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ADDITIONAL ULTRASOUND CAPABILITIES FOR LOCAL HAEMODYNAMICALLY SIGNIFICANT CAROTID DEFORMITY: A ONE-STAGE OBSERVATIONAL STUDY

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ABSTRACT

Background. Despite a wide range of studies, no consensus has been reached on the relative weight of ultrasound parameters for assessing local haemodynamically significant carotid deformations.

Objectives. To estimate a diagnostic value for an additional multiparametric ultrasound parameter for local haemodynamically significant carotid deformations.

Methods. In the first phase, 388 patients underwent an outpatient multiparametric ultrasound examination of the carotid arteries. The study involved patients of the age of 18 and older with a primary referral for carotid ultrasound by a resident physician, neurologist or cardiologist in order to rule out a carotid pathology. As a supplement to the main haemodynamic significance assessment parameters, we introduced an additional metric — the deformity coefficient — in order to diagnose carotid abnormalities. Based on the first phase results, two cohorts were selected. Cohort 1 (control) consisted of patients with no abnormalities in multiparametric carotid ultrasound. Cohort 2 consisted of patients with isolated unilateral internal carotid artery deformities at no haemodynamically significant stenosis of common and internal carotid arteries in multiparametric carotid ultrasound. In the second phase, the patients underwent transcranial duplex sonography of the middle cerebral arteries, in order to detect regional haemodynamically significant internal carotid artery deformities.

Results. Mathematical modelling of abnormal arteries produced the empirical upper deformity coefficient thresholds to distinguish acute angulation. This value is >1.41 for C-shaped and >1.34 — for S-shaped curves.

Subsequent statistical analysis revealed a clear positive correlation between angulation and the deformity coefficient at a $p < 0.01$ significance level. More acute angulation corresponds to higher coefficient values.

The Spearman correlation between the deformity coefficient and blood flow asymmetry values for middle cerebral artery was 0.89. This defines a significant positive correlation (higher deformity coefficient corresponds to higher blood flow asymmetry) at a $p < 0.01$ significance level.

Conclusion. The deformity coefficient is an additional ultrasound parameter for assessing local haemodynamically significant carotid abnormalities.

Keywords: arterial ultrasound, carotid tortuosity, haemodynamically significant deformity, ICA kink, ICA angulation

Conflict of interest: the authors declare no conflict of interest.

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ДОПОЛНИТЕЛЬНЫЕ ВОЗМОЖНОСТИ УЛЬТРАЗВУКОВОГО ИССЛЕДОВАНИЯ ПРИ ОЦЕНКЕ ЛОКАЛЬНЫХ ГЕМОДИНАМИЧЕСКИ ЗНАЧИМЫХ ДЕФОРМАЦИЙ СОННЫХ АРТЕРИЙ: ОДНОМОМЕНТНОЕ НАБЛЮДАТЕЛЬНОЕ ИССЛЕДОВАНИЕ

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АННОТАЦИЯ

Введение. Несмотря на многочисленные исследования, до сих пор нет единого мнения по поводу удельного веса тех или иных ультразвуковых параметров при оценке локальных гемодинамически значимых деформаций сонных артерий.

Цель исследования — определение диагностической ценности дополнительного параметра локальных гемодинамически значимых деформаций сонных артерий при мультипараметрическом ультразвуковом исследовании.

Методы. Первым этапом в амбулаторно-поликлинических условиях 388 пациентам выполнено мультипараметрическое ультразвуковое исследование сонных артерий. В исследование включены пациенты от 18 лет и старше, впервые направленные на ультразвуковое исследование сонных артерий участковым терапевтом, неврологом или кардиологом для исключения патологий сонных артерий. При выявлении деформаций сонных артерий кроме основных параметров для оценки гемодинамической значимости подсчитывался предложенный нами дополнительный параметр — коэффициент деформации. По результатам первого этапа исследования были сформированы две группы. В первую (контрольную) группу отобраны пациенты, у которых по результатам мультипараметрического ультразвукового исследования сонных артерий патологий не выявлено. Во вторую группу отобраны пациенты, у которых по результатам мультипараметрического ультразвукового исследования сонных артерий были выявлены изолированные односторонние деформации внутренней сонной артерии при отсутствии гемодинамически значимых стенозирующих поражений общей сонной артерии и внутренней сонной артерии. Вторым этапом этим пациентам выполнено транскраниальное дуплексное сканирование средних мозговых артерий с целью выявления региональных гемодинамически значимых деформаций внутренних сонных артерий.

Результаты. В результате математического моделирования деформированных артерий эмпирически были получены значения коэффициента деформации, выше которых деформация оценивается как деформация с острыми углами. При С-образных деформациях это значение более 1,41, при S-образных деформациях это значение более 1,34.

Дальнейший статистический анализ показал, что между углом деформации и соответствующим коэффициентом деформации наблюдается явно выраженная положительная корреляция на уровне значимости $p < 0{,}01$. Чем больше выражен угол деформации, тем больше значение коэффициента деформации.

Расчет коэффициента корреляции Спирмена между значениями коэффициента деформации и асимметрией кровотока по средней мозговой артерии дал значение $p = 0{,}89$, что соответствует значимой положительной корреляции (чем выше коэффициент деформации, тем более выражена асимметрия кровотока) на уровне значимости $p < 0{,}01$.

Заключение. Коэффициент деформации является дополнительным ультразвуковым параметром оценки локальных гемодинамически значимых деформаций сонных артерий.

Ключевые слова: ультразвуковое исследование артерий, деформация сонных артерий, гемодинамически значимая деформация, патологический изгиб ВСА, угол деформации ВСА

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BACKGROUND

Circulatory diseases account for a sizeable share of total mortality in the Russian Federation[1,2] [1, 2]. Among them, coronary heart and cerebrovascular diseases are the leading causes of death (53 and 31%, respectively) [1, 3].

Atherosclerotic carotid arteries and internal carotid artery (ICA) tortuosity comprise the factors of cerebral vascular failure [4–7]. Both pathologies provoke age-related haemodynamic abnormalities and aggravate cerebrovascular symptoms leading towards a higher risk of mortality and disability [8–10].

One-sixth of patients exhibit signs of cognitive impairment of varying severity preceding an acute cerebral accident [11–13]. Cognitive impairment ranges from mild cognitive deficits to severe dementia [14–16].

Modern carotid artery research cannot be viewed without employing multiparametric ultrasound — duplex scanning (DS) of the carotid arteries[3] [17–20]. This non-invasive imaging technique has several clear advantages over multislice computed tomography (MSCT), magnetic resonance angiography (MRA) and contrast X-ray angiogra-

[1] Rosstat. *Healthcare in Russia. 2019: A statistical digest.* Moscow: 2019. 170 pp.
[2] World Health Organization. *World's top 10 causes of death;* 2020. Available at: https://www.who.int/ru/news-room/fact-sheets/detail/the-top-10-causes-of-death
[3] Russian Society of Angiologists and Vascular Surgeons, Association of Cardiovascular Surgeons of Russia, Russian Scientific Society of Endovascular Surgeons and Interventional Radiologists, All-Russian Scientific Society of Cardiologists, Association of Phlebologists of Russia. *National recommendations on patient management in brachiocephalic artery disease*. Moscow, 2013. 72 pp.

phy, which are the gold standard in arterial basin research. Its most prominent advantages are non-invasiveness and the lack of contrast agents, radiation exposure or side effects. The technique is also less sophisticated, fast, inexpensive and easily reproducible.

DS usually allows a qualitative assessment of the carotid artery deformity localisation, shape and haemodynamic significance [21, 22].

The main parameters for estimating local haemodynamically significant abnormalities are flow turbulence at a deformation site, acute deformity angulation and before-vs.-after deformation peak flow velocity (PFV) ratio at a maximal angulation site[4] [17, 23, 24]. However, no consensus has been reached on the relative weight of these parameters in estimating local haemodynamically significant carotid deformations. The situation is also exacerbated by the rather subjective nature of the two of three parameters which strongly depend on the method (e.g., application of Doppler angle correction for PFV measurements), ultrasound scanner quality and settings (e.g., in measuring blood flow turbulence).

Therefore, research into additional ultrasound parameters for estimating local haemodynamically significant carotid artery deformities appears of particular relevance.

Objectives. A study of the diagnostic value of an additional multiparametric ultrasound parameter for estimating local haemodynamically significant carotid artery deformations.

METHODS

Experimental design

In order to achieve the goals, the first phase involved 388 individuals for outpatient multiparametric ultrasound examination of the carotid arteries. If carotid deformities were detected, the deformity coefficient (DC) could be estimated for downstream statistical analyses, in addition to the main parameters.

Two cohorts were selected based on the first phase results. Cohort 1 consisted of patients with no abnormalities in DS. It was taken as the control. Cohort 2 consisted of patients with DS-revealed isolated unilateral ICA deformities at no haemodynamically significant stenosis of ICAs and common carotid arteries (CCAs).

In the second phase, the patients underwent transcranial duplex sonography of middle cerebral arteries (MCAs) for detecting local haemodynamically significant ICA deformities. An >30% PFV asymmetry in MCA was assumed to mark a regional haemodynamically significant deformity. The phase aimed to infer the DC vs. blood flow asymmetry correlation for MCAs.

Facilities

Patient selection and carotid ultrasound scanning were performed in outpatient facilities at the City Polyclinic of Gelendzhik City Resort during October 2017 — September 2020. Statistical data analyses were carried out at the Department of Diagnostic Radiology of Kuban State Medical University.

Eligibility criteria

Inclusion criteria

The study involved 18-year and older patients with a primary referral for carotid ultrasound by a resident physician, neurologist or cardiologist, in order to rule out a carotid pathology.

Non-inclusion criteria

Previous acute cardiovascular events (acute myocardial infarction, stroke, transient ischaemic attack), rhythm disturbances detectable at the time of study, patient refusal to participate.

Description of eligibility criteria (diagnostic criteria)

The main eligibility criteria for outpatients (males and females) comprised the values of DC vs. deformity angulation and blood flow asymmetry correlation in MCA.

Cohort construction

All patients (n = 388) underwent an outpatient multiparametric ultrasound examination of the carotid arteries. If carotid deformities were detected, the DC values were estimated for downstream statistical analyses, in addition to the main parameters.

Two cohorts were selected based on the first phase results. Cohort 1 consisted of patients with no abnormalities in DS. It was taken as a control. Cohort 2 consisted of patients with DS-revealed isolated unilateral ICA deformities at no haemodynamically significant ICA or CCA stenosis.

[4] Kulikov V.P. *Fundamentals of vascular ultrasound.* Moscow: Vidar-M; 2015. 392 pp.

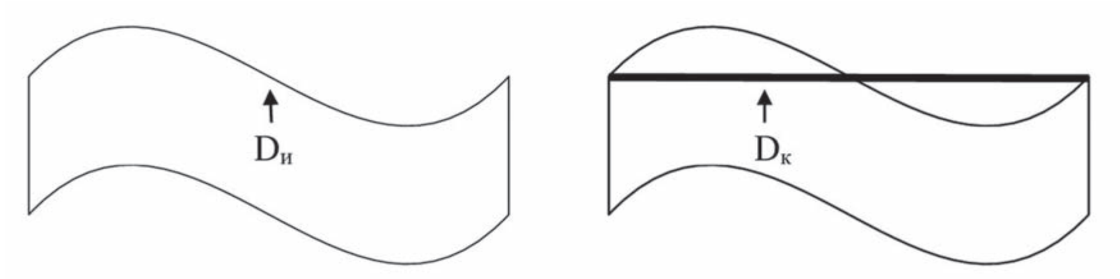

Fig. 1. Deformity coefficient estimation diagram. Note: $D_и$ — true length of vessel in deformed section, $D_к$ — shortest beginning-to-end length of deformed section.

The control cohort included 44 patients, and the second cohort 31 patients. In the second phase, the patients had transcranial duplex MCA sonography to detect local haemodynamically significant ICA deformities. The phase aimed to infer the DC vs. blood flow asymmetry correlation for MCAs.

Research targets

Main target

To collect evidence on the DC applicability for determining haemodynamically significant carotid artery deformities. To examine the DC correlation with deformity angulation and blood flow asymmetry in MCA.

Complementary targets

No complementary research targets were envisaged.

Table 1. DC for variant angulation, C-shaped curve

Deformity angulation	Deformity coefficient
150°	1.03
120°	1.15
90°	1.41
60°	2.00
45°	2.60
30°	3.85

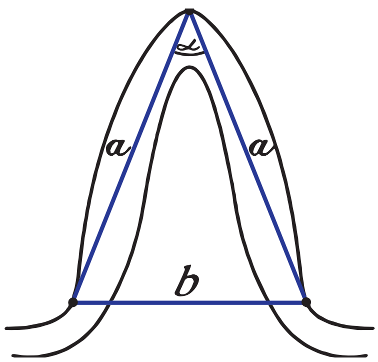

Fig. 2 presents a diagram of the C-shaped vessel curve.

Methods of target registration

If carotid deformities were detected in DS, the following actions were performed: deformity localisation assessment; deformity shape assessment; deformity angulation measurement; DC value estimation.

DC is the designated additional parameter that we have developed for estimating haemodynamically significant deformities (active application for invention “A method for differential diagnosis of haemodynamic status of carotid arteries”, No. 2021137029 of 14.12.2021). The true length of vessels in a deformed section ($D_и$) is estimated for DC calculation using ultrasound data. This is followed by measuring the shortest beginning-to-end length of the deformed section. The latter defines the assumed length of vessel in its straight course ($D_к$). DC is obtained by dividing $D_и$ by $D_к$ (Fig. 1).

Calculation Formula 1:

$$DC = D_и / D_к, \quad (1)$$

where DC is vessel’s deformity coefficient, $D_и$ — true length of vessel in deformed section, $D_к$ — shortest beginning-to-end length of deformed section.

A mathematical model of C- and S-shaped curves was developed, in order to obtain empirical DC values for different deformity angulations. To simplify the model, the sides formed by a deformation angle were assumed equal in all deformation types. The ratio of the true vs. assumed (straight-course) length of the deformed artery is then independent of the deformed sides length and varies only with angulation.

DC for C-shaped curves was calculated with Formula (2):

DC for S-shaped curves was calculated with Formula (3):

The DC values for variant angulation in C-shaped curves are provided in Table 1.

$$DC = \frac{a+a}{b} = \frac{a+a}{\sqrt{a^2+a^2-2*a*a*cos\propto}} = $$
$$= \frac{2*a}{\sqrt{2*a^2-2*a^2*cos\propto}} = \frac{1.41}{\sqrt{1-cos\propto}}. \quad (2)$$

The DC values for variant angulation in S-shaped curves are provided in Table 2.

$$DC = \frac{a+a+a}{2*\sqrt{a^2+(\frac{a}{2})^2-2*a*a/2*cos\propto}} = $$
$$= \frac{3*a}{2*\sqrt{5/4*a^2-a^2*cos\propto}} = \frac{1.5}{\sqrt{1.25-cos\propto}}. \quad (3)$$

Hence, the empirical DC estimates were obtained as shown above, in which a deformation is considered an acute angulation. This value is >1.41 in C-shaped and >1.34 — in S-shaped curves.

Practical DC values will exceed empirical estimates, since the true length of vessel exceeds the sum of the formed triangle sides.

Transtemporal access was used in transcranial duplex scanning, in order to assess the MCA velocity parameters. Upon MCA detection, PFV was measured in M1 segment. An ≥30% blood flow asymmetry in the right and left MCA was a measure of impaired regional circulation in a deformed ICA.

Variables (predictors)

Spearman's correlation coefficient was used to establish statistical significance of the dependency between DC, angulation and MCA blood flow asymmetry for detecting deformed ICAs.

Statistical analysis

Sample size determination

No prior sample size determination was carried out.

Methods of statistical analysis

Descriptive statistics, as well as comparative and qualitative data analyses, were employed for data processing to attain the study objectives. Analysis was performed with the Statistica v.12 software package (StatSoft, Russia).

The Mann—Whitney *U*-test was used to establish significance of the inter-cohort differences with non-normally distributed data, since the test has no prerequisite for data normality.

A single ranked series was constructed in ascending order for the values in compared samples.

Table 2. Deformity coefficient for variant angulation, S-shaped curve

Deformity angulation	Deformity coefficient
150°	1.03
120°	1.13
90°	1.34
60°	1.73
45°	2.04
30°	2.42

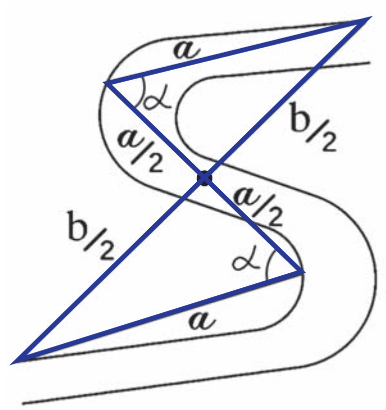

Fig. 3 presents a diagram of the S-shaped vessel curve.

This was followed by the Mann—Whitney criterion calculation with Formula (4):

$$U = n_1 \bullet n_2 + \frac{n_x(n_x+1)}{2} - T_x, \quad (4)$$

where n_1 and n_2 are the sizes of samples 1 and 2, respectively; T_x — max{T_1, T_2 }, T_1 and T_2 are the sum of ranks belonging to samples 1 and 2, respectively.

The empirical Mann—Whitney estimates are further compared vs. thresholds at a significance level *p*. An empirical value exceeding threshold denotes a significant difference between samples with error not exceeding *p*.

In order to examine the correlation between events described by non-normal data, Spearman's rank correlation coefficient was used as a non-parametric approach.

In doing so, each value compared was assigned an ordinal number (rank) in ascending or descending order. The rank difference (*d*) was then determined for each pair of values. Spearman's coefficient was calculated with Formula (5):

$$\rho = 1 - \frac{6 \bullet \sum d^2}{n(n^2-1)}. \quad (5)$$

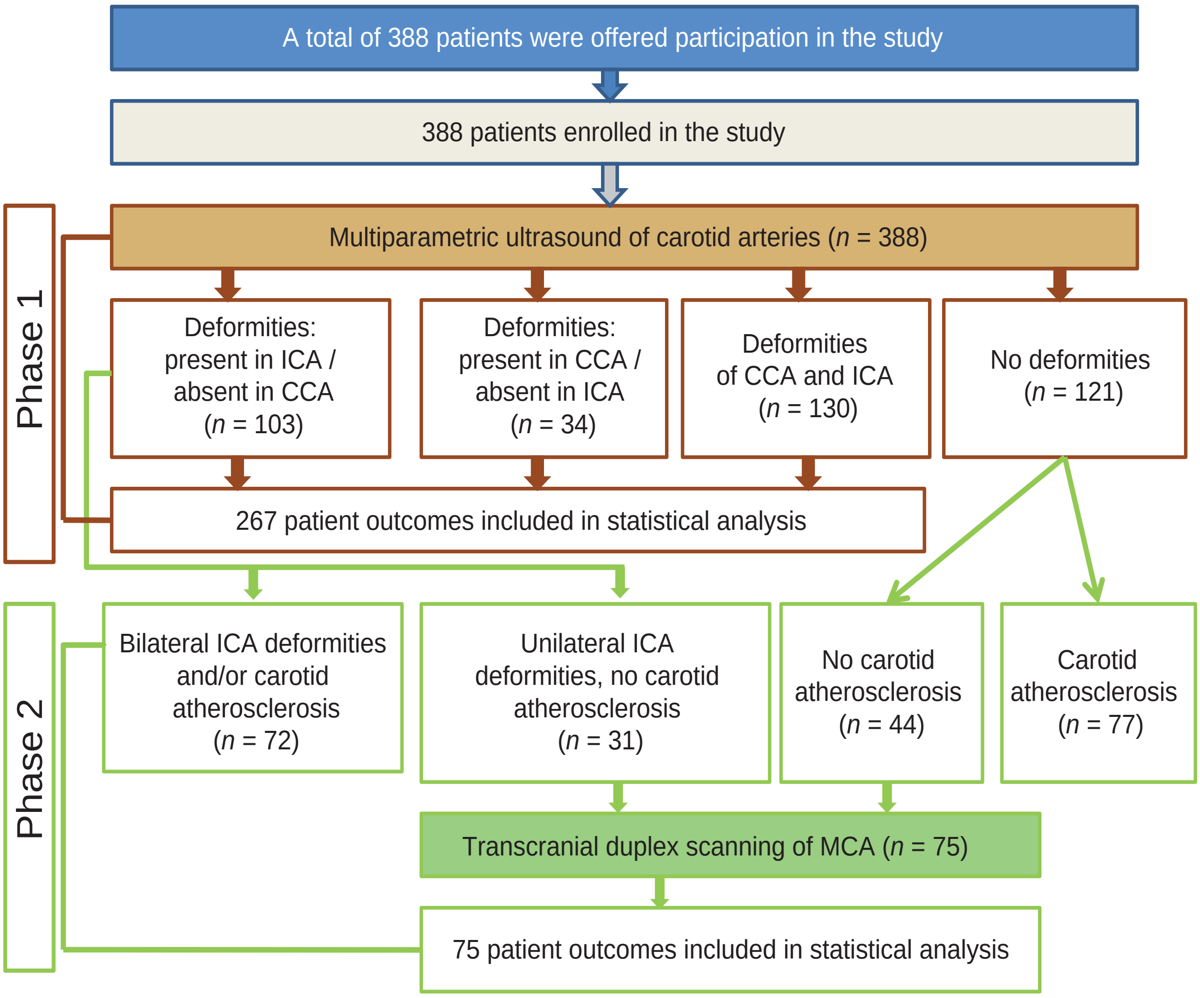

Fig. 4. Study design flowchart. Note: BCA — internal carotid artery, OCA — common carotid artery, CA — carotid artery, CMA — middle cerebral artery/

Spearman's coefficients ρ were interpreted according to the Chaddock scale.

RESULTS

Study sample selection workflow

The study sample selection and design flowchart are detailed in Fig. 4.

Sample (cohort) description

In the first study phase, 388 patients underwent multiparametric ultrasound of the carotid arteries.

Patient distribution by gender is detailed in Table 3.

The patients distribution by age is detailed in Table 4.

If carotid deformities were detected, the DC values were estimated for downstream statistical analyses, in addition to the main parameters.

Two cohorts were selected based on the first phase results. Cohort 1 consisted of patients with no abnormalities in DS. It was taken as a control. Cohort 2 consisted of patients with DS-revealed isolated unilateral ICA deformities at no haemodynamically significant ICA or CCA stenosis.

In the second phase, the patients underwent transcranial duplex MCA sonography, in order to detect local haemodynamically significant ICA deformities. An >30% PFV asymmetry in MCA was assumed to mark a regional haemodynamically significant deformity. The phase aimed to infer the DC vs. blood flow asymmetry correlation for MCAs.

The control cohort included 44 patients, and the second cohort — 31.

Patient distribution by gender and age in both cohorts is detailed in Table 5.

As Table 5 shows, patient distribution by age and gender does not significantly differ between cohorts.

Table 3. Patients distribution by gender

Number of individuals	Gender	
	males	females
388 (100%)	185 (48%)	203 (52%)

Table 4. Patients distribution by age (M ± SD)

Mean age, years	Mean age, years	
	males	females
53.63 ± 12.10	52.18 ± 12.40	54.19 ± 11.70

Table 5. Patient distribution by gender (%) and age (M ± SD)

Cohort	Number of individuals	Age	Gender	
			males	females
Cohort 1 (control)	44	43.0 ± 11.7	23 (52%)	21 (48 %)
Cohort 2	31	49.0 ± 15.5	16 (52%)	15 (48 %)

Table 6. Prevalence of carotid deformations

Number of patients	Deformities: present in ICA / absent in CCA	Deformities: absent in ICA / present in CCA	Deformities of CCA and ICA	No deformities
n = 388	103 (26.5%)	34 (8.8%)	130 (33.5%)	121 (31.2%)

Note: CCA — common carotid artery, ICA — internal carotid artery.

Key findings

In order to achieve the objectives, the first phase enrolled 388 individuals for an outpatient multiparametric ultrasound examination of the carotid arteries.

The prevalence of carotid artery deformations among the patients is shown in Table 6.

The detected deformations were subdivided according to angulation into possessing >90° (non-acute angulation) and <90° (acute angulation) angles. The shape categories were C-shaped and S-shaped deformations.

In this study, C-shaped non-acute angulations were established in 200 patients, while S-shaped non-acute angulations — in 99 patients. No acute angulation has been registered for the above deformity types. DC values were estimated in all cases (Table 7).

In this study, C-shaped acute angulations were revealed in 58 patients, while S-shaped acute angulations — in 55. Acute angulation has been registered for the above deformity types. DC values were estimated in all cases (Table 8).

A Spearman correlation analysis was performed for the total relevant patients sample (n = 267), in order to obtain primary estimates of the DC applicability and its association with deformity angulation. The results are shown in detail in Table 9.

The Table data suggests clear positive angulation vs. DC correlation at a $p < 0.01$ significance level. More acute angulation corresponds to higher DC values.

Two cohorts were selected based on the first phase results. Cohort 1 consisted of patients with no abnormalities in multiparametric carotid ultrasound. It was taken as a control. Cohort 2 consisted of patients with isolated unilateral ICA deformities at no haemodynamically significant ICA or CCA stenosis in multiparametric carotid ultrasound.

In the second phase, the patients had transcranial duplex MCA scanning to detect local

Table 7. Deformity coefficient estimates for non-acute angulations

Deformity type	DC (M ± SD)
C-shaped non-acute angulation	1.24 ± 0.04
S-shaped non-acute angulation	1.38 ± 0.04

Table 8. Deformity coefficient estimates for acute angulations

Deformity type	DC
C-shaped acute angulation	1.63 ± 0.04
S-shaped acute angulation	1.69 ± 0.041

Table 9. Angulation vs. deformity coefficient values correlation coefficients (n = 267, p < 0.01)

Parameter	DC (right)	DC (left)
Angulation (right)	0.8336	0.3849
Angulation (left)	0.3771	0.8566

haemodynamically significant ICA deformities. An >30% PFV asymmetry in MCA was assumed to mark a regional haemodynamically significant deformity. This phase was aimed at inferring the DC vs. blood flow asymmetry correlation for MCA.

The control cohort included 44 patients, and the second cohort — 31.

The distribution of MCA blood flow asymmetry data in cohorts 1 (Fig. 5) and 2 (Fig. 6) was further examined for normality.

A graphical data analysis revealed close-to-normal distribution, with certain deviations. We employed the Kolmogorov—Smirnov, Lilliefors and Shapiro-Wilk numerical criteria to analyse normality more finely (Figs 7, 8).

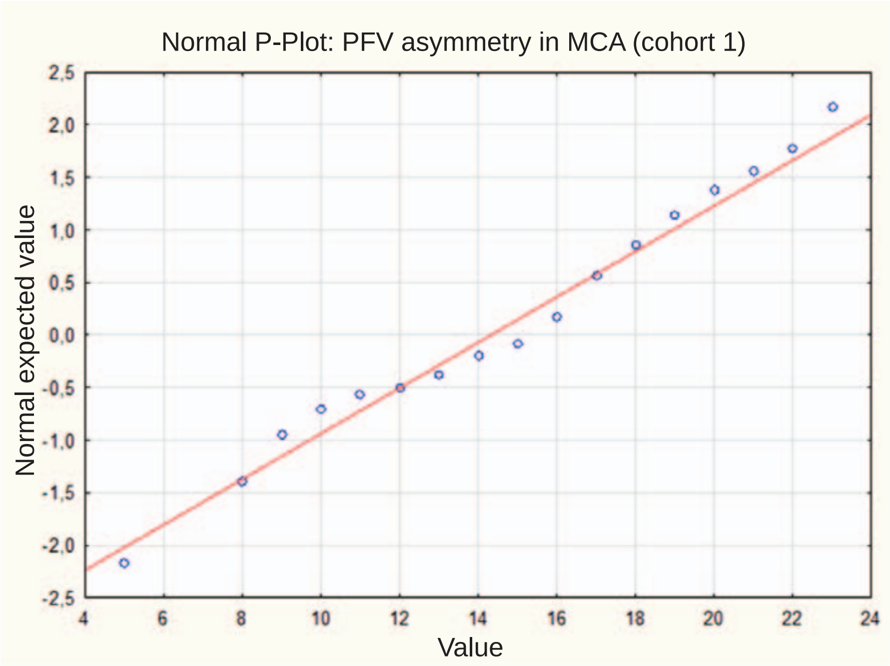

Fig. 5. MCA blood flow asymmetry distribution in cohort 1.
Note: ПСК — peak blood flow velocity, CMA — middle cerebral artery.

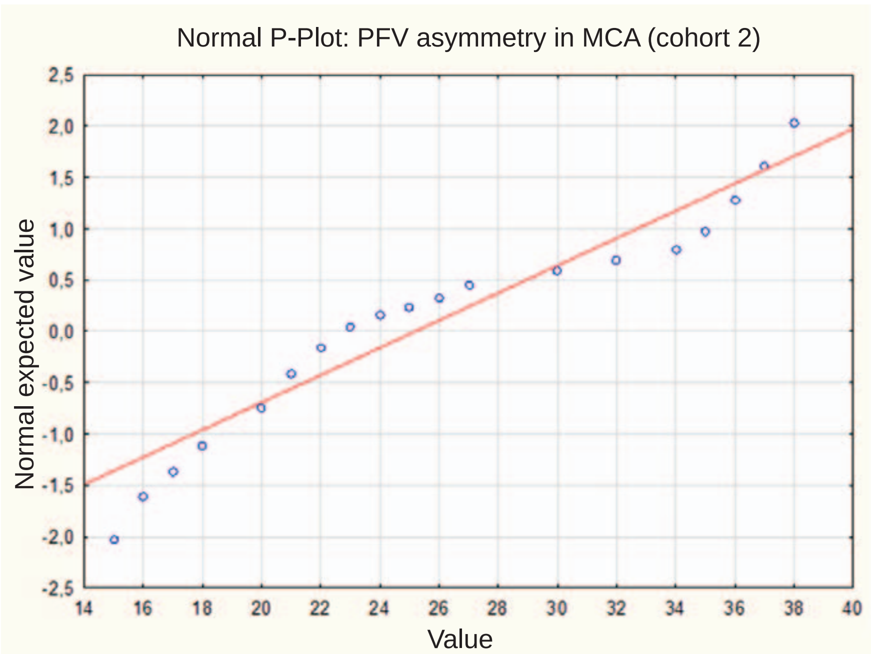

Fig. 6. MCA blood flow asymmetry distribution in cohort 2.
Note: ПСК — peak blood flow velocity, CMA — middle cerebral artery.

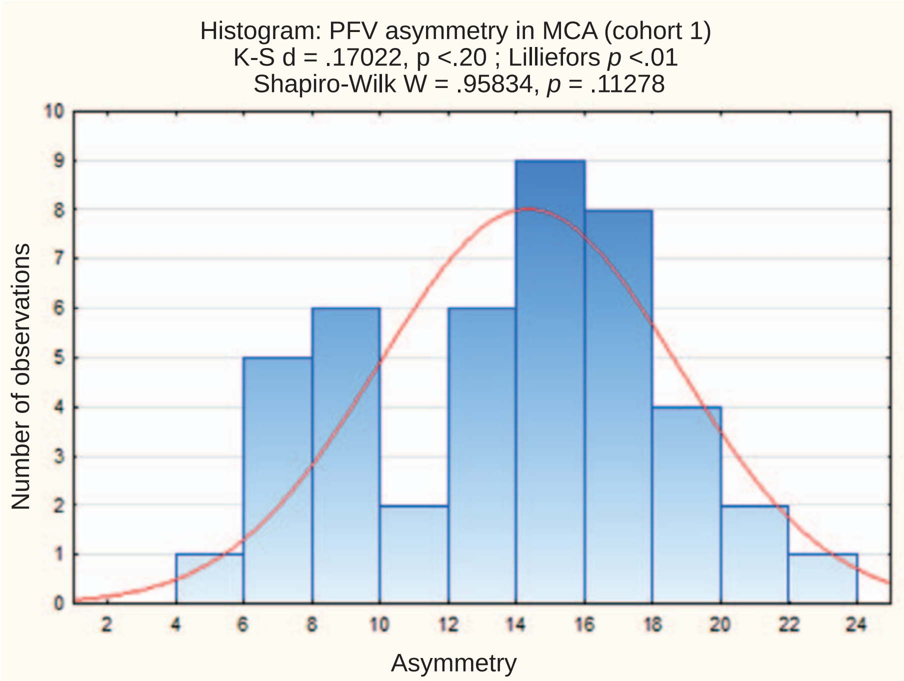

Fig. 7. Blood flow asymmetry histogram in cohort 1.
Note: ПСК — peak blood flow velocity, CMA — middle cerebral artery.

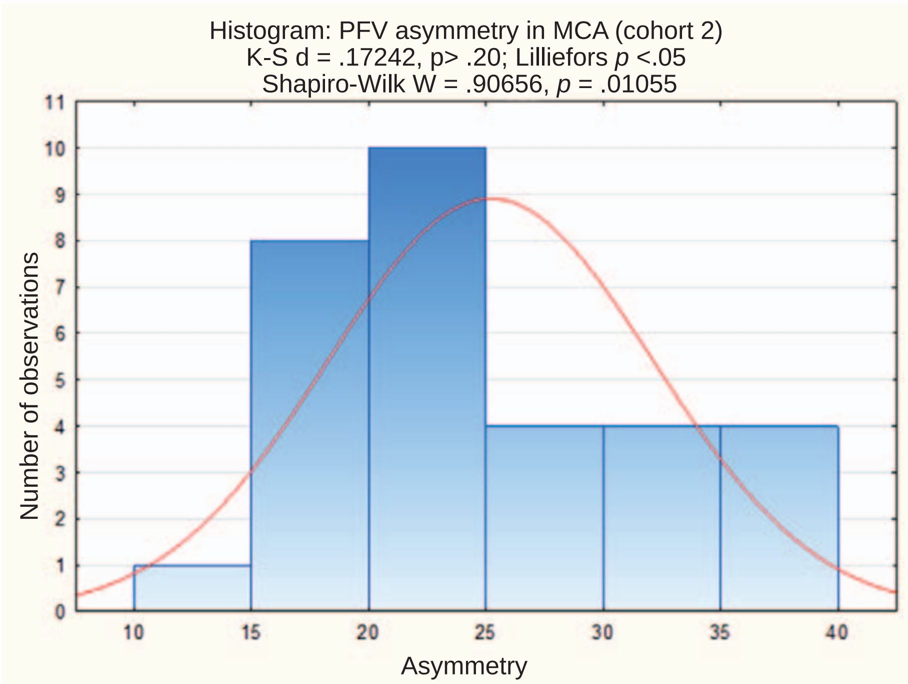

Fig. 8. Blood flow asymmetry histogram in cohort 2.
Note: ПСК — peak blood flow velocity, CMA — middle cerebral artery.

The normality test results in cohort 1 are equivocal. The Kolmogorov—Smirnov (D = 0.1702, p < 0.2) and Shapiro-Wilk tests (W = 0.958, p = 0.113) indicated no significant sample deviation from a normal distribution. Meanwhile, the Lilliefors test significance (p < 0.01) implied differences between the samples.

Cohort 2 revealed a similar situation. The Kolmogorov-Smirnov criterion (D = 0.172, p > 0.2) did not reject the hypothesis of no sample's deviation from normality. At the same time, significant deviations were indicated by the Shapiro—Wilk (W = 0.906, p = 0.011) and Lilliefors tests (p < 0.05).

Table 10. Mann—Whitney test results for middle cerebral artery blood flow asymmetry in cohorts 1 and 2

Parameter	Value
Sum of ranks T1	1,089
Sum of ranks T2	1,761
U-value	99
Significance level *p*	< 0.01

In cohort 1 (n_1 = 44), the mean blood flow asymmetry was 14.3%; standard deviation *S* = 4.38. In cohort 2 (n_2 = 31), the mean blood flow asymmetry was 25.2%; standard deviation *S* = 6.94.

In order to incorporate the incomplete fitness to normality in cohorts 1 and 2, the non-parametric Mann—Whitney criterion was employed. The aim was to estimate the significance of inter-cohort MCA blood flow asymmetry differences due to its robustness to non-normal data (Table 10).

The calculation shows significant differences between cohorts 1 and 2 at a $p < 0.01$ significance level.

The DC vs. MCA blood flow asymmetry was further examined. Spearman's correlation coefficient estimated for the DC vs. blood flow asymmetry was ρ = 0.89. This indicates a significant positive correlation (higher coefficient values correspond to more asymmetric blood flow) at a $p < 0.01$ significance level.

Complementary findings

No complementary findings were obtained.

DISCUSSION

Key findings summary

The study suggests that DC is applicable as an additional parameter for the estimation of local haemodynamically significant carotid artery deformities.

Study limitations

The small sample size does not allow confident extrapolation of the evidence to general population.

Interpretation of results

Ultrasound is currently the primary method for detecting carotid artery deformities. For suspected carotid steno-occlusive lesions, as well as deformities, examination should commence with DS and further supplemented with MRA or MSCT, if necessary [17–20]. Contrast X-ray angiography is applied only if the above non-invasive methods are contradictory [17]. Despite high informativity, no multicentre randomised trials that would help establish a unified approach to ICA deformity patients examination and treatment [17] were conducted or are under way (apart from atherosclerotic ICA studies). No consensus has been reached on the criteria or their thresholds to assess the haemodynamic significance of ICA deformities, which renders research into additional assessment parameters a timely requirement.

Any carotid deformation implies lengthening of the artery in a limited space. The elongated section therefore changes its rectilinear course and deforms into various shapes. The assumption behind the development of an additional assessment parameter was the putative mathematical relationship between the deformed and assumed straight-course artery lengths. Our aim was to establish this pattern.

In doing so, a mathematical model of C- and S-shaped deformations was developed. The model was used to obtain empirical DC estimates above which a deformity could be considered an acute angulation. This value is >1.41 in C-shaped and >1.34 — in S-shaped curves.

Many authors believe that the haemodynamic significance of the deformity is mainly associated with the degree of curvature of the carotid arteries [5, 11, 23]. Our study confirms these findings. The DC values significantly correlate both with deformity angulation (ρ = 0.85, $p < 0.01$) and blood flow asymmetry in MCA (ρ = 0.89, $p < 0.01$).

Most authors believe that the velocity parameters estimated at a maximal angulation site, before and after carotid deformation, provide reliable evidence for assessing haemodynamic significance. However, there are no commonly accepted PFV thresholds at maximal angulation above which a deformation becomes haemodynamically significant. A variety of sources suggests values of 150, 200 or 250 cm/sec. Nor is there a common view of the Doppler angle correction applicability to measuring PFV. Some evidence supports the Doppler correction, while others believe that the high labour intensity and occasional unfeasibility of adequate angle correction render its use unnecessary [17, 24]. Our study generated no results on velocity parameters in deformed arteries, since finding a link between those and DC was inapplicable to its current aim.

The DC parameter developed here (active application for invention "A method for differential diagnosis of haemodynamic status of carotid arteries", No. 2021137029 of 14.12.2021) can be easily estimated and does not require high-quality CDI. It can be estimated in B-mode, if necessary, or Doppler mode. It does not rely on knowledge of angulation, albeit incorporating it implicitly. In a dynamic observation, it is easily reproducible and mostly objective.

CONCLUSION

Thus, the application of the additional parameter developed herein for estimating haemodynamically significant carotid artery deformities is mathematically justified. The DC values clearly correlate positively with vessel angulation at the significance level of $p < 0.01$. More acute angulation corresponds to higher DC values.

In analysing the DC relationship with PFV asymmetry in MCA, Spearman's correlation coefficient estimate for the DC vs. blood flow asymmetry was $\rho = 0.89$. This indicates a significant positive correlation at a $p < 0.01$ significance level (higher coefficient values correspond to more asymmetric blood flow).

COMPLIANCE WITH ETHICAL STANDARDS

No expert evaluation of the trial protocol was requested. The study was approved by the Independent Committee for Ethics of Kuban State Medical University (Mitrofana Sedina str., 4, Krasnodar, Russia), Minutes No. 100 of 25.06.2021. All patients provided a free written informed consent of participation in the study.

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AUTHOR CONTRIBUTIONS

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Conceptualisation — concept statement; statement and development of key goals and objectives.

Conducting research — data analysis and interpretation.

Text preparation and editing — drafting of the manuscript, its critical revision with a valuable intellectual investment; contribution to the scientific layout.

Approval of the final manuscript — acceptance of responsibility for all aspects of the work, integrity of all parts of the article and its final version.

Methodology development — methodology and model development.

Visualisation — preparing data for visualisation.

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Conceptualisation — development of key goals and objectives.

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ВКЛАД АВТОРОВ

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Разработка концепции — формирование идеи; формулировка и развитие ключевых целей и задач.

Проведение исследования — анализ и интерпретация полученных данных.

Подготовка и редактирование текста — составление черновика рукописи, его критический пересмотр с внесением ценного замечания интеллектуального содержания; участие в научном дизайне.

Утверждение окончательного варианта статьи — принятие ответственности за все аспекты работы, целостность всех частей статьи и ее окончательный вариант.

Разработка методологии — разработка методологии, создание моделей.

Визуализация — подготовка визуализации данных.

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Утверждение окончательного варианта статьи — принятие ответственности за все аспекты работы, целостность всех частей статьи и ее окончательный вариант.

Разработка методологии — разработка методологии, создание моделей.

Визуализация — подготовка визуализации данных.

Проведение статистического анализа — применение статистических методов для анализа и синтеза данных исследования.

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