NONINVASIVE EVALUATION OF THE ELASTICITY
OF COMMON CAROTID ARTERY WALL

T. POWAŁOWSKI AND Z. TRAWIŃSKI

Ultrasnic Department
Institute of Fundamenatal Technological Research
Polish Academy of Sciences
(00—049 Warszawa. Świętokrzyska 21)

The elasticity of common carotid arteries was examined on the basis of noninvasive ultrasonic measurements of the diameter of the carotid artery and the systlic and diastolic pressures as determined by a cuff on the brachial artery. The measurements were performed for a group of 20 males, aged from 27 to 45 years. The examines were fighter plane pilots. The examinations were carried out for different systolic and diastolic pressures which were recorded along with measurements of the diameter of the carotid artery during rest, following an exercise test. This paper presents the results of measurements of the maximum and minimum diameters of the common carotid artery for different systolic and diastolic pressures in the brachial artery. Good coincidence was gained between the experimental results and the logarithmic function as described by POWAŁOWSKI. The coefficient of the determination R^2 fell between 0.993 and 0.999. On the basis of the results of the measurements of the artery diameter and the blood pressure, the values of coefficients describing the elastic properties of the common carotid arteries were defined. The investigated coefficients included: the elastic modulus E_p, the arterial distensibility coefficient DC, the cross-sectional compliance CC and the logarithmic stiffness coefficient α.

KEY WORDS:
Arterial wall elasticity, carotid artery, ultrasound

1. Introduction

The evaluation of the elasticity of arteries was based on the examination of changes in the transversal dimensions of the vessel which are caused by blood pressure variations. It involves differently defined coefficients which are often applied in references to characterise the elastic properties of arterial walls. E.g., they include:

1) the elastic modulus E_p as described by PETERSON in 1960 [14]:

$$E_p = \frac{\Delta P \, Dd}{\Delta D},$$
(1.1)

where $\Delta D/Dd$ is a relative increase in the vessel diameter as a function of the blood pressure growth ΔP;

2) the arterial distensibility coefficient DC and the cross-sectional compliance CC as applied in 1986 by RENEMAN *et al.* in carotid wall studies [19, 20]:

$$DC = \frac{2\,\Delta D/Dd}{\Delta P},$$ (1.2)

$$CC = \frac{\pi\,\Delta D\;Dd}{2\,\Delta P}$$ (1.3)

Experimental studies performed on large arterial vessels (the aorta, the carotid artery, and the femoral artery) by BERGEL [3], LOON [9], SIMON [22] and HAYASHI [6] demonstrated that there is a nonlinear dependence between the change in the transversal artery dimensions and that in the blood pressure. This means that the coefficients described by formulae (1.1)−(1.3) depend on the blood pressure, making it difficult the comparatively evaluate the arterial wall elasticity studies performed on their basis.

So far there has been no unambiguous agreement on the form of the analytical dependence between the blood pressure and the change in the transversal arterial dimensions. Most of the functions proposed in the references are empirical in nature. They include the functions described by LOON [9], HAYASHI [6], STETTLER [23], MEISTER [11], LANGEWOUTERST [8] and POWAŁOWSKI [15, 16, 17]. Out of these functions, it is only the one proposed by POWAŁOWSKI that can be determined via noninvasive measurements of systolic and diastolic blood pressures and the maximum and minimum vessel diameters. It has the following form:

$$D^2(P) = Dd^2\left[1 + \frac{1}{\alpha}\ln\frac{P}{Pd}\right],$$ (1.4)

where α is defined as the logarithmic coefficient of arterial wall stiffness, in the following form:

$$\alpha = \frac{Dd^2}{Ds^2 - Dd^2}\ln\left(\frac{Ps}{Pd}\right),$$ (1.5)

where Ds and Dd are vessel diameters for the systolic pressure Ps and the diastolic pressure Pd, respectively.

The coefficient α proposed by POWAŁOWSKI is an attempt to take into account the effect of the blood pressure on the stiffness coefficient in comparative examinations.

The coefficients described by formulae (1.1)−(1.3) and (1.5) are applied in evaluating the elasticity of arterial walls in noninvasive studies [1, 17, 19, 20]. In these studies, the ultrasonic method is used to determine the maximum and minimum arterial diameters. Cuff-measured systolic and diastolic pressures are subordinated to the above values. As the common carotid arteries are examined, the blood pressure is measured with a cuff on the brachial artery of a patient in a lying position.

The purpose of the work is to examine ultrasonically the dependence between the maximum and minimum diameters of the common carotid artery and the blood pressure in the brachial artery as well as to analyse the coefficients E_p, DC, CC and α for different blood pressures.

2. The results of research and discussion

The examinations were carried out on the common carotid arteries of a group of 20 men, aged from 27 to 45. The patients were fighter plane pilots. (The study was performed at the Military Institute of Aviation Medicine in Warsaw).

The examinations were performed using the measuring system, called the Vascular Echo Doppler, elaborated by the present authors. Its block diagram is shown in fig. 1. The equipment consisted of a pulsed ultrasound system tracking displacements of carotid artery walls. The accuracy of arterial wall displacement identification was 7 μm. The internal artery diameter was determined on the basis of digital measurements of the time between selected echo slopes detected from the internal layer of the arterial wall [5, 18].
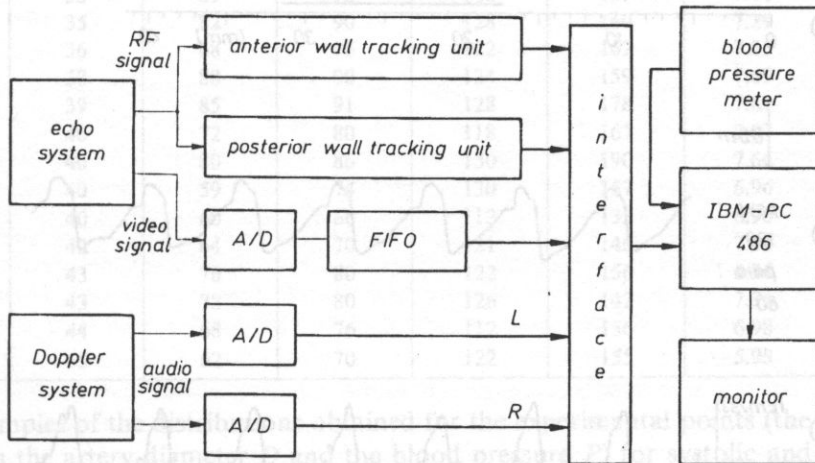

Fig. 1. A block diagram of the measuring system: A/D — an analog-to-digital converter; FIFO — memory (First Input, First Output) applied for collecting echo image data.

The frequency of the transmitted ultrsound was 6.75 MHz. The ultrasound was focused at the 1 − 3 cm depth from the surface of the skin. The width of the ultrasound beam at the focus was 1 mm (defined for the sound pressure of −20 dB compared with the maximum value on the beam axis). The width of the transmitted pulsed ultrasound was 0.3 μs (2 cycles of a high-frequency transmitter), representing its length of 0.45 mm in tissue. As an effect, it was possible to gain single echoes from the external and internal surfaces of the walls of the common carotid artery under study.

To facilitate the location of the artery under study in the course of the measurements, the pulse probe was mechanically coupled with that of a c.w. Doppler flowmeter. The pulse probe was set perpendicular to the artery, assuming as the measure of perpendicular position the gaining of the maximum amplitude of echoes from the blood vessel walls.

In the course of the evaluation, the measured data were displayed on the screen of an IBM PC connected on-line with an ultrasound system and memorized by this computer (Fig. 2). Along with the ultrasonically measured data, the values of the systolic and diastolic pressures which were cuff-measured were entered into the computer's memory.

The measurements were performed on a lying patient before and after exercise. The exercise examinations were carried out on a cyclometer. Directly following the exercise, the high blood pressure gradually dropped during rest, to reach after 8 — 10 minutes the pressure measured before the exercise test.
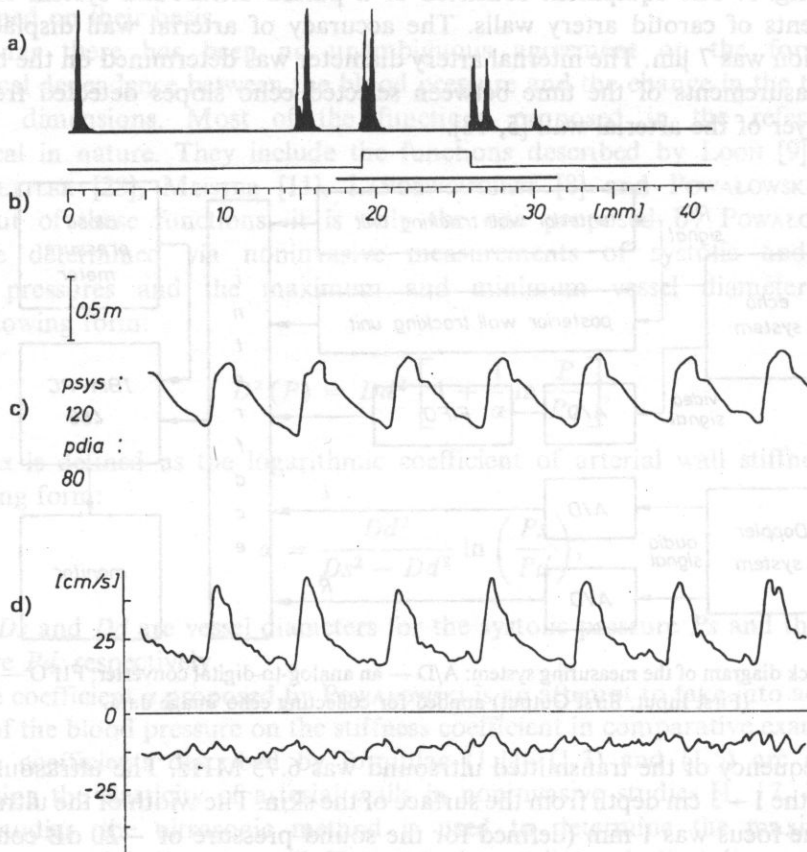
Fig. 2. The data presented in the course of the measurement on the monitor of an IBM PC: a) echoes from the walls of the common carotid artery, b) internal artery diameter, c) artery diameter variations (scale 0.5 mm), d) blood flow velocity; psys and pdia are the systolic and diastolic blood pressures (mm Hg) in the brachial artery.

The pressure was measured every minute. The pressures between the successive measuring points were calculated using linear interpolation. The intervals of systolic and diastolic pressures measured for particular examines are shown in Table 1. Changes in the systolic pressure were greater than those in the diastolic pressure, falling between 14 mmHg and 60 mmHg.

Table 1. The results of measurements of the systolic Ps and the diastolic Pd brachial blood pressures and the diameter D of the common carotid arteries in patients: R^2 — the coefficient of determination calculated for the evaluation of the degree of approximation of the results of experimental research using the logarithmic function $D(P)$ (formula (1.4)) $D\ min_a$ — the mean value of the minimum diameter

No.	Age [years]	Pd [mm Hg]		Ps [mm Hg]		$D\ min_a$ [mm]	R^2
		min	max	min	max		
1	27	75	80	125	150	7.59	0.999
2	28	84	90	141	164	6.44	0.997
3	30	69	71	118	146	7.19	0.999
4	32	58	64	128	152	6.35	0.998
5	33	68	78	120	156	6.98	0.997
6	33	60	69	122	136	5.73	0.998
7	35	69	72	118	139	7.60	0.999
8	35	82	90	128	160	7.29	0.999
9	36	68	76	122	162	7.25	0.998
10	38	88	90	134	159	7.69	0.999
11	39	85	91	128	178	7.69	0.999
12	40	72	80	118	167	7.07	0.998
13	40	80	86	130	190	7.64	0.999
14	40	59	74	130	157	6.96	0.993
15	40	60	66	112	133	6.90	0.998
16	42	64	70	121	146	7.01	0.998
17	43	76	80	122	156	6.36	0.998
18	43	78	80	126	142	7.96	0.998
19	44	68	76	112	156	6.98	0.996
20	45	62	70	122	155	5.98	0.998

Examples of the distributions obtained for the experimental points (the relations between the artery diameter D and the blood pressure P) for systolic and diastolic pressures are shown in Fig. 3.

The distribution of the experimental points was described using the logarithmic function $D(P)$ as obtained from formula (1.4). The coefficient of determination R^2 for the group of the people examined fell within the interval between 0.993 and 0.999 (see Table 1). The scatter of the majority of the experimental points round the theoretical curve fell in the interval of values corresponding to error of roughly $\pm 14\ \mu m$ as the change in the vascular diameter was measured.

The high coincidence between the results of the studies and the logarithmic function as described by POWAŁOWSKI indicates that the latter function can be adopted as the basis for the evaluation of the elasticity of common carotid arteries performed
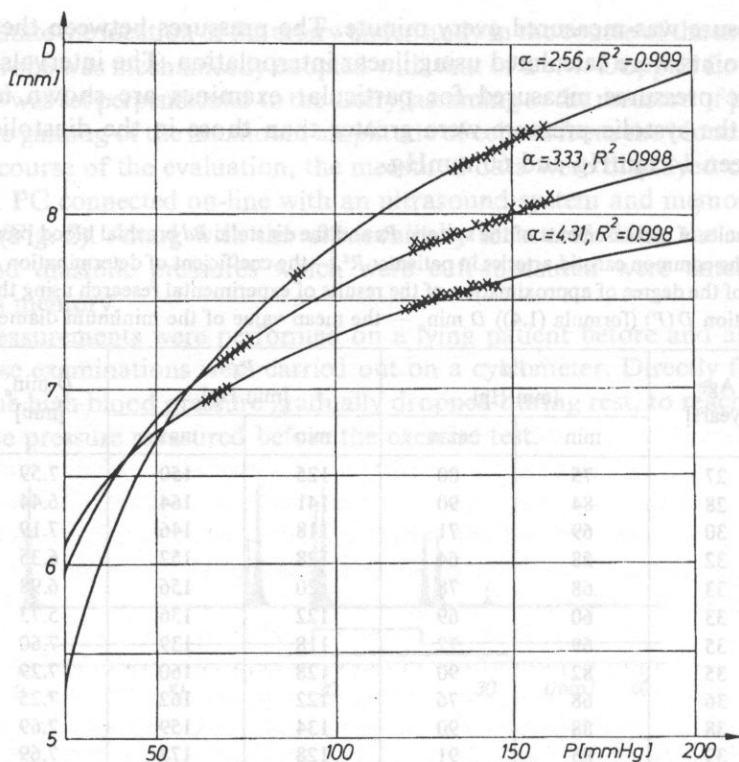
Fig. 3. The results of measurements of the dependence between the diameter D of the common carotid artery and the blood pressure P in the brachial artery for three patients numbered 9, 10 and 16 (compare Tables 1 and 2). The maximum and minimum carotid diameters were subordinated respectively to the systolic and diastolic pressures. The solid line represents the logarithmic function $D(P)$ determined from formula (1.4). The figure shows the mean values of the stiffness coefficients α (formula (1.5)) calculated for patients as well as the coefficient of determination R^2 calculated for the evaluation of the degree of approximation of the experimental research results as a function of the logarithmic function $D(P)$.

on the basis of measurements of the maximum and minimum diameters of the carotid artery and the systolic and diastolic pressures as measured in the brachial artery.

The logarithmic function $D^2(P)$ is an empirical one, which, as its author [17] showed, corresponds with good accuracy ($R^2 = 0.9868$) to the results of examinations performed directly in the carotid artery over the pressure range from 25 mmHg to 200 mmHg.

Assuming for the common carotid artery the values of the systolic and diastolic pressures determined in the brachial artery, it is necessary to discuss this type of comparative evaluation. The pressure wave which propagates along the vascular system changes its shape. As Mc DONALD [10] noticed, in moving from the aorta towards the lower-lying peripheral vessels, the systolic pressure is observed to increase as the diastolic and mean pressures drop slightly. There have been, e.g.,

attempts to explain this phenomenon with the effect of summation of the progressive and reflected pressure waves. Thus, the question arises whether a similar phenomenon takes place in the case of vessels in the upper part of the body and what are the possible blood pressure differences between the aorta and the brachial artery. The common carotid artery is very close to the aortic arch, and it can be assumed that the blood pressure difference between these vascular points can be neglected.

In 1955, in examining the blood pressure when using a catheter simultaneously in the brachial artery and the aortic arch, KROEKER [7] observed that for the same heart work cycle the systolic pressure in the brachial artery was 9% greater, and the diastolic pressure was 4% lower than the analogous pressures in the aorta. Some doubts have on the other hand been raised by the fact that when measuring in a similar way the blood pressures in the radial and femoral arteries this author obtained for all of the three arteries almost the same blood pressure differences between them and the aortic arch. Referring, in turn, to the experimental work performed by ARNDT [2], RILEY [21] noted that the pressure difference between the common carotid artery and the brachial artery can be neglected. A very significant argument for this view is provided by the research results presented in 1982 by BOROW [4]. They apply to comparative evaluation between the blood pressure in the brachial artery determined noninvasively by the oscillometric method (the automatic cuff method) and the blood pressure measured using a catheter in the ascending aorta. These studies, carried out on a group of 30 persons aged from 30 to 83 years, indicated that for a lying patient the differences in the systolic and diastolic pressures between the aorta and the brachial artery are 1% and 1.7% (the mean value), respectively, so they can be neglected in practice.

In the light of the research mentioned, it should be said that the method applied for the evaluation of the systolic and diastolic pressures in the common carotid artery as based on measurements of these pressures in the brachial artery should not introduce significant error into the noninvasive examination of the elasticity of the carotid arteries.

On the basis of the studies performed, in keeping with formulae $(1.1) - (1.3)$ and (1.5), the values of the coefficients E_p, DC, CC and α were determined. The mean values of the coefficients and the relative changes in their values are shown in Table 2. These results indicate that the relative changes in the value of the coefficient α are several times smaller than the changes in the values of the other coefficients. Figs. $4 - 7$ represent the relative (with respect to the mean value) values of particular coefficients as a function of the systolic pressure. They indicate that the value of the coefficient α does not depend significantly on the systolic pressure but the pressure has a distinct impact on the values of the coefficients E_p, DC and CC. The coefficient E_p increases, whereas the coeffcients DC and CC decrease as a function of the systolic pressure.

The effect of the diastolic pressure on the values of the coefficients under study which describe the elastic properties of arteries is difficult to identify in an experimental way, because the diastolic pressure changes in the patients examined were slight. Assuming as the starting point of discussion the previously considered
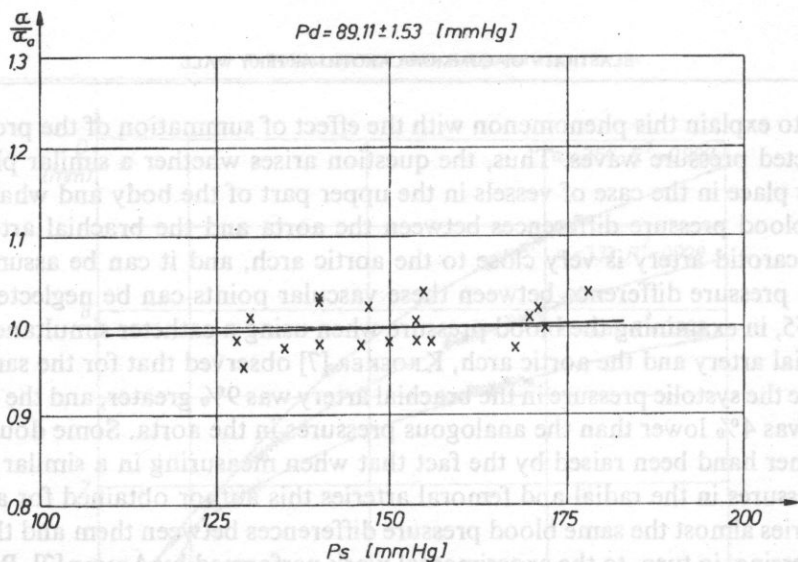
Fig. 4. The relative (with respect to the mean value of α_a) value of the logarithmic stiffness coefficient α as a function of variations in the systolic pressure Ps as calculated from examinations of a 39-year-old man (no. 11, see Tables 1 and 2). The correlation coefficient is 0.167.
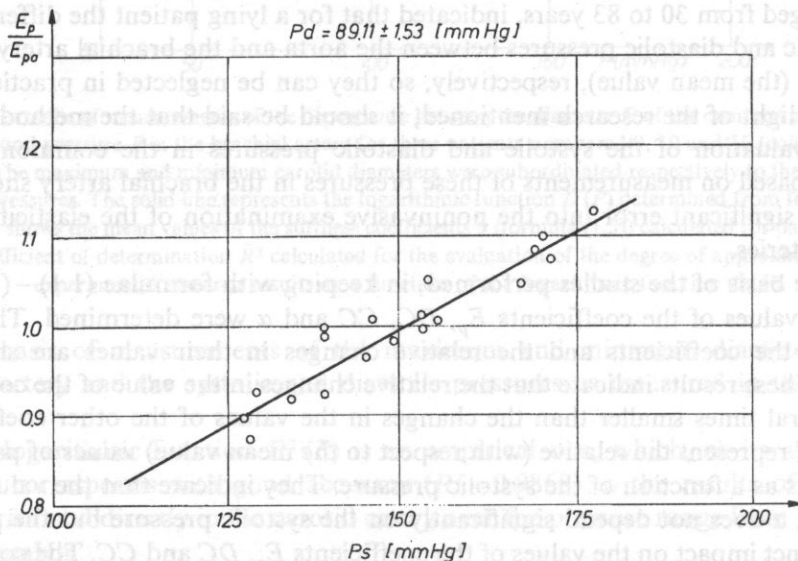

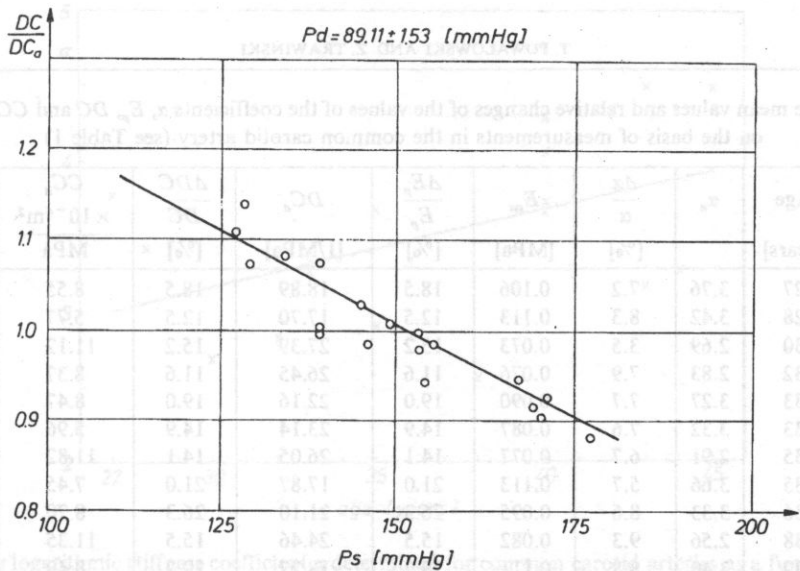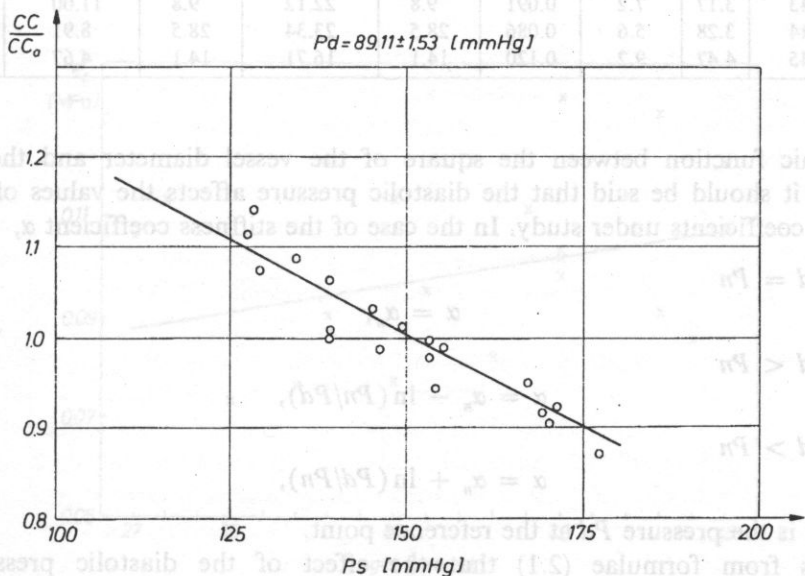Fig. 5. The relative (with respect to the mean value of E_{pa}) value of the elastic module E_p as a function of variations in the systolic pressure Ps calculated on the basis of examinations performed on a 39-year-old man (No. 11, see Tables 1 and 2). The correlation coeficient is 0.946.

Fig. 6. The relative (with respect to the mean value of DC_a) value of the arterial distensibility coefficient DC as a function of variations in the systolic pressure Ps calculated from examinations of a 39-year-old man (No. 11, see Tables 1 and 2). The correlation coeficient is -0.937.

Fig. 7. The relative (with respect to the mean value of CC_a) cross-sectional compliance CC as a function of variations in the systolic pressure Ps calculated on the basis of examinations performed on a 39-year-old man (No. 11, see Tables 1 and 2). The correlation coeficient is -0.944.

Table 2. The mean values and relative changes of the values of the coefficients α, E_p, DC and CC calculated on the basis of measurements in the common carotid artery (see Table 1)

No.	Age [years]	α_a	$\dfrac{\Delta\alpha}{\alpha}$ [%]	E_{pa} [MPa]	$\dfrac{\Delta E_p}{E_p}$ [%]	DC_a [1/MPa]	$\dfrac{\Delta DC}{DC}$ [%]	CC_a $\times 10^{-4} \mathrm{m}^2$ MPa	$\dfrac{\Delta CC}{CC}$ [%]
1	27	3.76	7.2	0.106	18.5	18.89	18.5	8.55	17.3
2	28	3.42	8.3	0.113	12.5	17.70	12.5	5.77	12.0
3	30	2.69	3.5	0.073	15.2	27.39	15.2	11.12	15.8
4	32	2.83	7.9	0.076	11.6	26.45	11.6	8.37	13.2
5	33	3.27	7.7	0.090	19.0	22.16	19.0	8.47	18.8
6	33	3.32	7.6	0.087	14.9	23.14	14.9	5.96	11.5
7	35	2.91	6.7	0.077	14.1	26.05	14.1	11.82	14.4
8	35	3.66	5.7	0.113	21.0	17.87	21.0	7.45	18.1
9	36	3.33	8.6	0.095	26.3	21.10	26.3	8.70	25.8
10	38	2.56	9.3	0.082	15.5	24.46	15.5	11.35	15.5
11	39	3.40	8.8	0.111	29.2	18.27	29.2	8.49	31.3
12	40	3.66	7.4	0.102	30.6	19.68	30.6	7.72	27.4
13	40	4.27	7.7	0.133	32.6	15.15	32.6	6.93	32.6
14	40	3.71	9.7	0.103	12.3	19.42	12.3	7.40	19.1
15	40	4.05	7.7	0.098	17.6	20.39	17.6	7.63	15.5
16	42	4.31	10.0	0.114	18.6	17.60	18.6	6.80	20.5
17	43	4.48	9.3	0.130	15.4	15.44	15.4	4.90	16.7
18	43	3.17	7.2	0.091	9.8	22.12	9.8	11.00	10.9
19	44	3.28	5.6	0.086	28.5	23.34	28.5	8.91	23.5
20	45	4.47	9.2	0.120	14.1	16.71	14.1	4.67	16.4

logarithmic function between the square of the vessel diameter and the blood pressure, it should be said that the diastolic pressure affects the values of all the elasticity coefficients under study. In the case of the stiffness coefficient α,

for $Pd = Pn$

$$\alpha = \alpha_n, \qquad (2.1)_1$$

for $Pd < Pn$

$$\alpha = \alpha_n - \ln(Pn/Pd), \qquad (2.1)_2$$

for $Pd > Pn$

$$\alpha = \alpha_n + \ln(Pd/Pn), \qquad (2.1)_3$$

where Pn is the pressure Pd at the reference point.

It results from formulae (2.1) that the effect of the diastolic pressure on the value of the coefficient grows smaller when the value of the coefficient α increases.

The evaluation of the effect of the blood pressure on the values of the particular elasticity coefficients is significant in comparative studies. An example of such studies in the references is the search for a correlation between the arterial elasticity and the age of patients [1, 12, 13, 17, 19, 20].
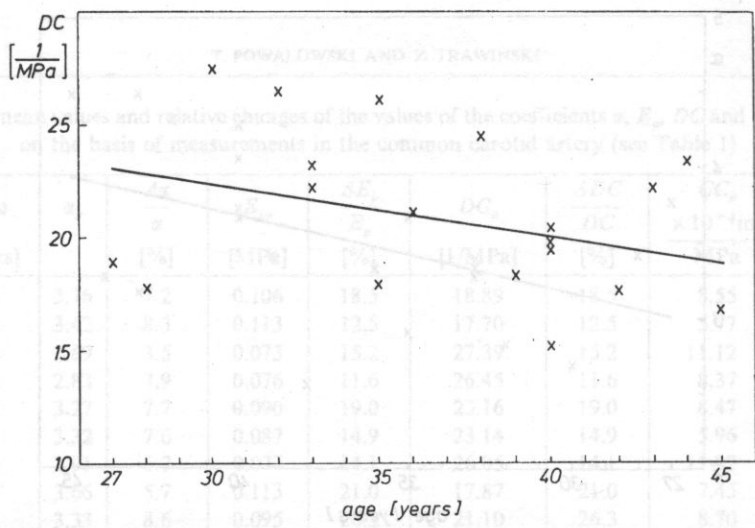
Fig. 8. The logarithmic stiffness coefficient α determined for common carotid arteries as a function of the age of patients. The solid line represents the linear regression function (Table 3).

Fig. 9. The elastic modulus E_p determined for common carotid arteries as a function of the age of patients. The solid line represents the linear regression function (Table 3).

Fig. 10. The arterial distensibility coefficient *DC* determined for common carotid arteries as a function of the age of patients. The solid line represents the linear regression function (Table 3).
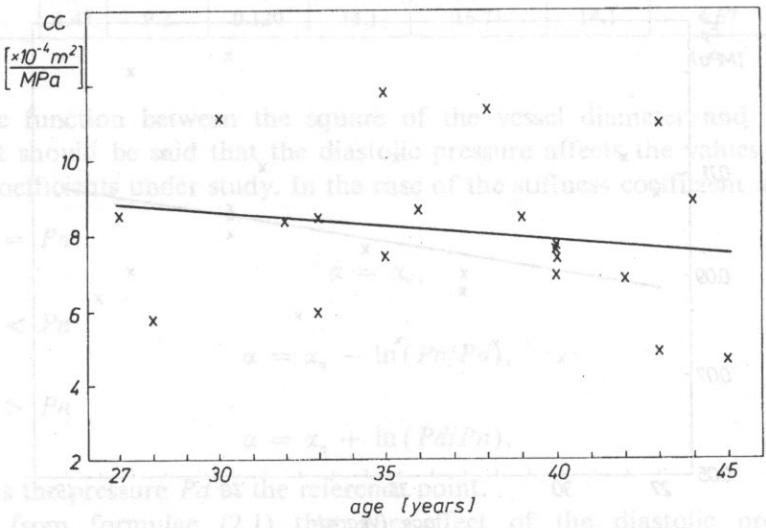

Fig. 11. The cross-sectional compliance *CC* determined for common carotid arteries as a function of the age of patients. The solid line represents the linear regression function (Table 3).

Figures 8−11 show the values of particular coefficients as a function of age. Linear regression was applied in analysing this dependence. For the group of the persons examined it is only the stiffness coefficient α that correlates significantly ($p < 0.05$) with age (Table3). As was demonstrated previously, the value of this coefficient do not depend on systolic blood pressure variations in the course of the examination.

Table 3. The coefficients describing the linear regression function $(ax+b)$ for dependencies between the values of α, E_p, DC and CC and the age of patients; r — the correlation coefficient

y	a	b	r
α	0.0509	1.6360	0.477
E_p	0.0011	0.0579	0.347
DC	−0.2360	29.4335	−0.348
CC	−0.0730	10.8113	−0.191

3. Conlusions

It is difficult to verify the noninvasive method for the evaluation of the elasticity of common carotid arteries because of the many factors which affect the ultimate result of measurements of the elasticity coefficients. They include: a) the function between the blood pressure and a change in the transversal dimensions of the common carotid artery; b) the relation between the systolic and diastolic pressures in the common carotid artery and the brachial artery; c) the accuracy of the brachial blood pressure measurement using cuff; d) the accuracy of acrotid artery diameter measurements using ultrasound. Instead of an analysis of particular factors the authors proposed a comprehensive evaluation. It consisted in ultrasonic measurements of the diameter of the common carotid artery for different blood pressures and in investigating the relation between the diameter of the common carotid artery and the blood pressure measured in the brachial artery.

The results of the measurements and calculations indicate that;

1) The distribution of points: the artery diameter - the blood pressure could be represented with high accuracy by the proposed logarithmic function described by formula (1.4). The coefficient of determination R^2 varied between 0.993 and 0.999 (Table 1). The scatter of most experimental points round the theoretical curve fell in the interval of values corresponding to an error of roughly ±14 μm in the measurement of vessel diameter changes.

2) The effect of the systolic pressure on the value of the logarithmic stiffness coefficient α (formula (1.5)) can be neglected. The calculations were carried out for a group of 20 persons for whom the systolic pressures fell between 112 mmHg and 190 mmHg, and the systolic pressure variations came between 14 mmHg and

60 mmHg (Table 1). The relative changes in the value of the coefficient α as a function of the systolic pressure in patients never exceeded 10% (Table 2 and fig. 4).

3) The logarithmic stiffness coefficient α is a more objective indicator of the mechanical properties of the wall of the common carotid artery than the parameters used so far, including the elastic modulus E_p, the arterial distensibility coefficient DC or the compliance CC. Its value does not change significantly as a function of the systolic pressure when the value of the coefficient E_p grows as a function of the systolic pressure and the values of the coefficients DC and CC decrease as a function of that pressure (Figs. 4–7). The relative changes in the values of the coefficients E_p, DC and CC as a function of variations in the systolic pressure were from 1.2 to 5.1 times larger than the changes of the value of the logarithmic stiffness coefficient α.

References

[1] G. ACARO, S. LAURENT, G. JONDEAU, A.P. HOEKS, M.E. SAFAR, *Stiffness of the common carotid artery in treated hypertensive patients*, Journal of Hypertension, 9, 947–954 (1991).

[2] J.O. ARNDT, J. KLAUSKE, f. MERSCH, *The diameter of the intact carotid artery in man and its change with pulse pressure*, Pflugers Arch.ges. Physiol., 301, 230–240 (1968).

[3] D.H. BERGEL, *The static elastic properties of the arterial wall*, J. Physiol, 156, 445–457 (1961).

[4] K.M. BOROW, J.W. NEWBURGER, *Noninvasive estimation of central aortic pressure using the oscillometric method for analyzing systemic artery pulsatile blood flow: Comparative study of indirect systolic, diastolic and mean brachial artery pressure with simultaneous direct ascending aortic pressure measurements*, Amer. Heart J. 103, 879–886 (1982).

[5] D.H. GROVES, T. POWAŁOWSKI, D.H. WHITE, *A digital technique for tracking moving interfaces*, Ultrasound in Med. and Biol., 8, 2, 185–190 (1982).

[6] K. HAYASHI, H. HANDA, S. NAGASAWA, A. OKUMURA, K. MORITAKE, *Stiffness and elastic behaviour of human intracranial and extracranial arteries*, J. Biomechanics, 13, 2, 175–184 (1980).

[7] E.J. KROEKER, E.H. WOOD, *Comparison of simultaneously record central and peripheral arterial pressure pulses during rest, exercise and tilted position in man*, Circulation Research, vol. III, 1955.

[8] G.J. LANGEWOUTERS, K.H. WESSELING, W.J. GOEDHARD, *The static elastic properties of 45 human thoracis and 20 abdominal aortas in vitro and the parameters of a new model*, J. of Biomechanics, 17, 6, 425–435 (1984).

[9] P. LOON, W. KLIP, E. BRADLEY, *Length-force and volume-pressure relationships of arteries*, Biorheology, 14, 181–201 (1977).

[10] D.A. MC DONALD, *Blood flow in arteries*, Edward Arnold Ltd., London, 1960.

[11] J.J. MEISTER, *Mesure par echographie doppler et modelisation theorique de leffet de troubles cardiaques sur la pression et le debit arteriels*, Thesis, EPFL, Lausanne, 1983.

[12] T. VAN MERODE, P.J.J. HICK, A.P.G. HOEKS, K.H. RAHN, R.S. RENEMAN, *Carotid artery wall properties in normotensive and borderline hypertensive subjects of verious ages*. Ultrasound in Med. & Biol., 14, 7, 563–569 (1988).

[13] T. VAN MERODE, P.J.J. HICK, a.P.G. HOEKS, F.A.M. SMEETS and R.S. RENEMAN, *Differences in carotid artery wall properties between presumed-healthy men and women*, Ultrasound in Med. and Biol. 14, 7, 571–574 (1988).

[14] L. PETERSON, R. JENSEN, J. PARNEL, *Mechanical properties of arteries in vivo*, Circulation Res., 8, 622–639 (1960).

[15] T. POWAŁOWSKI, B. PEŃSKO, *Noninvasive ultrasonic method of pressure and flow measurements for estimation of hemodynamical properties of cerebrovascular system*, Archives of Acoustics, **10**, 3, 303—314 (1985).

[16] T. POWAŁOWSKI, B. PEŃSKO, *Elasticite d' artere carotide de sujets normaux et pathologiqes*, Colloque sur les Ultra-sons et Acoustique Physique, 63—73, Paris 1987.

[17] T. POWAŁOWSKI, B. PEŃSKO, *A noninvasive ultrasonic method for the elasticity evaluation of the carotid arteries and its application in the diagnosis of the cerebro-vascular system*, Archives of Acoustics, **13**, 1—2, 109—126 (1988).

[18] T. POWAŁOWSKI, *Ultrasonic system for noninvasive measurement of hemodynamic parameters of human arterial-vascular system*, Archives of Acoustics, 13, 1—2, 89—108 (1988).

[19] R.S. RENEMAN, T. VAN MERODE, P. HICK, A.P.G. HOEKS, *Cardiovascular Applications of Multi-Gate Pulsed Doppler Systems*, Ultrasound in Med. & Biol. 5, 1, 357—370 (1986).

[20] R. RENEMAN, t. MERODE, P. HICK, A. MUYTJENS, A. HOEKS, *Age related changes in carotid artery wall properties in men*, Ultrasound in Med. and Biol., **12**, 6, 465—471 (1986).

[21] W.A. RILEY, R.W. BARNES, H.M. SCHEY, *An approach to the noninvasive periodic assessment of arterial elasticity in the young*, Preventive Medicine **13**, 169—184 (1984).

[22] B. SIMON, A. KOBAYASHI, D. STRANDNESS, C. WIEDERHIELM, *Large deformation analysis of the arterial cross section*, J. of Basic Eng. 93D, 2 (1971).

[23] J. STETTLER, P. NIEDERER, M. ANLIKER, *Theoretical analysis of arterial hemodynamics including the influence of bifurcations*, Annals of Biomedical Engineering, 9, 145—164 (1981).