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A NONINVASIVE ULTRASONIC METHOD FOR VASCULAR INPUT IMPEDANCE DETERMINATION APPLIED IN DIAGNOSIS OF THE CAROTID ARTERIES

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In this study, a new method is presented for diagnosis of the extracranial carotid arteries, based on analysis of the vascular input impedance noninvasively determined in human common carotid arteries. The input impedance calculations were based on simultaneous measurements of the blood pressure and the blood flow using the ultrasonic Doppler and echo methods. In the analysis of the vascular input impedance a four-element model was applied, whose elements represented the vessel resistance (R_0), the peripheral resistance (R_p), the vessel compliance (C) and the inertance (L). The values of these elements were determined by computer simulation of the vascular input impedance using the input impedance of the model. The index of the optimum impedance simulation was the degree of agreement between the blood flow measured in the common carotid artery and the blood flow calculated from the input impedance of the model and the blood pressure. Preliminary clinical investigations were performed in 43 healthy persons and 9 sick patients. The obtained results indicate that the ratio between the vessel resistance (R_0) and the peripheral resistance (R_p) as determined by the proposed measurement method and analysis of the vascular input impedance can be an indicator in identification of stenosis and occlusions of the extracranial carotid arteries. The method described in the study permits identification of stenosis of the internal carotid arteries of $\geqslant 30\%$. The degree of the patency of the carotid arteries in sick persons was determined from X-ray arteriographic examinations, which were confirmed by surgical operations in 8 cases.

Key words: vascular input impedance, carotid arteries, ultrasound.

W pracy przedstawiono nową metodę diagnostyki tętnic szyjnych pozaczaszkowych na podstawie analizy wejściowej impedancji naczyniowej, wyznaczanej nieinwazyjnie, w tętnicach szyjnych wspólnych człowieka. Podstawą do obliczeń wejściowej impedancji był równoczesny pomiar ciśnienia i prędkości objętościowej krwi trzy użyciu ultradźwiękowej metody dopplerowskiej i metody echa. Do analizy wejściowej impedancji naczyniowej zastosowany został model czteroelementowy, którego elementy reprezentują opór naczyniowy (R_0), opór peryferyjny (R_p), podatność (C) i inertancję (L). Wartości tych elementów wyznaczane były na drodze symulacji komputerowej wejściowej impedancji naczyniowej za pomocą impedancji wejściowej modelu. Wskaźnikiem optymalnej symulacji był stopień zgodności pomiędzy prędkością objętościową krwi zmierzoną w tętnicy szyjnej wspólnej a prędkością krwi obliczoną na podstawie wejściowej impedancji modelu i ciśnienia krwi.

Wstępne badania kliniczne przeprowadzono u 43 osób zdrowych i 9 chorych. Uzyskane wyniki wskazują, że wyznaczony na podstawie proponowanej metody pomiaru i analizy wejściowej impedancji naczyniowej stosunek oporu naczyniowego (R_0) do peryferyjnego (R_p) może być wskaźnikiem przy wykrywaniu zwężeń i niedrożności tętnic szyjnych pozaczaszkowych. Opisana w pracy metoda pozwala na wykrywanie zwężeń tętnic szyjnych wewnętrznych $\geqslant 30\%$. Stopień drożności tętnic szyjnych u osób chorych określany był na podstawie badań arteriograficznych, które w 8 przypadkach potwierdzone zostały operacyjnie.

1. Introduction

Diagnosis of the carotid arteries is important in prevention of the brain stroke. Apart from malignant tumors and heart strokes, this serious disease is, statistically, the third cause of death. The main reason of the brain stroke is ischemia of the brain caused by atherosclerotic changes in the brain-supplying arteries, including the carotid ones.

At the present moment, the basic method in noninvasive diagnosis of the carotid arteries is the ultrasonic Doppler method. It is used to identify stenosis and occlusions of the arteries [1, 6, 7, 13, 14, 15, 22, 30, 32, 33, 34, 36, 38, 39]. The evaluation of the patency of the examined vessel is based on analysis of blood velocity in the cross-section of the vessel determined by Doppler frequency measurements [13, 15, 30, 38], or on analysis of the Doppler signal spectrum [7, 14, 16, 34, 36, 39]. However, the results of clinical examinations show that the ultrasonic Doppler method does not always permit unambiguous evaluation of pathological changes in the carotid arteries. The reason for this is very complex form of the blood flow at the point of stenosis in the vessel and beyond this point, whose evaluation from Doppler frequency measurement is little accurate. Attempts to analyze the blood velocity measured by the Doppler method before the point of stenosis [30], also failed to give the expected results [39].

An attempt at a new approach to diagnosis of the carotid arteries is the method presented in this study based on analysis of the vascular input impedance determined noninvasively in the common carotid arteries. These arteries are important paths of blood supply to the brain. Atherosclerotic changes in the bifurcation of these arteries, at the inlet of the internal carotid arteries, are the main cause of the brain stroke.

2. Method of the noninvasive measurement of the vascular input impedance in the common carotid arteries

The vascular impedance is a function of the hemodynamic properties of the vascular system at the input of which it is measured. It is determined in the frequency domain and defined as the ratio between the blood pressure and the blood flow for n succesive harmonics of the heart beat frequency according to the dependence

$$Z(n\omega_0) = p(n\omega_0)/Q(n\omega_0) = Z_{\mathrm{mod}_n} e^{\mathrm{j}f_n} \tag{1}$$

where $\omega_0 = 2\pi f_0$; f_0 is the frequency of the heart; $n = 0, 1, 2, \ldots$; $Z(n\omega_0)$ is the vascular input impendance, Z_{mod_n} and φ_n are the modulus and phase; $p(n\omega_0)$ and $Q(n\omega_o)$ are the spectra of the signals of the blood pressure and the blood flow.

For $n = 0$, the vascular input impedance expresses the ratio between the meain pressure p_{med} and the mean blood flow Q_{med}. Assuming that the value of the pressure at the end of the vena cava is much smaller than the pressure in the arteries in which the measurement takes place, for $n = 0$, the input vascular impendance represents the mean resistance of the examined fragment of the vascular system.

In 1956, RANDALL and STACY [31] were the first to propose the concept of the measurement of the hydraulic impedance in blood vessels called the vascular input impedance. So far, the method of investigating the properties of the vascular system by the measurement of the vascular input impedance has not been widely applied in medical diagnosis. The reason for this was the inability to measure noninvasively the instantaneous blood pressure, which is, a part from the blood volume velocity, the basic parameter in the determination of the vascular input impedance. Investigations of the vascular input impedance performed in many centres in the world are based on invasive measurement made mainly on animals. They apply above all to such vessels as the aorta [4, 10, 17, 18, 37], the femoral artery [8, 19] and the pulmonary artery [2].

The method of the noninvasive measurement of the vascular input impedance presented in this study is based on previous investigations by the author [23, 24, 25, 26, 27, 28, 29]. In this method the instantaneous course of the blood pressure is determined from ultrasonic measurement of the instantaneous vessel diameter. It is assumed here that between the vessel diameter and the blood pressure there is the logarithmic dependence of the form

$$S(p) = (1/\gamma)\ln(p/p_0), \qquad \text{for } p > p_0 > 0, \tag{2}$$

where p is the blood pressure, S is the cross-section area of the vessel, and p_0 and γ are constant coefficients.

The coefficients p_0 and γ present in formula (2) can be determined from measurements of the systolic pressure p_s and the diastolic pressure p_d and the vessel cross-sections S_s and S_d for both of the pressures. Putting the two pairs of values (S_s, p_s) and (S_d, p_d) into expression (2), it is obtained that

$$p_0 = \frac{p_d}{\exp\left[\dfrac{S_d}{S_s - S_d}\ln\dfrac{p_s}{p_d}\right]}, \tag{3a}$$

$$\gamma = \frac{1}{S_s - S_d}\ln\frac{p_s}{p_d}. \tag{3b}$$

The examination carried out by the author in the common carotid arteries in healthy and sick persons aged between 9 and 64 showed that the value of the coefficient p_0 is positive and smaller than 15 mm Hg [27, 29]. The logarithmic function described by formula 2 is applied only to the pressure range between the systolic and diastolic pressures whose physiological values are greater than 50 mm Hg. For this range the condition $p > p_0 > 0$ shown in formula (2) is met. Putting the values of p_0 and γ described by formulae (3 a and 3 b) into formula (2), it is obtained that

$$S(p) = S_d\left[1 + \frac{(S_s - S_d)\ln(p/p_d)}{S_d \ln(p_s/p_d)}\right]. \tag{4}$$

It should be pointed out that the logarithmic function $S(p)$ discussed above, applies to the so-called static conditions where the blood pressure and the artery cross-section take values stationary in time. For time variable (dynamic loads), the vessel walls can show viscoelastic properties. Research by many authors [11, 20] showed that for large arterial vessels the phase shift between the blood pressure and a change in the vessel radius does not exceed 10°, permitting the viscoelastic effect to be neglected in a simplified model.

The assumptions presented here for the mutual relations between the artery cross-section and the blood pressure are the basis for the concept of noninvasive determination of the course of the blood pressure $p(t)$ in the common carotid artery from the measurement of the instantaneous diameter $d(t)$ of this artery by the ultrasonic echo method. For this purpose, from formula (4), the following dependence is applied

$$p(t) = p_d \exp\left(\frac{d^2(t) - d^2_{\min}}{d^2_{\max} - d^2_{\min}} \ln\left(\frac{p_s}{p_d}\right)\right), \tag{5}$$

where $d_{\max}$ and $d_{\min}$ are the maximum and minimum artery diameters for the systolic pressure p_s and the diastolic one p_d.

The blood pressure course $p(t)$ determined in this way in the common carotid artery is calibrated with the systolic pressure p_s and the diastolic pressure p_d, which are identifield by using a cuff method in the brachial artery, with the patient in supine position.

In assuming for the common carotid artery the value of the systolic and diastolic pressures determined in the brachial artery, account was, e.g., taken of the results of the investigations carried out in 1982 by Borow [3]. They were concerned with the comparative evaluation between the blood pressure in the brachial artery determined noninvasively by the oscillometric method and the blood pressure found using a catheter in the ascending aorta. Performed on a group of 30 persons, aged between 30 and 83, these studies showed that, for the patients, in supine position, the differences in the values of the systolic and diastolic pressures between the aorta and the brachial artery were respectively 1% and 1.7% mean values, and could, therefore, be neglected in practice. Since the common carotid artery has a diameter close to that of the brachial one, it can be believed that the assumed method of the evaluation of the systolic and diastolic pressures in the common carotid artery from measurements of these pressures in the brachial artery should not introduce any significant error.

The necessary condition for the present method of the determination of the blood pressure course is the full patency of the arterial vessels between the point of measurement of the diameter of the common carotid artery and the point of measurement of the blood pressure in the brachial artery. The presence of stenosis means that the blood pressures from the two measurements points are different.

Parallel to the measurements of the instantaneous artery diameter, in the same vessel cross-section, the instantaneous blood velocity $v_s(t)$ is measured by the noninvasive continuous wave ultrasonic Doppler method. Information on the instantaneous artery diameter, used previously to reconstruct the blood pressure course, also serves for determining the course of the instantaneous blood flow $Q(t)$, according to the dependence

$$Q(t) = v_s(t)\frac{\pi d^2(t)}{4}, \tag{6}$$

where $v_s(t)$ is the blood velocity averaged over the vessel cross-section.

The simultaneous measurement of the blood pressure and the blood flow, made in the above way, in the same cross-section of the common carotid artery, is the basis for the noninvasive determination of the vascular input impedance in this artery, from formula (2).

3. Measurement system

A schematic diagram of the measurement system is shown in Fig. 1. It was constructed by the author [27, 28] for noninvasive investigations of the vascular input impedance in the common carotid arteries. This system includes two ultrasonic probes $P1$ and $P2$ set at an angle of 30° to each other. The probe $P2$ is connected with a bi-directional continuous wave Doppler flowmeter *cwDF*, meant for blood velocity measurements. The probe $P1$, set perpendicularly to the blood vessel, is connected with the transmitter T and the receiver R of the pulsed system meant for the measurement of the instantaneous vessel diameter by the ultrasonic echo method. To gain large measurement resolution, the ultrasonic beams transmitted by the probes $P1$ and $P2$ are focused. The width of the ultrasonic beam (defined for the -20 dB acoustic pressure level relative to the maximum value on the beam axis) is 1 mm at the focus of the probe $P1$, and 2.5 mm at that of the probe $P2$. For both probes, the ultrasonic wave focusing range varies between 1 and 3 cm. The probe $P1$ and $P2$ transmit ultrasonic waves at two different frequencies. The frequency of the impulse wave transmitted by the probe $P1$ is 6.75 MHz, and the frequency of the continuous wave transmitted by the probe $P2$ is 4.5 MHz.

Information on the instantaneous vessel diameter is gained from ultrasonic measurements of the instantaneous distances between the probe $P1$ and the internal surfaces of the two vessel walls. The measurement of the internal diameter of the blood vessel requires high resolution of the ultrasonic pulsed system. For this

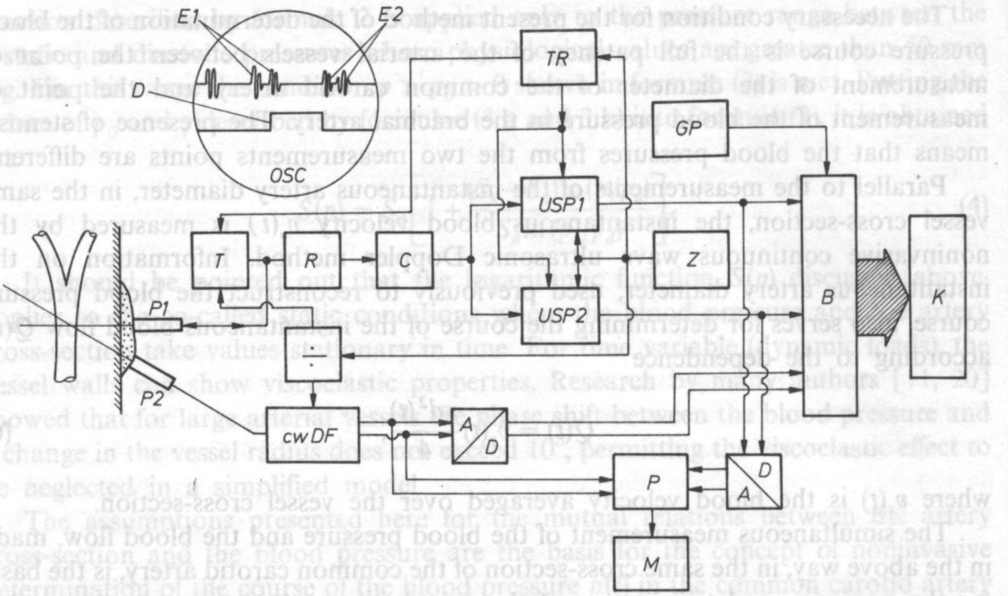

Fig. 1. A schematic diagram of the developed system: A/D and D/A — analog to digital and digital to analog converters, B — buffer, C — comparator, $cwDF$ — bi-directional continuous wave Doppler flowmeter, GP — oscillator of impulse for copying data into the computer, K — computer, M — monitor, OSC — oscilloscope tube, P — recorder, $P1$ and $P2$ — ultrasonic probes, T — impulse transmitter, R — impulse receiver, TR — trigger impulse oscillator, $USP1$ and $USP2$ — digital systems for tracking and measuring the position of echos. Z — clock impulse oscillator

purpose, apart from the previously mentioned focusing of the probe $P1$, a narrow transmitted impulse was used in the measurements, with the duration of 0.3 μs (2 cycles of a transmitted wave) corresponding to its length in tissue equal to 0.45 mm. As a result this made it possible to obtain single echos from the external and internal surfaces of the walls of the investigated common carotid arteries. The repetition frequency of the transmitted ultrasonic wave impulses was 18 kHz. This permits the measurement range to reach 4.2 cm into the patient's body.

The echos obtained in the course of the measurement at the output of the receiver R are transformed into rectangular signals by the level comparator C. The echos thus formed are fed to two digital systems ($USP1$ and $USP2$), using which it is possible to track the displacements of chosen slopes of echos detected from the front and back walls of the blood vessel [12, 27, 28]. In these systems for every work cycle of the impulse transmitter T the time is digitally measured between the on set of the transmitted pulse and the tracked slopes of the echos from both walls of the vessel. This provides the basis for calculation, by the computer K, of the instantaneous distances u_1 and u_2 between the ultrasonic probe and the blood vessel surface. For the successive n-th measurement cycle, these distances are

$$u_1 = \frac{cN_n}{2f_z}, \quad u_2 = \frac{cM_n}{2f_z} \tag{7}$$

where N_n and M_n are the numbers of clock impulses counted in the n-th cycle of the impulse transmitter by the two channels $USP2$ and $USP2$ of the measurement system; f_z is the clock frequency and c is the ultrasonic wave velocity in the investigated medium.

From dependence (7), there follows the accuracy of representation of displacements of the vessel walls, which for the clock frequency used in the measurements, $f_z = 27$ MHz, was $3 \cdot 10^{-5}$ m.

11-bit data obtained at the outputs of $USP1$ and $USP2$ are fed to the output buffer B of the device, along with two 8-bit data on the frequencies f_{zc} of the Doppler signals. These frequencies are measured by the ultrasonic Doppler flowmeter cwDF for blood velocity in two directions. The frequency f_{zc} is determined by the method of "zero crossings" and is proportional to mean blood velocity v_s in the vessel cross-section, from the dependence [9, 21, 27]

$$v_s = a \frac{c f_{zc}}{2 f_n \cos\theta}, \tag{8}$$

where: f_n is the frequency of the ultrasonic wave transmitted by the probe $P2$ of the flowmeter $cwDF$, c is the ultrasonic wave velocity in the studied medium, θ is the angle between the direction of the transmitted and received ultrasonic wave and that of the blood flow, and a is the proportionality coefficient [9, 21, 27].

In calculating the blood velocity from the Doppler frequency f_{zc} measured by the flowmeter, it was assumed that the angle θ between the direction of the transmitted and received ultrasonic wave and the axis of the blood vessel was 60°. This resulted from the constant angle of 30° between the probes and from the assumption that the probe $P1$ was set perpendicularly to the vessel axis. The gaining of the maximum amplitude of the echos from both vessel walls was assumed to indicate the perpendicular position of the probe $P1$ relative to the blood vessel. These echos can be observed in the course of measurements, on the oscilloscope tube OSC of the system. At the same time, on the oscilloscope screen the measured diameter of the studied vessel is shown in the form of the gate D.

The digital data from the buffer B of the measurement system were fed to a MERA-60 computer (equivalent to PDP-11) and written into its memory. Along with them, the values p of the systolic and diastolic pressures, measured by using a cuff method in the brachial artery for the patient's supine position, were fed to the computer. The data set thus formed provided the basis for the determination of the instantaneous blood volume velocity $Q(t)$ and of the blood pressure $p(t)$, according to the previously given dependencies (5) and (6).

The input vessel impedance was measured from the discrete Fourier transforms of the time courses of the blood flow and blood pressure for a cardiac cycle. 64 discrete values of the blood pressure and flow, occurring for one cardiac cycle, were used in the calculations. The sampling frequency was defined by using the oscillator GP of the impulses for copying data from the output of the measurement system into the computer. In the calculations, the fast Fourier transform, FFT, algorithm was applied [5]. In its final form, the vascular input impedance is represented by the modulus Z_{mod_n} and the phase φ_n (see Fig. 2).

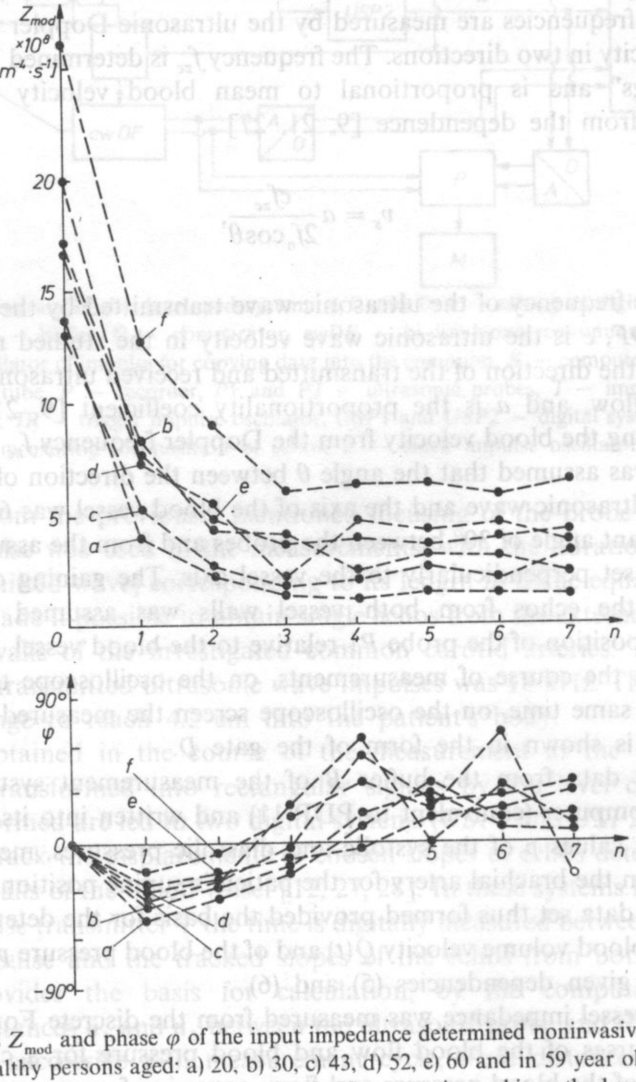

Fig. 2. The modulus Z_{mod} and phase φ of the input impedance determined noninvasively in the common carotid artery in healthy persons aged: a) 20, b) 30, c) 43, d) 52, e) 60 and in 59 year old patient in whom occlusion of the internal carotid artery was found by the X-ray arteriographic method on the studied side (f).

4. Analysis of the vascular input impedance determined noninvasively in the common carotid arteries in healthy and sick persons

The previously described method and equipment were applied is noninvasive measurements of the vascular input impedance in the common carotid arteries. The investigations were carried out, for two groups of persons. The first group (38) persons, aged between 9 and 64, did not show any pathological changes in the carotid arteries. The second group (9 persons) included patients aged between 53 and 62, in whom, using X-ray arteriography, atherosclerotic changes were found in the area of the extracranial carotid arteries in the form of stenosis or occlusions of these arteries. In 8 cases the results of the X-ray examinations were confirmed by surgical operations[1].

In all the examined persons, the measurements were performed at a distance of 2–3 cm before the bifurcation of the common carotid artery.

As an example the courses of the vascular input impedance determined for 5 healthy persons aged between 20 and 60 and for a 59-year-old patient with occlusion of the internal artery are shown in Fig. 2.

The results of the investigations of the vascular input impedance obtained for healthy and sick persons indicate the characteristic course of the modulus and phase for the first few **n** harmonics of the heart, beat frequency. The value of the modulus shows a small minimum between the second and fifth harmonics, which is accompanied by a change in the phase from negative to positive. This form of the vascular input impedance suggests that its course is affected by the compliance properties the (negative phase) and the inertia properties the (positive phase) of the studied vascular system. In older persons, in particular those with atherosclerotic changes in the area of the examined arteries, less negative phase was found compared with that for young healthy persons.

The modulus of the vascular input impedance for $n = 0$ represents the mean resistance of the vascular system supplied by the common carotid artery. This resistance was determined in kg $m^{-4} s^{-1}$, (u.r.).

The value of the resistance determined for the examined group of healthy persons aged between 19 and 64 fell in the interval $11.6 \cdot 10^8 - 22.9 \cdot 10^8$ u.r., whereas its mean value was $(15.8 \pm 2.6)\ 10^8$ u.r. A distinct increase in the resistance was observed in the sick in whom the critical (90%) stenosis of the internal carotid artery (1 person) and occlusion of the internal carotid artery (3 persons) were found. For these patients the resistance varied between $25.8 \cdot 10^8$ and $27.3 \cdot 10^8$ u.r., and, in one case, was $40.2 \cdot 10^8$ u.r. An arteriographic examination for this person showed the occlusion of the internal carotid artery and a stenosis in the initial section of the external carotid artery.

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[1] The examinations on the group of sick persons were carried out in cooperation with the Department of General and Thoratic Surgery of the Institute of Surgery, Medical Academy of Warsaw headed by Prof. dr M. SZOSTEK.

For the others in the group of sick persons, in whom the stenosis of the internal carotid arteries, determined by the X-ray arteriographic method, were found to be vary between 30% and 70%, the values of the resistance fall in the upper range of the value internal for healthy persons, varying between $17.9 \cdot 10^8$ and $21.9 \cdot 10^8$ u.r.

Assuming the linearity of the studied vascular system, a four-element model was used in further analysis of the vascular input impedance. The electric equivalent circuit of the model is shown in Fig. 3 [24, 27].

This model includes the elements representing the inertance L, the vessel compliance C, the vessel resistance R_0 and the peripheral resistance R_p. These elements were determined through computer simulation of the input vascular impedance by means of the impedance $Z_M(\omega)$ of the model

$$Z_M(\omega) = R_0 + j\omega L + R_p/(1 + j\omega C R_p) \tag{9}$$

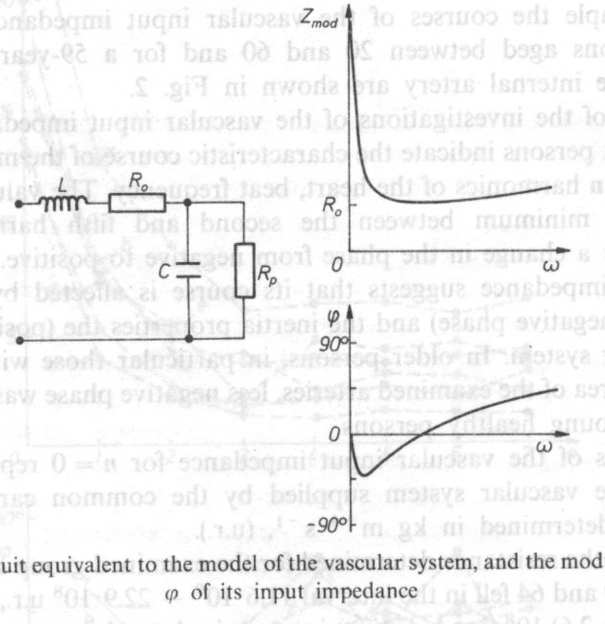

Fig. 3. The electric circuit equivalent to the model of the vascular system, and the modulus Z_{mod} and phase φ of its input impedance

In the simulation of the vascular input impedance, the following parameters were taken into account:

- the value of the modulus Z_{mod_0} of the impedance for $n = 0$,
- the real value RE_1 and the imaginary value IM_1 of the impedance for the first harmonic, and
- the frequency f_m for which the impedance phase changes its sign from negative to positive.

The frequency f_m was matched. In a general case, it cannot be determined from the course of the discrete values of the input vascular impedance. Only the internal of values where it falls, is known. The limits of this interval are defined by two frequencies corresponding to two adjacent harmonics between which the impedance phase changes its sign for the first time (see Fig. 2).

The assumption of the first harmonic of the vascular input impedance as the basis of the simulation resulted from the fact that its value is the quotient of two components with the greatest amplitude in the spectra of the signals of the blood pressure and flow rate, therefore, it is least dependent on the noise of the measurement device.

From the above-mentioned parameters, the elements of the model were determined by solving for this purpose the following system of equations

$$\begin{gathered} R_0+R_p=Z_{\mathrm{mod}_0}, \\ R_0+R_p/[1+(2\pi f_0 C R_p)^2]=RE_1, \\ 2\pi f_0 L-2\pi f_0 C R_p^2/[1+(2\pi f_0 C R_p)^2]=IM_1, \\ L=CR_p^2/[1+(2\pi f_m C R_p)^2], \end{gathered} \tag{10}$$

where L, C, R_0 and R_p are the elements of the model, f_0 is the frequency of the heart rate and f_m is the frequency for which the impedance phase changes its sign.

It follows from the above system of equations that the values of the elements L,

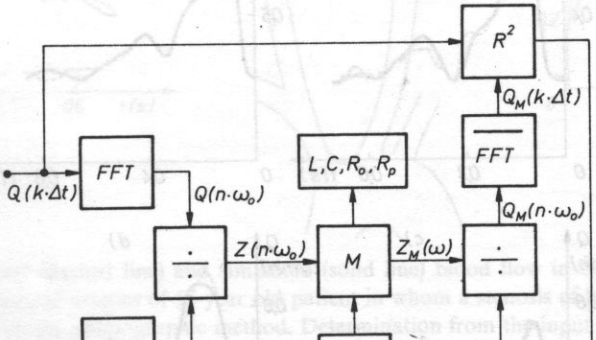

Fig. 4. The flow chart of operations in the computer analysis of the input impedance: M — model of the vascular input impedance by means of the impedance $Z_M(\omega)$ of the four-element equivalent model, FFT and $\overline{\mathrm{FFT}}$ — the algorithms of the fast Fourier transform and inverse fast Fourier transform, R^2 — the coefficient of agreement between the measured Q and simulated Q_M blood flows described by formula (11)

C, R_0 and R_p depend on f_m. This frequency is so matched as to ensure the best simulation of the input vascular impedance. The optimum simulation was indicated by the degree of agreement between the measured course of the blood flow Q and the course of the flow Q_M determined from the measured pressure and from impedance of the model $Z_M(\omega)$. The agreement between the two courses of the blood flow was compared by means of the determination coefficient R^2 given by the formula [35]:

$$R^2 = 1 - \frac{\sum_k (\hat{y}_k - y_k)^2}{\sum_k (\bar{y} - y_k)^2}, \tag{11}$$

where y_k is the value of y measured experimentally for the independent variable

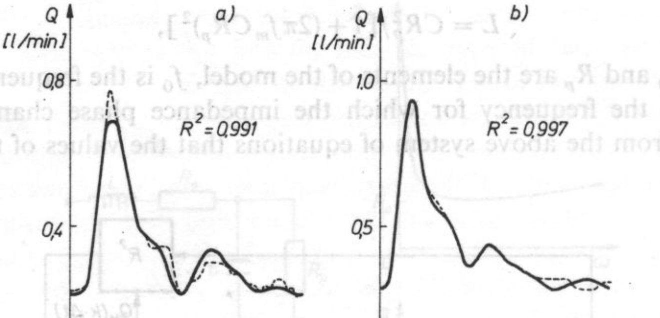

Fig. 5. The measured (dashed line) and simulated (solid line) blood flows in the common carotid artery in healthy persons aged: a) 12, b) 30, c) 52, d) 64. The simulated flow was determined from the course of the blood pressure and the input impedance of the model (see Fig. 3.). The value of the determination coefficient R^2 applied in evaluating the agreement between the simulated and measured courses (see formula 11) is marked in this figure

x equal to x_k, y is the arithmetic mean of N measurements, and $y_k = f(x_k)$, if $f(x)$ denotes the approximating function applied.

The flow chart of the operations performed in the implementation of the above computer simulation of the vascular input impedance is shown in Fig. 4.

For all the investigated cases, the value of R^2 was close to unity, falling in the interval from 0.988 to 0.998, meaning an almost ideal agreement between the compared flow courses (see Figs. 5 and 6). The elements of the model thus determined were the basis for comparative examinations of healthy and sick persons (Tables 1 and 2). It was found that the parameter which distinguished best between the sick and the healthy was the ratio between the vascular resistance R_0 and the peripheral ratio R_p. For the healthy the ratio R_0/R_p was less than 0.5, whereas for most sick persons with atherosclerotic changes identified in the area of the carotid arteries, it was greater than 0.5.

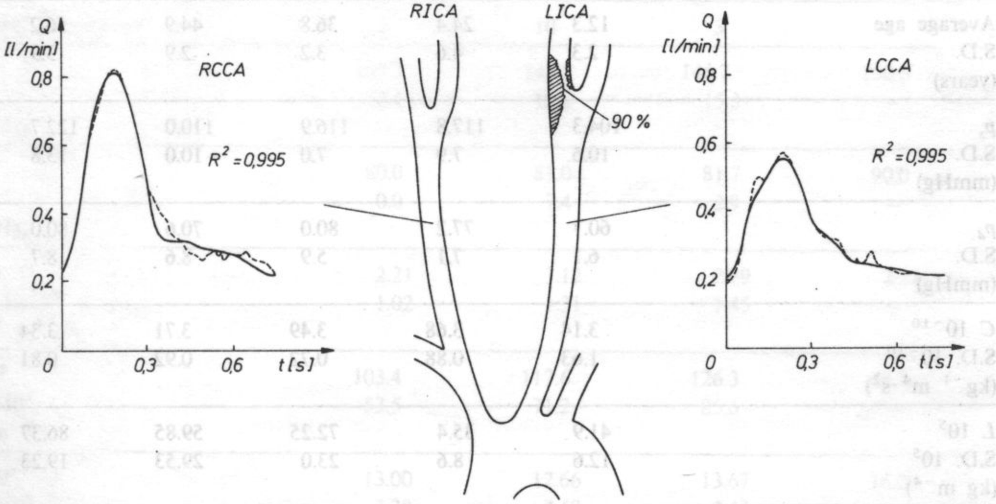

Fig. 6. The measured (dashed line) and simulated (solid line) blood flow in the left (LCCA) and right (RCCA) common carotid arteries of 58-year old patient in whom a stenosis of left internal carotid artery (LICA) was found by the arteriographic method. Determination from the input impedance of the model, the ratio between the vascular resistance R_0 and the peripheral one R_p was: 0.37 in the artery RCCA and 1.03 in the artery LCCA. R^2 – determination coefficient

The values of the ratio R_0/R_p determined for healthy and sick persons are shown in Fig. 7. Assuming values of this ratio exceeding 0.5 to indicate pathology this criterion was evaluated on the basis of the results of X-ray arteriographic examinations. It is shown in Table 3. It follows from the table that for the total number of 17 examined arteries in the sick, only in two cases a false, negative result was obtained, in terms of the X-ray arteriographic diagnosis. These cases were those of small stenosis of the internal carotid artery.

Table 1. The values of the elements L, C, R_p and R_0 of the equivalent model of the vascular system, determined from the vascular input impedance in the common carotid arteries for a group of healthy persons; p_s and p_d are the systolic and diastolic pressures in the brachial artery.

Age group (years)	9–16	19–30	32–40	41–50	52–64
No. of persons	7	9	8	8	11
Average age	12.3	24.4	36.8	44.9	56.2
S.D. (years)	2.3	4.6	3.2	2.9	3.9
p_s	104.3	117.8	116.9	110.0	122.7
S.D. (mmHg)	10.6	7.9	7.0	10.0	13.8
p_d	60.7	77.2	80.0	70.6	80.0
S.D. (mmHg)	6.1	7.1	5.9	8.6	8.7
$C\ 10^{-10}$	3.14	3.68	3.49	3.71	3.34
S.D. 10^{-10} ($kg^{-1}\ m^4\ s^2$)	1.63	0.88	0.72	0.92	0.81
$L\ 10^5$	41.9	35.4	72.25	59.85	86.37
S.D. 10^5 ($kg\ m^{-4}$)	12.6	8.6	23.0	29.53	19.23
$R_p\ 10^8$	15.51	13.38	12.25	10.35	13.53
S.D. 10^8 ($kg\ m^{-4}\ s^{-1}$)	2.06	2.14	1.73	1.43	2.11
$R_0\ 10^8$	3.72	2.55	3.14	3.16	4.09
S.D. 10^8 ($kg\ m^{-4}\ s^{-1}$)	0.68	0.73	0.99	0.68	1.28
R_0/R_p	0.26	0.20	0.26	0.31	0.30
S.D.	0.06	0.06	0.09	0.07	0.08

S.D. — standard deviation

Table 2. The values of the elements L, C, R_p and R_0 of the equivalent model of the vascular system determined from the vascular input impedance in the common carotid arteries in sick patients; p_s and p_d are the systolic and diastolic pressures in the brachial artery ICA-internal carotid artery, ECA-external carotid artery

Degree of stenosis	Without stenosis	Stenosis of ICA 30–80%	Stenosis of ICA 90% (1) occlusion of ICA (2)	Occlusion of ICA and stenosis of ECA
Number of arteries	3	10	3	1
p_s S.D. (mmHg)	141.7 16.1	148.5 19.2	146.7 15.3	150.0
p_d S.D. (mmHg)	80.0 0.0	81.0 7.4	81.7 2.9	90.0 –
$C\,10^{-10}$ S.D. 10^{-10} ($\mathrm{kg^{-1}\,m^4\,s^2}$)	2.21 1.02	3.12 1.31	2.29 1.45	2.27 –
$L\,10^5$ S.D. 10^5 ($\mathrm{kg\,m^{-4}}$)	103.4 53.5	117.6 71.2	126.3 85.6	48.7
$R_p\,10^8$ S.D. 10^8 ($\mathrm{kg\,m^{-4}\,s^{-1}}$)	13.00 3.38	12.66 2.48	13.67 2.43	16.08 –
$R_0\,10^8$ S.D. 10^8 ($\mathrm{kg\,m^{-4}\,s^{-1}}$)	4.90 1.61	7.06 2.09	12.87 2.17	24.14 –
R_0/R_p S.D.	0.39 0.08	0.58 0.17	0.98 0.32	1.50

S.D. – standard deviation

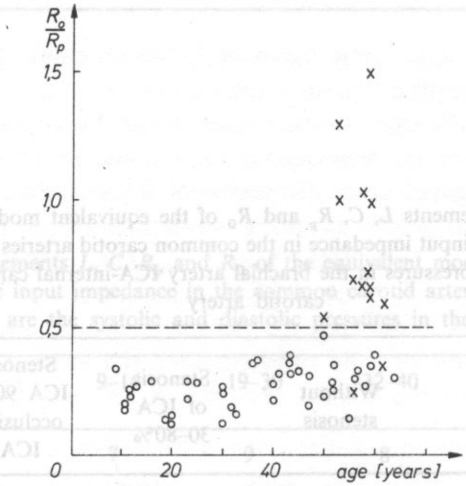

Fig. 7. The ratio between the vascular resistance R_0 and the peripheral one R_p determined from the vascular input impedance in the common carotid arteries in healthy (o) and sick (×) persons with atherosclerotic changes in the extracranial carotid arteries (see Table 3). The age of the examined persons is marked on the horizontal axis

Table 3. Evaluation of detectability of pathological changes in the carotid arteries by means of the resistance ratio compared with the X-ray arteriography results

Arteriography	Vascular input impedance		
	$R_0/R_p > 0.5$		$R_0/R_p < 0.5$
		Number of cases	
ICA occlusion	3	3	–
ICA stenosis >75%	2	2	–
ICA stenosis 50%–75%	1	1	–
ICA i CCA stenosis 40%–50%	1	1	–
ICA stenosis 30%–50%	4	3	1
ICA stenosis 30%	3	2	1
no stenosis	3	–	3
Number of arteries	17	12 true positive	3 true negative 2 false negative

ICA – internal carotid artery

CCA – external carotid artery

5. Conclusions

The method and system presented in the study for the noninvasive determination of the input impedance in the common carotid artery is a proposed of a new approach to diagnosis of human circulation system. The results of the investigations permit the following conclusions to be drawn:

a. The investigations of the vascular input impedance in the carotid artery carried out on a group of 38 healthy persons aged between 9 and 64 and a group of sick patients (17 arteries) aged between 53 and 62. indicate a characteristic course of the values of the modulus and the phase of the vascular impedance for the first 6-7 harmonics of the heart beat frequency (see Fig. 2). The value of the modulus show a slight minimum between the second and fifth harmonics, accompanied by a change in the sign of the phase from negative to positive. This form of the dependence suggests the influence of the compliance properties (the negative phase) and the inertia properties (the positive phase) in the vascular system supplied with blood by the common carotid artery.

b. Using a simple four-element equivalent model of the vascular system, it is possible to simulate the course of the vascular input impedance determined noninvasively in the common carotid artery. This is indicated by large agreement obtained for all examined persons between the measured blood flow and that determined from the impedance of the model and the blood pressure. The determination coefficient R^2 determining this agreement, fell within the interval between 0.988 and 0.998.

c. The method of analysis of the vascular input impedance elaborated by the author permits the determination of the element of the equivalent model of vascular system. These elements represent the four basic hemodynamics parameters, namely the compliance of the vascular system C the inertance L, the vessel resistance R_0 and the peripheral resistance R_p.

d. The total mean resistance of the vascular system $(R_0 + R_p)$, determined in the common carotid artery for the examined group of healthy persons aged between 19 and 64, fell in the internal $11.6 \cdot 10^8$–$22.9 \cdot 10^8$ kg m^{-4} s^{-1}. A distinct increase in the resistance was observed in the patients in whom a critical (90%) stenosis in the internal carotid artery (1 persons) or occlusion of the internal carotid artery (3 persons) were found. For these sick persons, the resistance varied between $25.8 \cdot 10^8$ and $27.3 \cdot 10^8$ kg m^{-4} s^{-1}, and, in one case, it was $40.2 \cdot 10^8$ kg m^{-4} s^{-1}. In this person, an X-ray arteriographic examination showed occlusion of the internal carotid artery and a stenosis in the initial section of the external carotid artery. For the others in the sick group, in whom, using the arteriographic method, stenosis of the interval carotid arteries were found to vary between 30% and 70%, the values of the resistance fell in the upper range of the values for the healthy. varying between $17.9 \cdot 10^8$ and $21.9 \cdot 10^8$ kg m^{-4} s^{-1}.

e. Atherosclerotic changes in the extra-cranial carotid arteries are identified from the input impedance and the adopted model of the vascular system by the ratio between the vessel resistance R_0 and the peripheral resistance R_p. This ratio increases if stenosis or occlusions of the carotid arteries are present. Assumed by the author to indicate pathology, the ratio $R_0/R_p > 0.5$ seems to be a sufficiently sensitive criterion for identifying stenosis or occlusions. It permits the detection of 30% of stenosis of the internal carotid arteries (see Table 3).

f. The preliminary results of clinical investigations indicate that the determined resistance ratio R_0/R_p tends to increase as a function of the degree of stenosis the carotid arteries beyond the point of measurement of the vascular input impedance (see Table 2).

g. The method for detecting stenosis and occlusion of the extracranial carotid arteries proposed in this study has a few advantages over the currently used ultrasonic methods. Firstly, the measurement is performed before the point of stenosis where the blood flow is not perturbed. Secondly, the measurement is taken in the common carotid artery which is easily accessible to ultrasonic examinations. The blood flow rate measurement carried out so far in this artery does not detect so small stenosis as those in the case of the vascular input impedance. Analysis of blood flow changes based on the pulsatility index permits only the detection of critical stenosis of more than 80% [30, 33, 39].

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