The zero-crossing method was used for determination of the diameter changes of the artery model. The transit time between the waveforms of instant artery diameter was measured at two points of the artery model, separated by the distance of 5 cm. The transit time was determined using the criteria of similarity of the first derivatives of the raising slopes of the curves describing instant vessel's diameter changes. The pulse wave velocity obtained by the proposed two-point method was compared with the results obtained by the one-point method based on the modified Bramwell–Hill relation.

Keywords: ultrasound, local pulse wave velocity, model of artery.

1. Introduction

The most frequently used methods of measuring the elasticity of vessels are the methods based on the changes of the artery diameter, resulting from the blood pressure variations (Powałowski, Trawiński, 1994). The functional dependence between the artery cross-section S and the pressure P inside the artery can be defined as follows (Filipczyński *et al.*, 1988):

$$S = (1/g)\ln(P/P_o) \quad [\mathrm{m}^2], \tag{1}$$

where g – constant coefficient, P_o – reference pressure ($P > P_o > 0$).

Assuming, as the starting point, the dependence described by Eq. (1), we can determine coefficients g and P_o on the basis of the values of the artery cross-section S, measured in two characteristic points S_s and S_d. S_s and S_d correspond to the artery cross-sections determined respectively at the systolic P_s and diastolic P_d blood pressure.

After inserting the values g and P_o into the formula (1), the following expression is obtained:

$$S(P) = S_d \left[1 + \frac{S_s - S_d}{S_d \ln(P_s/P_d)} \ln\left(\frac{P}{P_d}\right)\right] \quad [\mathrm{m}^2]. \tag{2}$$

Assuming that the shape of the arterial cross-section is circular, the $S(P)$ can be replaced by the dependence $\pi D^2(P)/4$, where D is a diameter of an artery and expression (2) can be transformed to

$$D^2(P) = D_d^2 \left[1 + \frac{1}{\alpha} \ln \frac{P}{P_d}\right] \quad [\mathrm{m}^2], \tag{3}$$

where

$$\alpha = \frac{D_d^2}{D_s^2 - D_d^2} \ln\left(\frac{P_s}{P_d}\right), \tag{4}$$

D_s and D_d are the artery diameter for the systolic P_s and diastolic P_d blood pressure respectively.

The coefficient α was named the logarithmic coefficient of the artery wall stiffness (Filipczyński *et al.*, 1988). For the examinations of α coefficient, the ultrasonic apparatus VED, developed by the author, was used.

The VED consists of the pulse wall tracking system, which follows the movements of the artery walls with the accuracy of $7 \cdot 10^{-6}$ m. A lot of examination of healthy people of different age, and patients suffering from the atherosclerosis (Powałowski, Trawiński, 1994; Trawiński, 2000), were carried out using the VED system. The usefulness of this apparatus for the classification of the examined people for the atherosclerosis high-risk group was presented in the author's doctoral thesis (Trawiński, 2000).

For people suffering from the atherosclerosis of the common carotid arteries (CCA), the big variation of the coefficient α has been observed. Development of the illness process in the artery wall may occur with a different intensity. It makes difficult to establish a uniform criterion for assigning of the patients to the healthy or ill groups.

As a criterion for the prediction of the atherosclerotic changes occurring in the artery wall, the assumed value of the critical stiffness coefficient $\alpha = \alpha_{\mathrm{cr}}$ is defined in the following way:

$$\alpha_{\mathrm{cr}}(x) = \alpha_r(x) + SD, \tag{5}$$

where x is the age of the examined person, SD is the standard deviation of $\alpha(x)$, and $\alpha_r(x)$ is the linear regression function of the coefficient $\alpha(x)$, calculated for the healthy people, and is given (Trawiński, 2000) by the formula

$$\alpha_r(x) = 0.0589x + 0.723. \tag{6}$$

The value of the standard deviation SD is equal to 20% of the average value of the $\alpha(x)$. Inserting the value of the standard deviation SD and the regression function $\alpha_r(x)$ into Eq. (5), we receive:

$$\alpha_{\rm cr}(x) = 1.2(0.0589x + 0.723). \tag{7}$$

The age dependence of the stiffness coefficient α measured using VED, for the people without and with arthrosclerosis in the common carotid arteries, that was diagnosed by ultrasonic examination (USG), is presented in Fig. 1. Also the $\alpha_{\rm cr}(x)$ curve, used for the prediction of atherosclerotic changes, is shown. In this study people with and without the risk factor for atherosclerosis were included. The factors like the age, body mass index, arterial hypertension, hyperlipidemia, smoking and diabetic mellitus, are recognized as the risk factors for atherosclerosis.

a) b)

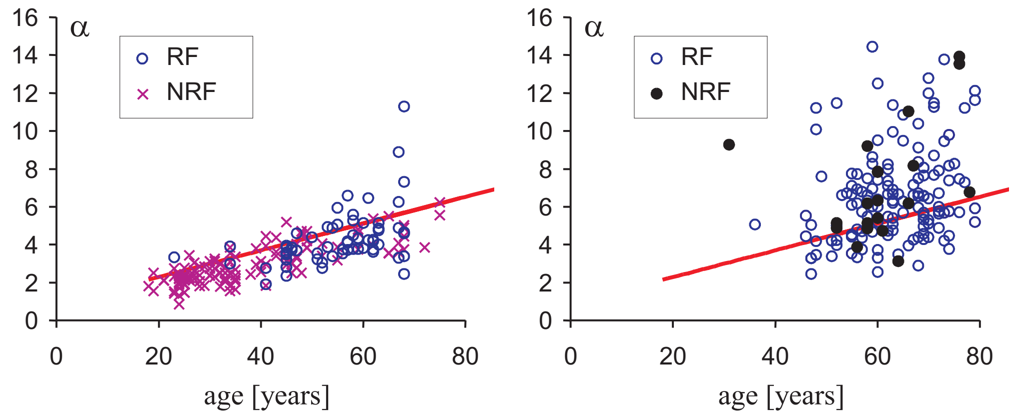

Fig. 1. The coefficient α measured in the CCA, determined for persons without the symptomatic atherosclerosis (a) and for patients with the atherosclerosis in carotid arteries (b). NRF – people without risks factors for atherosclerosis, RF – people with risk factors for atherosclerosis.

The results presented in Fig. 1 indicate that the stiffness coefficient α of an artery wall increases with age – that means that the elasticity of the arterial wall decreases with age. The solid line in Fig. 1 ($\alpha_{\rm cr}(x)$) represents the critical level of the stiffness coefficient. Above this level the value of the coefficient α could be used as an indicator of the risk of arthrosclerosis. The validation of the proposed criteria based on $\alpha_{\rm cr}(x)$ (7), in comparison with the results of USG diagnosis of atherosclerosis, is presented in Table 1.

The assessment showed that in the group of people with atherosclerosis the true positive result was obtained in 66%, while in the group of healthy people the true negative result was obtained in 79%, in relation to the USG diagnosis of atherosclerosis.

Table 1. Assessment of the selection of people on the account of the risk of atherosclerosis, based on measurement of the stiffness coefficient α in the common carotid artery (CCA), in relation to the results of USG examinations of people at the age of x years.

USG diagnosis	α(x)$>\alpha_{\mathrm{cr}}(x)$	α(x)$\leq\alpha_{\mathrm{cr}}(x)$
Atherosclerosis in the CCA 160 arteries	106 arteries	54 arteries
Lack of atherosclerosis in the CCA 192 arteries	40 arteries	152 arteries

The results obtained indicate that the method of selecting people on account of the risk for arthrosclerosis on the basis of the elasticity of carotid artery walls, has a higher sensitivity and is more specific than the usually applied selection based on the risk factors for atherosclerosis (Bots *et al.*, 2002).

This paper presents possibility of calculation of the coefficient α by measurements of the pulse wave velocity (PWV). The pulse wave is a phenomenon of propagation of the blood pulse pressure from the heart to the peripheral arteries in the body. The PWV depends on the blood density and diameter of the artery. The PWV is a very important indicator of the elasticity of the artery. Increase of the PWV informs about the decrease of the arterial wall elasticity.

Different methods of measurement of the local PWV were described by the author in the previous papers (Powałowski, Trawiński, 1994; 2004). They were based on the ultrasonic measurement of the blood velocity, with the use of the two-point and one-point Doppler method. Also, the PWV was measured in 2004 by Meinders and Hoeks, where the pulse wave in the artery was determined using the correlation analysis of ultrasonic RF signals reflected from arterial walls. But authors didn't take into account the effect of pulse wave reflections. In the present paper for the analysis of the RF signals, instead of the correlation method, the zero-crossing method was applied.

2. Methodology

The most well-known dependence describing the PWV is the formula introduced by Korteweg and Moens:

$$PWV = \sqrt{\frac{Eh}{2\rho R}} \quad [\mathrm{m/s}], \tag{8}$$

where ρ – density of blood, E – Young's modulus of an artery wall, h – vessel wall thickness, R – internal artery radius at minimal blood pressure.

In 1922 Bramwell and Hill (Bots *et al.*, 2002) proposed the one-point method for determination of the PWV based on the formula presented below:

$$PWV = \sqrt{\frac{S_d(P_s - P_d)}{\rho(S_s - S_d)}} \quad [\mathrm{m/s}]. \tag{9}$$

Assuming that the artery cross-section is circular, the formula (9) can be expressed as

$$PWV = \sqrt{\frac{D_d^2(P_s - P_d)}{\rho(D_s^2 - D_d^2)}} \quad \text{[m/s]}. \tag{10}$$

Transforming (10)

$$\frac{D_d^2}{D_s^2 - D_d^2} = \frac{PWV^2\rho}{P_s - P_d} \tag{11}$$

and inserting (11) into the formula (4), the coefficient α can be calculated:

$$\alpha = \frac{PWV^2\rho}{P_s - P_d} \ln\left(\frac{P_s}{P_d}\right). \tag{12}$$

Formula (12) shows that the α coefficient can be calculated on the basis of the PWV, the blood density ρ and the systolic P_s and diastolic P_d blood pressure.

The new two-point method of measurement of the local pulse wave velocity c is presented in this work. The PVW determined with a two-point method was labeled with c to distinguish it from the PVW measured with other techniques. For the determination of c, the instant diameter of the elastic model of the artery was measured. The two-point method applied for evaluation of c was based on the measurement of the transit time (TT) of the pulse wave, traveling the distance of 5 cm (L) along the modeled artery. In the medical practice, the measurement of c can be disturbed by the reflections from the arterial tree. To avoid these interferences, the transit time was measured using the initial part of rising slope of the pulse wave, where influence of the reflected waves could be neglected. The method applied for the measurement of TT was described in the author's previous paper (Powałowski, Trawiński, 2004; Powałowski *et al.*, 2005). It is based on the criteria of similarity of the first derivatives of the rising slopes of the pulse wave. The velocity c can be determined using the formula:

$$c = \frac{L}{TT} \quad \text{[m/s]}. \tag{13}$$

Another very important parameter, describing arterial condition, is the modulus of elasticity. The newest trends for USG applications concern the arterial elastography. Most of them present only the strain of the vessel walls, but more indicative parameter from diagnostic point of view is the Young's modulus E of the artery wall. It is very difficult to measure the Young's modulus of an human artery in the non-invasive way in the clinical conditions. The main problem concerns a non-invasive measurement of the thickness h of the arterial wall.

To demonstrate the possibility of the presented methods and the equipment for elastography examinations of arterial walls, the Young's modulus was calculated using two approaches. Applying of VED apparatus enabled to determine h – vessel wall thickness and R – internal artery radius, when blood pressure is minimal, and using the formula (8) the Young's modulus E was calculating.

The Young's modulus E also was evaluated experimentally, directly from the strain-stress relation.

3. Experimental setup

The measuring setup consisted of the bottom (R1) and the overflow (R2) tank, both made of polyethylene, and the rotor water pump (Fig. 2). The level of distilled water in the overflow tank was constant. Water from the overflow tank flowed due to gravity through the silicone pipe (diameter = 13 mm) into the computer-controlled piston pump, and through artificial cardiac valves – to the silicon arterial model placed in the aquarium filled with distilled water. The level of water in the aquarium was 3 cm above the level of the model. The rhythm of the pump was simulating the conditions in the left ventricle of the human heart (pulse frequency equaled 1 Hz).

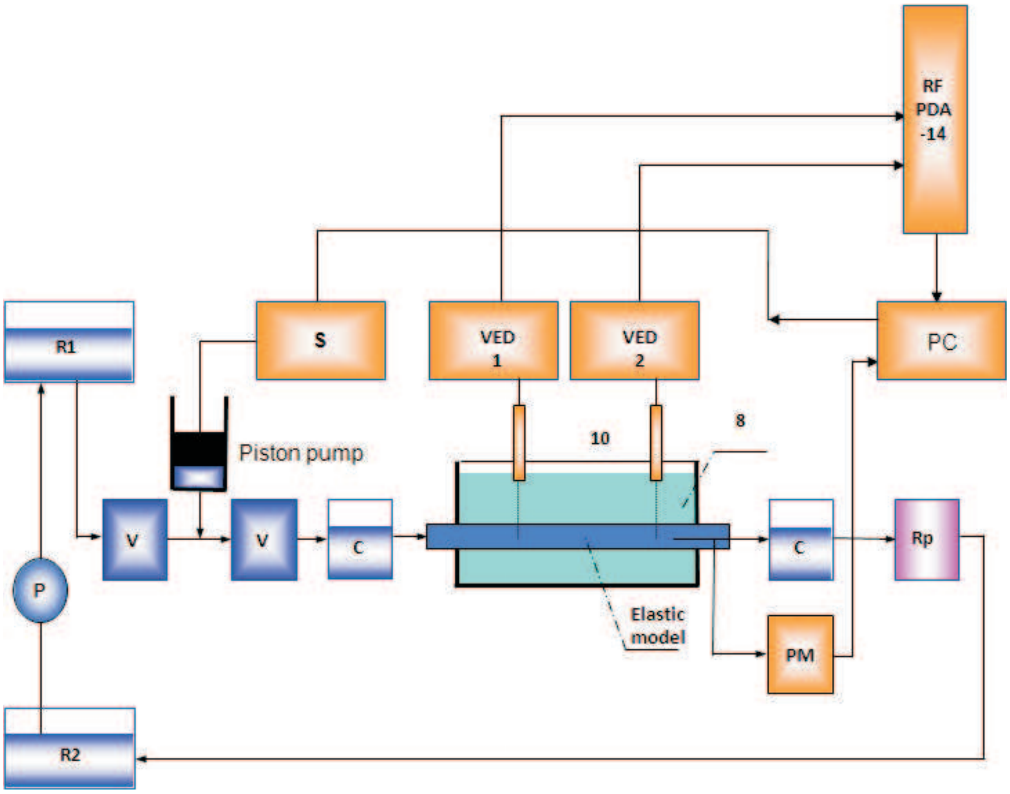

Fig. 2. Diagram of experimental setup: R1 – upper overflow tank, R2 – bottom tank, piston pump – SPA3891 Vivitro Co., P – rotor pump, V – artificial cardiac valve, C – windkessel model, Rp – hydraulic resistor, Elastic model – silicone model of the artery, VED1 and VED2 ultrasonic apparatus, 8 – aquarium, 10 – ultrasonic measuring heads, PM – pressure gauge with catheter, S – computer driver for the piston pump, RF PDA-14 – two-channel RF Signatec PC card for the acquisition of RF signals, PC – IBM-PC.

The diagram of the experimental setup used for measurement of the local PWV in the elastic model of the artery, by means of the two-point method, is presented in Fig. 2.

The measurements of the local PWV (c) were performed using two ultrasonic VED apparatus. The ultrasonic pulses were transmitted with the frequency of 6.75 MHz and with the repetition frequency of 9 kHz. The acquisition of the ultrasonic RF signal was performed with 14 bit precision and with the sampling frequency equal to 62.5 MHz, simultaneously in the two channels, by means of the Signatec PC card.

The artery was modeled with the silicon pipe of the internal diameter of 7.5 mm, the wall thickness equal to 1.25 mm and the length equal to 96 cm and 100 cm, respectively, before and after initial stretching up.

4. Results

Figure 3 presents the variation of the modeled artery diameter (normalized), measured in two points D1 and D2 separated by the distance of 5 cm. The time variation of the diameter describes the pulse wave.

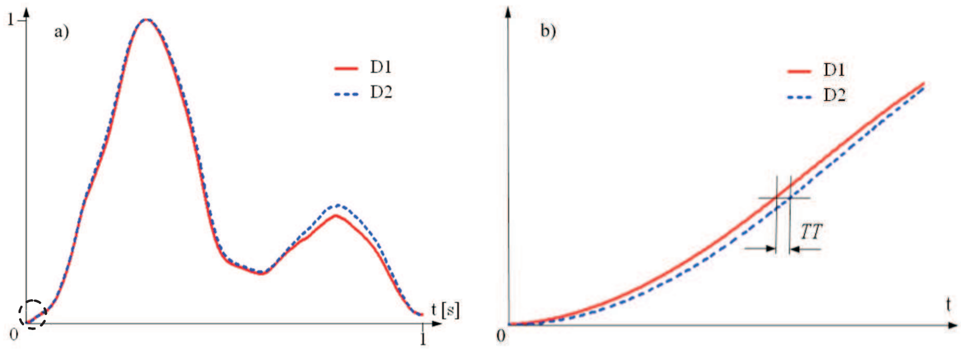

Fig. 3. a) Normalized pulse waves (the internal diameter D1 and D2 of the pipe) measured at two points of the model of the artery, b) zoom of region z marked by dashed circle in a), where the transit time of the pulse wave TT was determined.

Using the same model of artery and the same experimental conditions (D_s, D_d and P_s and P_d), the PVW was determined by means of the one-point method, in accordance with the Bramwell–Hill dependence (9). The measurement results of the c and PWV, averaged over 30 measurements, are presented in Table 2.

Table 2. PWV determined by one-point and two-point methods.

One-point method PWV [m/s]	Two-point method c [m/s]
28.1 ± 0.12	32.4 ± 0.13

The Young's modulus of the material from which the examined elastic model of the artery had been made, was calculated using the formula (8) and it was equaled to $E = 5.03$ Pa.

The Young's modulus was evaluated basing on the stress-strain relation determined experimentally at the deformation of 15% and it was equaled to $E =$ 4.97 MPa.

5. Conclusions

This paper presents the new method of non-invasive measurement of the arterial local Pulse Wave Velocity.

Also the new approach of determination of the logarithmic coefficient of the artery wall stiffness α, on the basis of the PWV, was presented.

The main advantage of the proposed two-point method applied for the arterial local pulse wave velocity measurement is avoidance of the blood pressure determination and the errors arising from this measurement, what usually leads to a large additional error at a level of $\pm 10\%$.

The application of the zero-crossing method for determination of the pulse wave, in comparison with the usually applied correlation method, enables to avoid the errors arising from the ambiguity of constant integrals, which can cause ambiguous trends (the bias) (Rabben *et al.*, 2002).

The PWV was measured using the criteria of similarity of blood velocity gradients of the initial parts of rising slopes of the pulse wave, what eliminated the influence of the reflection from the arterial tree.

For both the c and the PWV, the coefficient of variation (standard deviation/mean) was 0.4%. It means that measurement repeatability was very good.

The values of the local pulse wave velocity$c$ and the PWV differed by 13%. It could be considered an acceptable error in comparison with the results of the clinical research published by various authors.

The difference between the values of Young's modulus measured from strain-stress relation and that calculated from Korteweg and Moens Eq. (8) is 1.2%. This fact shows that the ultrasonic non-invasive technique for determination of the Young's modulus of the arterial wall could be possible.

The method of examination of the local pulse velocity presented in this paper was carried out on the model of the artery. Further clinical verification on a large group of persons is necessary to assess the usefulness of the presented method for the in vivo diagnosis.

Acknowledgments

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