ARCHIVES OF ACOUSTICS
28, 4, 325–337 (2003)

ULTRASONIC EXAMINATION OF COMMON CAROTID ARTERY WALL ELASTICITY OF PERSONS WITH DIFFERENT STAGES OF INTERNAL CAROTID ARTERY ATHEROSCLEROSIS

T. POWAŁOWSKI, Z. TRAWIŃSKI

Ultrasonic Department
Institute of Fundamental Technological Research
Polish Academy of Sciences
Świętokrzyska 21, 00-049 Warszawa, Poland

L. HILGERTNER

Department of General and Thoracic Surgery
Medical University of Warsaw
Banacha 1a, 02-097 Warszawa, Poland

Ultrasonic methods were used in this study to examine the association between the common carotid artery (CCA) wall elasticity and the atherosclerosis stage in the internal carotid artery (ICA). The degree of stenosis determined ultrasongraphically was used as an indicator of the atherosclerosis stage in the ICA. The examined persons were 45 to 80 years old. They had no arterial hypertension, diabetes mellitus and were not smokers. A comparative study was carried out for cases with ICA atherosclerosis (66 arteries) and without ICA atherosclerosis (61 arteries). In both groups there were persons without and with hypercholesterolemia, which according to our studies had no significant influence on CCA wall elasticity. The CCA wall elasticity was determined by the stiffness coefficient α and the distensibility coefficient DC based on ultrasonic measurements. The influences of age and arterial blood pressure on the CCA wall elasticity were taken into account in the analysis. The study revealed a significant decrease of the CCA wall elasticity in the case of patients with atherosclerosis compared with persons without atherosclerosis, and showed a significant correlation between the increase of the ICA stenosis degree and the decrease of CCA wall elasticity.

1. Introduction

The atherosclerotic process and its relationship to the changes occurring in the arterial wall is a matter of interest of numerous research and clinical centers. In noninvasive examinations, the change of elastic properties is taken as one of the indicators of changes occurring in the arterial wall. An increasing number of articles appeared in recent years on the arterial wall elastic properties determined by ultrasound methods.

Until now, the results of such studies involving atherosclerotical patients remain contradictory. Changes of arterial wall elasticity were observed mostly in the most advanced cases of atherosclerosis [14, 20]. Different opinions on the effect of atherosclerosis on the arterial wall elasticity are caused by the presence of other factors affecting the arterial wall elasticity and masking the influence of atherosclerosis. Such factors include the age of the examined persons and their arterial blood pressure. There is also an ongoing search to find the relationship between the risk factors of atherosclerosis and the arterial wall elasticity.

The aim of this study was to assess, basing on ultrasonic examinations, the association between the common carotid artery (CCA) wall elasticity and the atherosclerosis stage in the internal carotid artery (ICA). The degree of internal carotid artery stenosis determined by ultrasound methods was used as an indicator of the atherosclerosis severity. The effects of age and arterial blood pressure were included in the analysis. The examinations of the CCA wall elasticity were performed at the Medical University of Warsaw using the ultrasound device VED designed by the authors.

2. Method and equipment

The CCA wall elasticity was assessed using noninvasive ultrasound measurements of the maximum diameter $D_{\max}$ and the minimum diameter $D_{\min}$ on the systolic arterial blood pressure P_s and the diastolic arterial blood pressure P_d, measured by a sphygmomanometer in the brachial artery. On the basis of these measurements, the stiffness coefficient α and the distensibility coefficient DC were calculated according to the formulae:

$$\alpha = \frac{D_{\min}^2}{\left(D_{\max}^2 - D_{\min}^2\right)} \ln\left(\frac{P_s}{P_d}\right), \tag{1a}$$

$$\mathrm{DC} = \frac{\left(D_{\max}^2 - D_{\min}^2\right)}{D_{\min}^2\left(P_s - P_d\right)}. \tag{1b}$$

The nonlinear relationship between the arterial blood pressure and the cross-sectional size of the artery causes a dependence of these coefficients, calculated according to formulae (1a), (1b), on the arterial blood pressure. In a comparative analysis of the results, the effect of arterial blood pressure was eliminated by determining the isobaric value of the coefficients for infinitely small increases of the arterial blood pressure in relation to the reference blood pressure P_0 [11]. In order to determine the isobaric form of coefficients α and DC, we have assumed that the relationship between the CCA diameter D and the arterial blood pressure P has the following form [15, 16, 17]

$$D^2\left(P\right) = D_{\min}^2\left[1 + \frac{1}{\alpha}\ln\left(\frac{P}{P_d}\right)\right]. \tag{2}$$

Applying the formula (2), a dependency has been substantiated experimentally by POWAŁOWSKI *et al*. [16] in the human CCA for various values of the systolic and diastolic blood pressure measured by the Korotkoff sounds method in the brachial artery.

On the basis of Eqs. (1a), (1b), (2), the following isobaric relationships of the coefficients α and DC on the reference blood pressure P_0 [4] were determined

$$\alpha_{P_0} = \alpha + \ln\left(\frac{P_0}{P_d}\right), \tag{3a}$$

$$\mathrm{DC}_{P_0} = \frac{1}{P_0\ \alpha_{P_0}}. \tag{3b}$$

According to the research results published, the age of the examined person is a crucial factor having a significant effect on the CCA elastic properties [6, 18]. In order to include the effect of arterial blood pressure and age on the coefficients α and DC in the analysis of results, we introduced the following relative values of the isobaric coefficients α_{P_0} and DC_{P_0} related to the mean values resulting from the age of the examined person:

$$W_{\alpha_{P_0 x}} = \frac{\alpha_{P_0}}{\alpha_{P_0 x}}, \tag{4a}$$

$$W_{\mathrm{DC}_{P_0 x}} = \frac{\mathrm{DC}_{P_0}}{\mathrm{DC}_{P_0 x}}, \tag{4b}$$

where x is the age of the examined person and P_0 = 100 mmHg.

The values of $\alpha_{P_0 x}$ and $\mathrm{DC}_{P_0 x}$ were calculated from regression functions describing the relationship between each of the isobaric coefficients and the age. These functions were determined on the basis of examinations of the CCA of healthy persons without risk factors of atherosclerosis and without carotid atherosclerosis.

The level of significance in the description of differences in the values of the above presented parameters between the examined groups were calculated with the statistical non-parametric Mann–Whitney test with a 95% confidence interval. For statistical analysis, we used the computer software Statistica version 5.

The examinations of the stiffness coefficient α and the distensibility coefficient DC in the CCA were performed using the ultrasonic apparatus VED (Vascular Echo Doppler) designed by the authors at the Ultrasonic Department of the Institute of Fundamental Technological Research of the Polish Academy of Sciences [17, 18]. The apparatus consisted of an ultrasonic pulse system tracking the displacement of the vascular wall with a precision of $7 \cdot 10^{-6}$ m. The inner diameter was determined by digital time measurements between selected echoes (RF signal) received from the inner vascular wall layer. The frequency of the transmitted ultrasound was 6.75 MHz. The ultrasonic wave was focused at 1 to 3 cm below the skin surface. The longitudinal resolution of the apparatus obtained in model examinations was 0.33 mm in water.

During the examinations, the measurements were displayed on the screen of an IBM PC connected "on line" with the ultrasound apparatus, and were stored in the computer memory (Fig. 1). Apart from the data obtained from ultrasonic measurements, also the values of the systolic and diastolic blood pressure were transmitted to the computer memory.

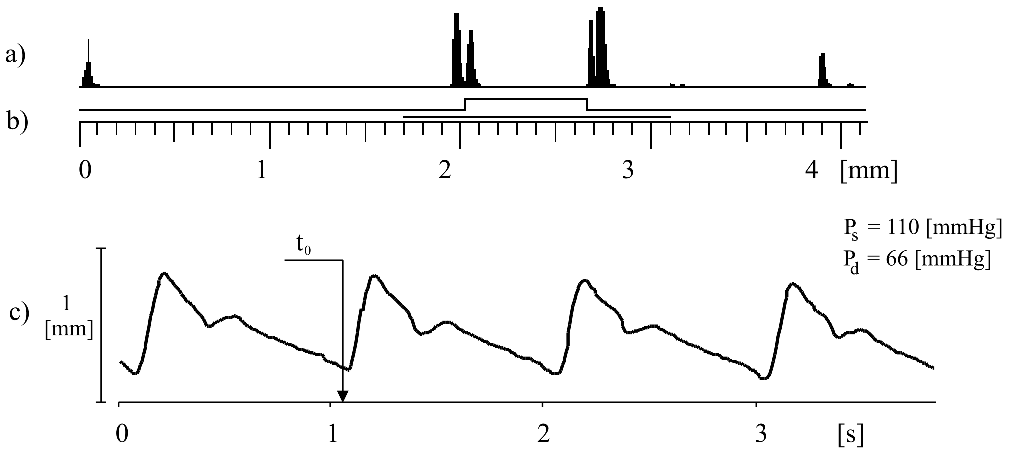

Fig. 1. Data presented in the course of the measurements in the common carotid artery as shown on the screen of the IBM PC in the VED apparatus [18]: a) echoes from the wall of the artery, b) range gate imaging the inner vascular diameter; c) artery diameter variations; t_0 – time of registering the echoes.

The reproducibility of the measurements of the stiffness coefficient α and of the distensibility coefficient DC in the CCA by means of the VED apparatus was tested on a control group of 10 healthy volunteers: 5 women and 5 men aged 23 to 30 [23]. Two examiners experienced in such measurements tested each person independently. The coefficient of the variation of CV was taken as the criterion of reproducibility. It was calculated for each parameter investigated as the ratio of the standard deviation between the two compared groups of results to the mean value of one of the groups chosen as reference for the comparative evaluation.

The mean value of the coefficient of variation of CV was as follows: 9.61 ± 0.46 [%] for the stiffness coefficient α, and 11.98 ± 1.09 [%] for the measurements of the distensibility coefficient DC.

3. Characteristics of the examined groups

The examinations were carried out in the CCA for persons at the age of 45 to 80 years. These persons had no arterial hypertension, diabetes mellitus and did not smoke. Comparative examinations were carried out for the control group (K) of healthy persons, for the group (HC) with hypercholesterolemia without carotid atherosclerosis and for groups with carotid atherosclerosis without hypercholesterolemia (AT) and with hypercholesterolemia (AT + HC). The description of the examined groups is presented in Table 1. Carotid atherosclerosis was diagnosed on the basis of combined ultrasound and

Table 1. Characteristics of the examined groups.

Examined group	K	HC	AT	AT + HC
% women	58	61	32	26
Number of arteries	38	23	19	47
Age [years]	45–75	45–63	45–79	47–80
Mean age [years]	57 ± 9.5	55 ± 6	63.5 ± 11.5	63 ± 9
TC [mg/dl]	163 ± 23	255 ± 53	178 ± 8	245 ± 37
HDL [mg/dl]	46 ± 6	62 ± 10	47 ± 10	47 ± 10
LDL [mg/dl]	99 ± 18	173 ± 51	116 ± 7	173 ± 37
TG [mg/dl]	89 ± 34	108 ± 37	97 ± 26	128 ± 45
ICA stenosis $\leq 70\%$	0	0	9	20
ICA stenosis $> 70 < 90\%$	0	0	3	6
ICA stenosis $\geq 90\%$	0	0	7	21

Doppler examinations using the Toshiba ECCOCEE with a linear transducer 7.5 MHz. For all of the cases, atherosclerotic plaques were located in the origin of the ICA. The degree of stenosis was estimated using the generally accepted criteria [3]. The lipid parameters were examined by enzymatic tests after fasting. Hypercholesterolemia was diagnosed when the total cholesterol (TC) ≥ 200 mg/dl, LDL-cholesterol concentration ≥ 135 mg/dl and the triglyceride (TG) concentration < 200 mg/dl [25].

4. Results

The examinations were performed in the CCA, 3–4 cm below its bifurcation. For none of the examined persons atherosclerotic plaques in the CCA were detected. The examinations were done in the supine position after 15 minute rest. Earlier examinations [18] of patients with the unilateral ICA atherosclerosis, carried out by the authors of this study, revealed that the CCA wall elasticity did not depend significantly on the site of the measurement.

4.1. Results of examinations of persons without carotid atherosclerosis

The examinations were carried out in 38 CCAs for the control group (K) and in 23 CCAs for the group (HC) with hypercholesterolemia without carotid atherosclerosis. The results are presented in Table 2 and Figs. 2a and 2c. The examinations did not reveal any significant differences in the values of the parameters describing the CCA elastic properties for persons with and without hypercholesterolemia.

Table 2. Results of examinations of persons without carotid atherosclerosis.

Examined group	K (A)	HC (B)	K + HC (C)
Number of arteries	38	23	61
P_s [mmHg]	128.6 ±13.6	125.2 ±18.6	127.4 ± 15.7
P_d [mmHg]	77.6 ± 8.3	76.6 ± 12.4	77.2 ± 9.9
$D_{\min}$ [10^{-3}m]	6.91 ± 0.75	6.64 ± 1.14	6.81 ± 0.92
α	4.10 ± 0.88	4.14 ± 0.87	4.12 ± 0.87
α_{P_0}	4.36 ± 0.92	4.42 ± 0.84	4.38 ± 0.88
$W_{\alpha_{P_0x}}$	1.01 ± 0.19	1.05 ± 0.19	1.03 ± 0.19
DC [1/MPa]	19.05 ± 4.15	19.61 ± 5.13	19.26 ± 4.51
DC_{P_0} [1/MPa]	17.99 ± 4.02	17.52 ± 3.14	17.81 ± 3.69
$W_{\mathrm{DC}_{P_0x}}$	1.03 ± 0.20	0.98 ± 0.16	1.01 ± 0.18

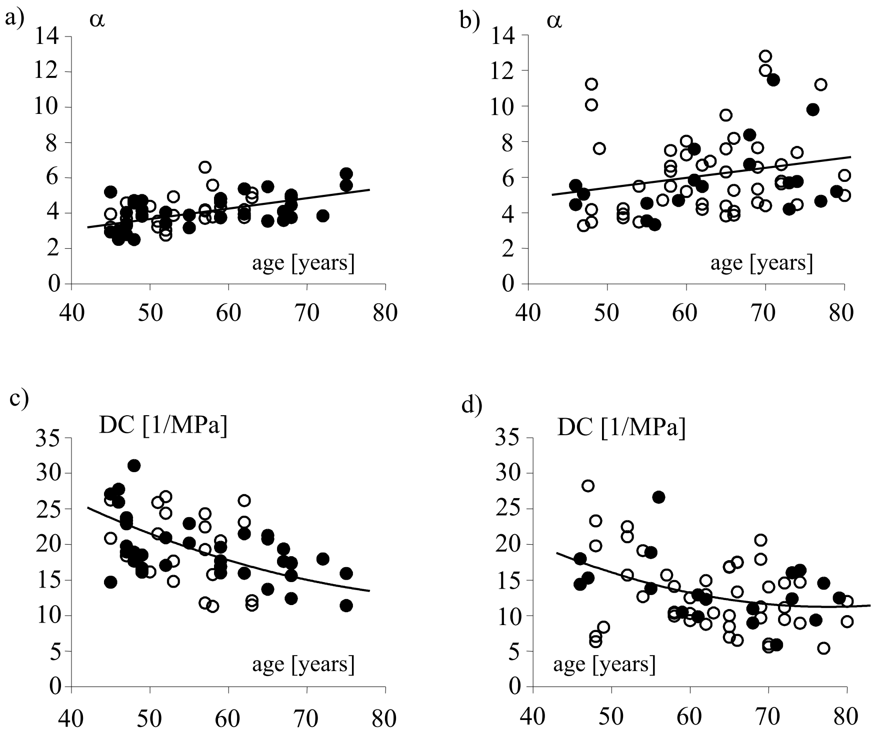

Fig. 2. Results of examinations of the stiffness coefficient α and the distensibility coefficient DC for persons without carotid atherosclerosis (a, c) and with ICA atherosclerosis (b, d); (•) – results for persons without hypercholesterolemia; (o) – results for persons with hypercholesterolemia. The solid line shows the regression function describing the distribution of experimental points.

4.2. *Results of examinations of persons with ICA atherosclerosis*

The examinations were performed in the CCA on the side where ICA atherosclerosis was diagnosed. In 47 cases of the 66 examined arteries hypercholesterolemia was diagnosed. The results are presented in Figs. 2b and 2d. The association between the CCA wall elasticity and the atherosclerosis stage in the ICA was analyzed. The degree of ICA stenosis was assumed as the criterion of atherosclerosis severity. The results are presented in Fig. 3. Despite of the marked variation of the results, a statistically significant correlation between the stiffness coefficient α and the degree of the ICA stenosis ($r = 0.31$; $p < 0.01$) were observed. For the distensibility coefficient DC, the correlation is worse, ($r = -0.23$, $p < 0.06$), which was caused by the effect of arterial blood pressure on the results of the measurements. As shown earlier [16], the values of the stiffness coefficient α did not depend on the arterial systolic blood pressure in contsrats to the distensibility coefficient DC. Introducing both the coefficients (for $P_0 = 100$ mmHg) in the analysis the results of the study of the isobaric values of α_{P_0} and DC_{P_0} enabled the achievement of a significant correlation ($p < 0.01$) with the degree of the ICA stenosis (Fig. 3).

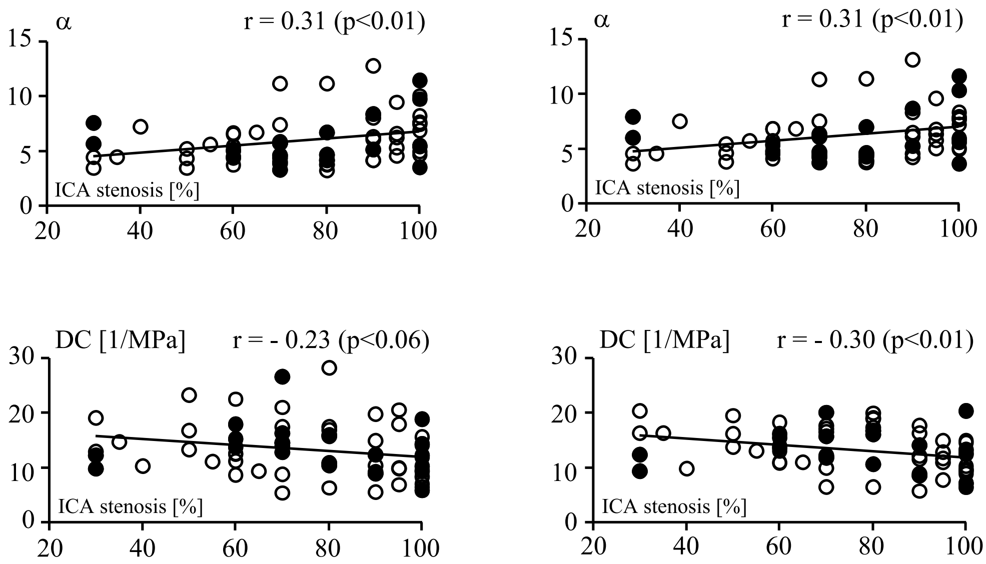

Fig. 3. The stiffness coefficient α and the distensibility coefficient DC and their isobaric values α_{P_0} and DC_{P_0} (for $P_0 = 100$ mmHg) determined in the CCA for persons with ICA atherosclerosis at different degrees of ICA stenosis; (•) – results for persons without hypercholesterolemia; (o) – results for persons with hypercholesterolemia. The solid line is the regression function describing the distribution of experimental points; r is the correlation coefficient.

In the further analysis, three groups of arteries were distinguished: group (1) without atherosclerosis (Table 2), group (2) with ICA stenosis $\leq 70\%$ (Table 3), and group (3) with ICA stenosis $\geq 90\%$ (Table 4). Each of these groups consisted of arteries in the case of persons without hypercholesterolemia (subgroup A) and with hypercholes-

Table 3. Results of examinations of persons with ICA stenosis $\leq 70\%$.

	Total (C)	AT (A)	AT + HC (B)
Number of arteries	29	9	20
Mean age [years]	63 ± 9.5	61 ± 11.5	64 ± 9
P_s [mmHg]	142 ± 19	135 ± 18	146 ± 19
P_d [mmHg]	78 ± 10	72 ± 11	81 ± 8
$D_{\min}$ [10^{-3}m]	8.19 ± 1.07	7.97 ± 0.72	8.29 ± 1.20
α	5.39 ± 1.64	5.21 ± 1.20	5.48 ± 1.84
α_{P_0}	5.65 ± 1.63	5.55 ± 1.24	5.70 ± 1.81
$W_{\alpha_{P_0x}}$	1.20 ± 0.29	1.22 ± 0.27	1.19 ± 0.31
DC [1/MPa]	14.48 ± 4.77	15.52± 4.79	14.01± 4.81
DC_{P_0} [1/MPa]	14.18 ± 3.45	14.12± 3.14	14.20± 3.66
$W_{\text{DC}_{P_0x}}$	0.87 ± 0.19	0.85 ± 0.19	0.88 ± 0.19

terolemia (subgroup B). A statistical analysis revealed that in each of these three groups the parameters of elasticity did not differ significantly for persons with and without atherosclerosis. Therefore, in the further analysis, the subgroups A and B were combined into a single group C common for persons with and without hypercholesterolemia. This analysis showed that for persons with ICA atherosclerosis, the CCA wall elasticity was significantly lower in the cases without carotid atherosclerosis. The elastic properties of the CCA wall were also associated with severity of ICA atherosclerosis. For persons with ICA stenosis $\geq 90\%$, the CCA elasticity was significantly lower than in the group with ICA stenosis $\leq 70\%$. The statistical analysis of these CCA elasticity parameters is presented in Fig. 4.

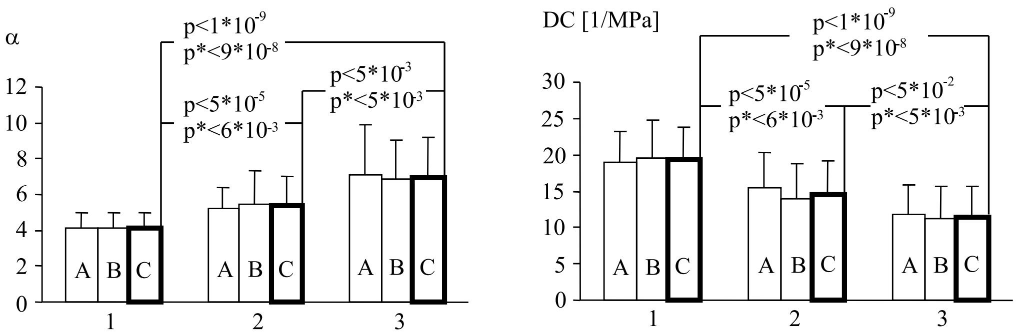

Fig. 4. Mean values of the stiffness coefficient α and the distensibility coefficient DC for the CCA for persons without ICA atherosclerosis (1) and with ICA atherosclerosis, when ICA stenosis $\leq 70\%$ (2) and $\geq 90\%$ (3); A – persons without hypercholesterolemia; B – persons with hypercholesterolemia; C – combined subgroups A and B (Tables 2–4); p, p^* – significance of the differences respectively for the absolute values (formulae (1a), (1b)) and for the relative isobaric values (formulae (4a), (4b)) of examined coefficients for persons of group C.

Table 4. Results of examinations of persons with ICA stenosis $\geq$ 90%.

	Total (C)	AT (A)	AT + HC (B)
Number of arteries	28	7	21
Mean age [years]	63 $\pm$ 9.5	65 $\pm$ 12	63 $\pm$ 9
P_s [mmHg]	140 $\pm$ 18	137 $\pm$ 13	142 $\pm$ 20
P_d [mmHg]	79 $\pm$ 11	77 $\pm$ 12	79 $\pm$ 11
$\mathrm{D}_{\min}$ [10^{-3}m]	7.71 $\pm$ 1.06	7.34 $\pm$ 0.87	7.84 $\pm$ 1.11
α	6.93 $\pm$ 2.28	7.05$\pm$ 2.87	6.88 $\pm$ 2.13
α_{P_0}	7.18$\pm$ 2.3	7.32$\pm$ 2.95	7.13$\pm$ 2.13
$W_{\alpha_{P_0 x}}$	1.54 $\pm$ 0.49	1.51 $\pm$ 0.52	1.55 $\pm$ 0.49
DC [1/MPa]	11.40$\pm$ 4.20	11.75$\pm$ 4.21	11.29$\pm$ 4.30
DC_{P_0} [1/MPa]	11.47$\pm$ 3.53	11.82$\pm$ 4.86	11.35$\pm$ 3.11
$W_{\mathrm{DC}_{P_0 x}}$	0.71$\pm$ 0.22	0.74 $\pm$ 0.27	0.71 $\pm$ 0.21

5. Discussion

The influence of atherosclerosis on the elastic properties of the CCA has not been fully recognized so far. The existence of such an influence was described by POWAŁOWSKI *et al*. [15] and VAN POPELE *et al*. [14]. In both of these studies, the carotid stenosis was diagnosed basing on ultrasound examinations [15]. The results obtained indicate a decrease of the CCA elasticity in the case of carotid atherosclerosis.

There are also reports showing a decrease of the CCA elasticity in the case of patients with an advanced coronary atherosclerosis [1, 7] and of patients with an abdominal aortic aneurysm [12].

Until now, there are no unequivocal criteria to assess the degree of atherosclerosis severity. Attempts have been made to assess the degree of atherosclerosis by identifying the number of areas affected by plaques [14] or basing it on the size and homodynamic effects of plaques and its relation to the degree of changes in the intima-media thickness of the vessel wall [2]. It has been also suggested to get a measure of the atherosclerosis severity by summing up the plaque thickness in the CCA, its bifurcation and the ICA [13]. All of the abovementioned propositions of classifying the degree of the atherosclerosis severity are based on ultrasound methods.

In the present study, the CCA elasticity was assessed for patients with different degrees of ICA stenosis. The degree of stenosis determined by duplex scanning ranged from 30% to 100% .

The main difficulty in the interpretation of most of the studies published to date was the coexistence of atherosclerosis risk factors, which also affect the arterial wall elasticity. The most important of them were the arterial hypertension and diabetes mellitus.

Age also has an influence on the elasticity of the arterial wall of the examined persons. The increase of the arterial wall stiffness as function of age is explained by an increase of the collagen fibres included in the arterial wall, which leads to an increase of the ratio of the collagen fibres to elastin ones [5]. This results in an increase of the stiffness coefficient α and a decrease of the distensibility coefficient DC as function of age as observed in this study (Fig. 2). The influence of age on the CCA wall elastic properties was also observed by other authors [6, 8, 10, 19]. When assessing the influence of other factors on the elastic properties, the influence of age should be taken into account. For this purpose POWAŁOWSKI *et al.* [18, 24] introduced for the analysis of the CCA elasticity the relative values of elasticity parameters in relation to their mean values resulting from the age of examined person. In this study, a similar approach was used in the analysis of the isobaric coefficients α_{P_0} and DC_{P_0} (formulae (4a), (4b)).

The examinations were carried out for persons with and without hypercholesterolemia. The results indicate that hypercholesterolemia had no influence on the elastic properties of the CCA arterial wall, neither for persons without atherosclerosis nor for patients with ICA atherosclerosis (Fig. 4, Tables 2–4). Also, no effect of hypercholesterolemia on the elastic properties of the CCA was observed by other authors [1, 21]. There was no influence of the total cholesterol concentration on the values of the CCA distensibility and the compliance [1, 9, 22]. The influence of hypercholesterolemia on the arterial wall elasticity is still a matter of debate. Hypercholesterolemia is one of the risk factors of atherosclerosis. The results presented in this study are based on the examinations of small groups and can be considered to be an argument in the discussion of the effect of hypercholesterolemia on the CCA elasticity.

The results of examinations of the distensibility coefficient DC and the stiffness coefficient α of the CCA wall as function of age (Fig. 2) indicate an increase of its variations for patients with ICA atherosclerosis in comparison to persons without atherosclerosis. For the 61 examined arteries without atherosclerosis, the value of SD/mean was 21% for α and 23% for DC. For the 66 examined arteries with atherosclerosis, the value of SD/mean was 37% for α and 38% for DC. This can signify that the process of aging of the arteries is affected with different intensity by pathological processes associated with the varied degree of the ICA atherosclerosis.

In the analysis the effects of age and arterial blood pressure were taken into account by using the isobaric coefficients α_{P_0} and DC_{P_0} (formulae (3a), (3b)) and their relative values resulting from the age of the examined persons (formulae (4a), (4b)).

The influence of age and arterial blood pressure on the examined parameters, included in the analysis, generally caused an increase of the statistical significance of the differences between groups of results (Fig. 3 and Fig. 4).

The variations of the isobaric parameters α_{P_0} and DC_{P_0} (for $P_0 = 100$ mmHg), calculated as SD/mean, were 20% and 21% for α_{P_0} for DC_{P_0}, respectively, for the patients without atherosclerosis. For the persons with ICA stenosis ≤ 70%, they were respectively 29% for α_{P_0} and 24% for DC_{P_0}, and for the persons with ICA stenosis ≥ 90% they were the highest: 32% for α_{P_0} and 31% for DC_{P_0}.

An increase of variations of the distensibility coefficient DC for severe atherosclerotic lesions in the CCA was also observed by VAN POPELE *et al.* [14].

The results obtained indicate a statistically significant increase in the stiffness coefficient α and decrease of the distensibility coefficient DC as function of the ICA stenosis degree (Figs. 3 and 4). The mean increase of coefficient α was 0.638 per ICA stenosis increase of 20%. For comparison, the same change of the value of the stiffness coefficient α is observed for healthy people per 11 years of life [18, 24].

6. Conclusions

The ultrasound examinations performed in the CCA indicate that CCA wall elasticity has a significant association with ICA atherosclerosis. This is expressed by an increase in the stiffness coefficient α and a decrease of the distensibility coefficient DC for persons with ICA atherosclerosis in comparison to those without carotid atherosclerosis. The influence of age and arterial blood pressure on the assumed values of the parameters α and DC was taken into account in the analysis of results of the study. The CCA elastic properties were also associated with the severity of the ICA atherosclerosis expressed in our study as the degree of the ICA stenosis.

We found significant correlations between the degree of the ICA stenosis and the value of the α coefficient ($p < 0.01$) and the values of the isobaric coefficients α_{P_0} and DC_{P_0} ($p < 0.01$). For persons with ICA stenosis $\geq 90\%$, the CCA wall elasticity was significantly lower than for those with ICA stenosis $\leq 70\%$. The stiffness coefficient α for persons with ICA stenosis $\leq 70\%$ was 5.39 ± 1.64 and 5.65 ± 1.63 for the isobaric value α_{P_0}. For patients with the ICA stenosis $\geq 90\%$, it was: 6.93 ± 2.28 and 7.18 ± 2.3 for α_{P_0}. The distensibility coefficient DC for persons with ICA stenosis $\leq 70\%$ was 14.48 ± 4.77 [1/MPa] and 14.18 ± 3.45 [1/MPa] for isobaric the value DC_{P_0}. For patients with with ICA stenosis $\geq 90\%$, it was: 11.40 ± 4.20 [1/MPa] and 11.47 ± 3.53 [1/MPa] for DC_{P_0}.

References

[1] M. BARENBROCK, C. SPIEKER, S. KERBER, C. VIELHAUER, A. P. G. HOEKS, W. ZIDEK, K.-H. RAHN, *Different effects of hypertension, atherosclerosis and hyperlipidemia on arterial distensibility*, J. Hypertension, **13**, 1712–1717 (1995).

[2] G. BELCARO, G. LAURORA, M. R. CESARONE, M. T. DE SANCTIS, S. RENTON, L. C. CHONG, *Evaluation of arteriosclerosis progression with ultrasonic biopsy and intima-media thickness measurements*, VASA Band, **22**, 15–21 (1993).

[3] J. M. DE BRAY, B. GLATT, *Quantification of atheromatous stenosis in the extracranial internal carotid artery*, Cerebrovasc. Dis., **5**, 414–426 (1995).

[4] M. CZARKOWSKI, L. HILGERTNER, T. POWAŁOWSKI, D. RADOMSKI, *The stiffness of the common carotid artery in patients with Graves' disease*, International Angiology, **21**, 152–157 (2002).

[5] P. B. DOBRIN, *Mechanical properties of arteries*, Physiol. Rev., **58**, 397–460 (1978).

[6] F. HANSEN, P. MANGELL, B. SONESSON, T. LANNE, *Diameter and compliance in the human common carotid artery-variation with age and sex*, Ultrasound in Med. & Biol., **21**, 1, 1–9 (1995).

[7] T. HIRAI, S. SASAYAMA, T. KAWASAKI, S. YAGI, *Stiffness of systemic arteries in patients with myocardial infarction. A noninvasive method to predict severity of coronary atherosclerosis*, Circulation, **80**, 78–86 (1989).

[8] T. KAWASAKI, S. SASAYAMA, S. YAGI, T. ASAKAWA, T. HIRAI, *Non-invasive assessment of the age related changes in stiffness of major branches of the human arteries*, Cardiovascular Research, **21**, 9, 678–687 (1987).

[9] M. KOOL, F. LUSTERMANS, H. KRAGTEN, H. STRUIJKER BOUDIER, A. HOEKS, R. RENEMAN, H. RILA, I. HOOGENDAM, L. VAN BORTEL, *Does lowering of cholesterol levels influence functional properties of large arteries?*, Eur. J. Clin. Pharmacol., **48**, 217–223 (1995).

[10] T. LANNE, F. HANSEN, P. MANGELL, B. SONESSON, *Differences in mechanical properties of the common carotid artery and abdominal aorta in healthy males*, J. Vasc. Surg., **20**, 218–225 (1994).

[11] S. LAURENT, B. CAVIEZEL, L. BECK, X. GIRERD, E. BILLAUD, P. BOUTOUYRIE, A. HOEKS, M. SAFAR, *Carotid artery distensibility and distending pressure in hypertensive humans*, Hypertension, **23**, part 2, 878–883 (1994).

[12] S. MAKITA, A. OHIRA, R. TACHIEDA, S. ITOH, Y. MORIAI, H. NIINUMA, M. NAKAMURA, K. HIRAMORI, *Dilation and reduced distensibility of carotid artery in patients with abdominal aortic aneurysms*, Am. Heart. J. Aug., **140**, 2, 297–302 (2000).

[13] Y. NAGAL, K. KITAGAWA, H. YAMAGAMI, K. KONDO, H. HOUGAKU, M. HORI, M. MATSUMOTO, *Carotid artery intima-media thickness and plaque score for the risk assessment of the stroke subtypes*, Ultrasound in Med. & Biol., **28**, 10, 1239–1243, (2002).

[14] N. M. VAN POPELE, D. E. GROBBEE, M. L. BOTS, R. ASMAR, J. TOPOUCHIAN, R. RENEMAN, A. P. G. HOEKS, D. A. M. VAN DER KUIP, A. HOFMAN, J. C. M. WITTEMA, *Association between arterial stiffness and atherosclerosis*, The Rotterdam Study Stroke, **32,** 454–460 (2001).

[15] 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).

[16] T. POWAŁOWSKI, Z. TRAWIŃSKI, *Noninvasive evaluation of the elasticity of common carotid artery wall*, Archives of Acoustics, **19**, 451–465 (1994).

[17] T. POWAŁOWSKI, *Analysis of blood pressure wave in the human common carotid artery on the basis of non-invasive ultrasonic examinations*, Archives of Acoustics, **25**, 191–204 (2000).

[18] T. POWAŁOWSKI, *Metody ultradźwiękowe w diagnostyce ścian tętnic szyjnych*, Biocybernetyka i Inżynieria Biomedyczna 2000, Biopomiary, vol. **2**, Akademicka Oficyna Wydawnicza, Warszawa 2001.

[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., **12**, 5, 357–370 (1986).

[20] W. A. RILEY, G. W. EVANS, A. R. SHARRETT, G. L. BURKE, R. W. BARNES, *Variation of common carotid artery elasticity with intimal-medial thickness: the ARIC Study: Atherosclerosis Risk in Communities*, Ultrasound in Med. & Biol., **23**, 157–164 (1997).

[21] P. S. SABA, M. J. ROMAN, C. LONGHINI, D. SCORZONI, R. PINI, R. B. DEVEREUX, A. GANAU, *Carotid intimal-medial thickness and stiffness are not affected by hypercholesterolemia in uncomplicated essential hypertension*, Arterioscler. Thromb. Vasc. Biol., **19**, 2788–2794 (1999).

[22] T. J. Smilde, F. W. van den Bergmortel, H. Wollersheim, H. van Langen, J. J. Kastelein, A. F. Stalenhoef, *The effect of cholesterol lowering on carotid and femoral artery wall stiffness and thickness in patients with familial hypercholesterolemia*, Eur. J. Clin. Invest., **30**, 473–480 (2000).

[23] T. Szymoński, T. Powałowski, Z. Trawiński, M. Łapiński, *Evaluation of the reproducibility of vascular echo doppler system for the assessment of the carotid artery elasticity*, Acta Angiologica, **3**, 2, 83–91 (1997).

[24] Z. Trawiński, T. Powałowski, L. Hilgertner, *Influence of atherosclerosis risk factors on the common carotid artery wall elasticity*, Lecture notes of the ICB Seminars Ultrasound in Biomeasurements, Diagnostics and Therapy, Warsaw, September 1998, Ed. ICB, 42, 192–199 (1999).

[25] *Recommendations of the European Atherosclerosis Society prepared by the International Task Force for Prevention of Coronary Heart Disease*, Nutr. Metab. Cardiovasc. Dis., **2**, 113 (1992).