

# Internal carotid and vertebral arteries diameters and their interrelationships to sex and left/right side

G. Spasojević<sup>1</sup>, S. Vujmilović<sup>2</sup>, Z. Vujković<sup>3</sup>, R. Gajanin<sup>4</sup>, S. Malobabić<sup>5</sup>, N. Ponorac<sup>6</sup>, L. Preradović<sup>7</sup>

<sup>1</sup>Department of Anatomy, Faculty of Medicine, University of Banja Luka, Bosnia and Herzegovina

<sup>2</sup>Department of Radiology, Faculty of Medicine, University Clinical Centre of Republic Srpska, University of Banja Luka, Bosnia and Herzegovina

<sup>3</sup>Neurology Clinic, Faculty of Medicine, University Clinical Centre of Republic Srpska, University of Banja Luka, Bosnia and Herzegovina

<sup>4</sup>Department of Pathology, Faculty of Medicine, University Clinical Centre of Republic of Srpska, University of Banja Luka, Bosnia and Herzegovina

<sup>5</sup>Institute of Anatomy Dr. Niko Miljanić, Faculty of Medicine, University of Belgrade, Serbia

<sup>6</sup>Department of Physiology, Faculty of Medicine, University of Banja Luka, Bosnia and Herzegovina

<sup>7</sup>Informatic in Medicine, Faculty of Medicine, University of Banja Luka, Bosnia and Herzegovina

[Received: 17 May 2019; Accepted: 13 June 2019]

**Background:** The available anatomical data about diameters of inflow vessels to the circle of Willis reflect various diagnostic and imaging methods used, sample sizes, levels of measurements, and lack of possible specific ethnic, regional or genetic data. Additionally, the data are often without distinctions about left-right or sex.

**Materials and methods:** Therefore, using computed tomography angiography (CTA) we investigated diameters of internal carotid (ICA) and vertebral (VA) arteries in 70 adult persons (28–75 years) of both sexes (34 males and 36 females), at predefined cervical parts of ICA (2 cm above carotid bifurcation) and of VA (5 mm before VA penetrated the dura).

**Results:** Sex differences were expressed as highly significant larger diameters of left VA (LVA) in males (3.49 mm) than in females (3.00 mm), and as significantly larger diameters of right VA (RVA) in males (3.20 mm) than in females (2.82 mm), as well as of right ICA (RICA) diameters in males (5.04 mm) than in females (4.56 mm), but without such difference for left ICA (LICA) between males (4.82 mm) and females (4.60 mm). Intrasex (in males or in females) left-right differences of ICA and VA diameters were not significant. Significant positive correlations were found in females between RICA and RVA, and in males between RICA and LICA. Calculated mean sum of ipsilateral diameters of right arteries (RAA = RICA + RVA) was in males 8.25 mm, in females 7.38 mm, and of left arteries (LAA = LICA + LVA) was in males 8.31, and in females 7.60 mm, without statistically significant difference between RAA and LAA, neither in males, nor in females. Statistically highly significant larger sums of diameters were in males than in females for both, RAA and LAA.

**Conclusions:** Our findings, as the first data about diameters of ICA and VA systematically obtained by CTA in the population of western Balkans, suggest that in the studies of these diameters is absolutely necessary to analyse separately the data for sex, and to use defined standard levels. (Folia Morphol 2020; 79, 2: 219–225)

**Key words:** internal carotid, vertebral artery, diameters, left-right differences, sex differences

## INTRODUCTION

In normal circumstances both, internal carotid arteries (ICAs; "anterior circulation") and vertebral arteries (VAs; "posterior circulation"), completely deliver the blood to the circle of Willis (COW) providing the inflow to the brain. The data about arterial luminal diameters are one of important underlying factors for understanding the haemodynamics of other factors (such as anatomical data, pulses, end-diastolic and peak velocities, total blood flow, etc.). In spite of existence of these multiple factors, large studies always discuss only the degree of stenosis — "only size (diameter) does matter" [20]. However, stenosis of any of the brain-supplying arteries (including VA), triggers an increase in blood flow in all available vessels that can supply the brain. The importance of compensatory mechanisms is strongly supported by the increased intracerebral blood flow in patients with ICA obstruction [9]. In patients with impaired collateral system the prognosis of ischaemic stroke is worse [41], and in patients with unilateral ICA occlusion, the presence of collateral flow in COW is associated with a low prevalence of border zone infarcts [11]. Hence, the data about arterial diameters can help in understanding of interrelationships between the contralateral or ipsilateral ICA and VA, in the normal and impaired blood supply of the brain. This can be important in considering endarterectomy in cases of asymptomatic 60–79% ICA stenosis which cannot be justified for these patients, for which predominate indications for conservative therapy and presence of collateral circulation is an argument for the initiation of conservative treatment [9, 21, 25]. The potential of the tributaries of COW as collateral pathways [24] could be related to their diameters. Knowledge of the expected normal vessel flows incorporating patient-specific age and accounting for anatomy is critical to interpreting the haemodynamic effects of cerebrovascular disease [1]. The data about variability of COW are available worldwide (see for example [8, 11, 16, 38, 40]), including regions of Balkans [4, 32, 36], but the data about the diameters of proximal vessels of COW, potentially associated with different specific patterns of normal inflow are not yet known.

The aim of this study is to investigate the luminal diameters of ICA and VA as feeding vessels to COW, and to analyse the relationships and potential side (right-left) and sex differences between their diameters in the population of Republika Srpska (Western part of Bosnia and Herzegovina). Also we calculated sums of diameters of ipsilateral ICA and VA, as ipsi-

**Table 1.** Demographic data of investigated sample

Sex	N	Min	Max	Range	Median	Mean	SD
Male	34	35	75	40	67.50	63.53	10.157
Female	36	28	75	47	64.00	59.14	13.755
Total	70	28	75	47	65.00	61.27	12.256

Min — minimum; Max — maximum; SD — standard deviation

lateral vessels delivering the blood to the COW and further to the brain.

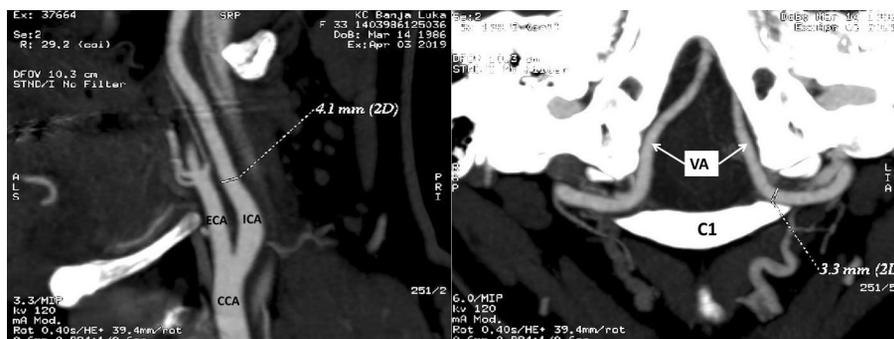
## MATERIALS AND METHODS

We investigated luminal diameters of ICA and VA in 70 subjects (140 ICAs and 140 VAs) of both sexes (34 males and 36 females) and between 28 and 75 years of age (Table 1). From the study were excluded the patients with previous or current cerebrovascular accidents or impairment, with the history of cervical injuries, vertebrobasilar insufficiency, abnormal morphology of ICA and VA (variations of origin, kinking and coiling), atherosclerotic changes (affecting more than of 50% of arterial luminal diameter), developmental abnormalities of cervical spine and with severe spondylarthrosis, as well as patients who did not provided consent to be included into this study. Data were collected and stored in accord to Helsinki Declaration [39] with additional verbal informed consent obtained from the all subjects.

Places for computed tomography angiography (CTA) measurements of ICA diameters were about 2 cm distally from the common carotid artery (CCA) bifurcation, in order to exclude influence of carotid sinus size in region of CCA bifurcation (Fig. 1). Diameters of VA were measured at atlantic (V3) segment of VA (5 mm before entrance into dural porion of VA), in order to exclude the potential influence of variable collateral branches anatomy from V2 segment [30].

### Imaging-generation and visualisation

All measurements were performed in Clinical Radiology Department, University Clinical Centre of Republika Srpska (Banjaluka). Patients were placed in a supine position with their arms alongside the body, head and neck kept at a neutral position. The imaging examination was performed on a 64-detector row CT scanner (GE Lightspeed CT, GE Healthcare, Milwaukee, WI, USA) with the scanning protocol as follows: 120 kVp, 697 mAs, beam collimation 64 × 0.625 mm, gantry rotation time 0.4 s, section thickness of 0.625 mm, pitch 0.969:1 and reconstruction interval of 0.625 mm. During the procedure, infused 80 mL of non-ionic



**Figure 1.** Dotted lines indicate the levels of measurements of diameters of internal carotid artery (left) and of vertebral artery (right); female (33 years).

**Table 2.** Diameters of right and left internal carotid artery and vertebral artery in males and females (in mm)

Sex	N	Min	Max	Range	Median	Mean	SD	
RICA	Males	34	3.7	6.9	3.2	5.000	5.044	0.8418
	Females	36	3.2	6.6	3.4	4.450	4.561	0.7346
	Total	70	3.2	6.9	3.7	4.700	4.796	0.8196
LICA	Males	34	3.8	6.3	2.5	4.700	4.821	0.5835
	Females	36	3.6	6.9	3.3	4.550	4.600	0.6908
	Total	70	3.6	6.9	3.3	4.600	4.707	0.6459
RVA	Males	34	1.8	4.9	3.1	3.300	3.206	0.6884
	Females	36	1.4	3.8	2.4	3.000	2.825	0.6026
	Total	70	1.4	4.9	3.5	3.100	3.010	0.6690
LVA	Males	34	2.0	4.5	2.5	3.600	3.497	0.5750
	Females	36	1.7	4.1	2.4	2.900	3.008	0.5973
	Total	70	1.7	4.5	2.8	3.400	3.246	0.6322

Min — minimum; Max — maximum; SD — standard deviation; RICA — right internal carotid artery; LICA — left internal carotid artery; RVA — right vertebral artery; LVA — left vertebral artery

iodinated contrast was followed by 40 mL saline and injected via a double power injector into the patient’s antecubital vein (4 mL/s).

Post-processing of source images was performed by using maximum intensity projection and evaluation and measurements of CTA dataset were performed on 3 mm thick coronal sections.

**Statistical analysis**

After demographic statistics (Table 1) results for each single vessel were analysed (including the sums of values of ipsilateral diameters — separately for right and for left arteries). In testing of normal distribution of continuous investigated variables we used Kolmogorov-Smirnov test. If the sample had normal distribution we applied parametric T tests (independ-

ent samples test for differences between the sexes and paired samples test for intrasex differences). If the sample deviated from the normal distribution, we used nonparametric tests (Mann-Whitney U test for differences between the sexes and Wilcoxon signed ranks test for intrasex differences).

Additionally, we calculated the Spearman’s rank correlation coefficients between the right ICA (RICA) and right VA (RVA), between the left ICA (LICA) and left VA (LVA), as well as between RICA and LICA, and between RVA and LVA, in total sample, and separately in males, and in females. Results were analysed using statistical software package SPSS (Statistical Product and Service Solutions), version 20.

**RESULTS**

Demographic statistics of the sample are presented in Table 1.

There was not statistically significant difference (Mann-Whitney U test;  $U = 511.500$ ,  $z = -1.183$ ,  $p = 0.237$ ) in age between males and females.

Results of measurements of diameters of RVA and LVA and ICAs in males and females are presented in Table 2.

**Internal carotid artery**

On the total sample mean luminal diameters of RICA (4.796 mm) and of LICA (4.707 mm) (Table 2) were without statistically significant difference (Wilcoxon signed ranks;  $z = -0.404$ ,  $p = 0.686$ ). The statistically significant difference (Mann-Whitney U test;  $U = 404.000$ ,  $z = -2.450$ ,  $p = 0.014$ ) was in mean diameters of RICA between males and females, but not ( $U = 479.500$ ,  $z = -1.560$ ,  $p = 0.119$ ) for diameter of LICA between males and females.

**Table 3.** Sums of diameters of ipsilateral internal carotid artery (ICA) and vertebral artery (VA)

Sex	N	Min	Max	Range	Median	Mean	SD	
RAA	Males	34	5.60	10.60	5.00	8.4000	8.2500	1.21012
	Females	36	4.70	9.80	5.10	7.4000	7.3861	1.11436
	Total	70	4.70	10.60	5.90	8.0000	7.8057	1.23263
LAA	Males	34	6.30	10.30	4.00	8.3000	8.3176	0.88574
	Females	36	5.30	9.70	4.40	7.7500	7.6083	0.98659
	Total	70	5.30	10.30	5.00	8.0000	7.9529	0.99822

Min — minimum; Max — maximum; SD — standard deviation; right arteries: RAA = RICA + RVA; left arteries: LAA = LICA + LVA

### Vertebral artery

In the total sample there was not statistically significant difference (Wilcoxon signed ranks test;  $z = -1.946$ ,  $p = 0.052$ ) of mean arterial diameters between RVA (3.10 mm) and LVA (3.246 mm) (Table 2). However, LVA in males had highly significantly (Mann-Whitney U test;  $U = 335.000$ ,  $z = -3.263$ ,  $p = 0.001$ ) larger diameters than in females, and RVA in males had significantly larger ( $U = 403.000$ ,  $z = -2.460$ ,  $p = 0.014$ ) diameters than in females.

### Correlations

In total sample highly significant positive correlations were between diameters of RVA and RICA ( $r = 0.371$ ,  $n = 70$ ,  $p < 0.01$ ), and between RICA and LICA ( $r = 0.327$ ,  $n = 70$ ,  $p < 0.01$ ). Significant positive correlations were found between right ipsilateral vessels (RICA and RVA) in females ( $r = 0.375$ ,  $n = 36$ ,  $p < 0.05$ ), and between contralateral anterior vessels (RICA and LICA) in males ( $r = 0.346$ ,  $n = 34$ ,  $p < 0.05$ ). Other investigated relationships did not show significant correlations.

### Sum of ipsilateral diameters (total diameters on one side)

Calculated sums of diameters of right (RAA = RICA + RVA) and left arteries (LAA = LICA + LVA) are presented in Table 3.

In a total sample the sums of diameters on left (LAA) and right (RAA) side were without statistically significant difference (paired samples test;  $t = -0.919$ ,  $df = 69$ ,  $p = 0.361$ ), as well as the sums of diameters between RAA and LAA, neither in males ( $t = -0.281$ ,  $df = 33$ ,  $p = 0.780$ ), nor in females ( $t = -1.033$ ,  $df = 35$ ,  $p = 0.309$ ). However, independent samples t-test revealed highly statistically significant larger diameters in males than in females for both, the sum

of diameters of right arteries (RAA: males 8.25 mm; females: 7.38 mm;  $t = -3.109$ ,  $df = 68$ ,  $p = 0.003$ ), and of left arteries (LAA: males 8.31 mm; females: 7.60 mm;  $t = -3.159$ ,  $df = 68$ ,  $p = 0.002$ ).

## DISCUSSION

Using CTA we found significantly larger mean diameter of RICA in males (5.05 mm) than in females (4.56 mm), but without such difference for LICA (males 4.82 mm; females 4.60 mm), and without significant intrasex (in males or in females) left-right differences of ICA or VA diameters (Table 2). In males the calculated sums of diameters of RAA and of LAA were highly significantly larger than in females. This could explain the greater stroke-protective effect of carotid endarterectomy, and lower rates of complications after surgery, in men. These gender differences may be caused by biological, anatomical (smaller vessel diameter in women) or hormonal differences [31].

Other authors reported mean diameters of cervical ICA close to our results, as 4.6 mm [5], and with statistically significantly larger mean diameters of cervical ICA in men (men 0.5 cm; women 0.49 cm) [37], even after adjusting for body and neck size, age, and blood pressure (men: 5.11 mm; women: 4.66 mm) [18]. In adults was found the correlation among ICA luminal diameter, flow velocities and overweight between the groups with normal (RICA 5.25 mm, LICA 5.55 mm) and with high body mass index (RICA 5.15 mm, LICA 5.10 mm), but without significant right-left or sex differences for the paired ICAs between the groups [26]. On carotid arteriograms of 25% of patients right-left differences in cervical carotid calibre were of at least 5%, and normally diameter of ICA on the two sides can vary up to about 40% [21], with generally wide range of dimensions [37].

The mean diameters of intracavernous portion of ICA before the origin of significant branches (ophthalmic artery) could be used for analysis (RICA 4.1 mm; LICA 4.0 mm [15], or RICA 4.24 mm; LICA 4.32 mm [40]). Intracavernous ICA diameter of 5.0 mm (men 5.1 mm; women 4.9 mm) was without change based on gender or side, but with significantly larger cavernous ICA diameters and tortuosity in patients aged > 60 years [27]. Increased tortuosity in non-diseased ICA with increasing age may be related to degradation and fragmentation of intramural elastin [14], and vessel diameters generally increase with age [19]. The CCA diameters can be also indicative, because the close relationship between the diameters

of CCA and ICA enables predicting of ICA size [37]. Additionally, increased ICA diameter can be result of malfunction of factors involved in vasoregulation (cerebral autoregulation), leading to disturbed blood flow regulation [12, 26]. Diameters of the cervical ICA can undergo dynamic transient changes in form of vasospasm [35], and dysregulation in extracranial ICA showed laterality and sex dependence, but no significant age dependence [29].

For investigated atlantic (V3) part of VA, the mean diameters found in our previous study [30] for RVA (males 3.27 mm; females 2.88 mm) and for LVA (males 3.39 mm; females 3.01 mm), were practically identical as in current study, because the sample population was same, with the exclusion of few patients having ICA abnormalities. In previous studies [30, 33], also were found in males larger diameters highly significantly of LVA and significantly of RVA, but not significant intrasex left-right differences. Because of the high interindividual variability, the normal range for diameter, peak systolic velocity and VA blood flow is wide in both VAs [24]. Age range of subjects in our study could not influence the results, because diameters, as well as flow volumes of VA, did not change with age [10, 22].

We found significant positive correlations in females between RICA and RVA (ipsilateral right anterior-posterior circulation), and in males between RICA and LICA (anterior bilateral or left-right circulation). The correlation of the diameters of only the right arteries (RICA and RVA) could not be related to their common origin from brachiocephalic trunk (via right subclavian and from right CCA), because it is found only in females. Highly significant positive correlations found in the total sample between RICA and LICA, and between RICA and RVA, probably reflected specific different values found in males and in females.

Hypothetically, the data about investigated normal diameters could be important in cases of reduced blood flow in one of vessels proximal to COW (smaller diameter of one ICA or VA). Beside the diameters of ICA and VA as potential compensatory pathways, the data about haemodynamics can help in estimation of risk of cerebrovascular ischaemia in considering conservative treatment in asymptomatic stenosis of ICA. Possible cerebral cross-perfusion, as essential for ipsilateral brain viability during unilateral insult, is complicated by the wide variability of COW anatomy [23]. The recognition of the impact of the anatomical variants in the COW is critical to the interpretation of

flow measured in the proximal intracranial vessels [1]. The COW is known from very old times [3, 6], and descriptions of its variations originate even more than 100 years ago [38], but the relationships of ICAs and VAs diameters to its variations are not clear. There are reports about the absence (Iranian male sample) [8], or the presence of significant differences in the variations of COW between the studies and different populations [16, 40]. In Balkans population (Serbia) [36], among 13 morphological types of COW, most frequent prenatally was normal type, and postnatally COW with unilateral hypoplasia of posterior communicating artery with calibres of right parts of the posterior cerebral artery and ICA significantly higher in male than in female adults [36]. In corresponding population (Serbia), origins of posterior communicating artery were basilar (82.5%), carotid (10.5%) and mixed (7%) [4], but the relationships of these variations of COW and of ICA and VA diameters, and their adequacy to flows in different types of COW, are not yet known. Our findings in males of highly significant larger diameters of LVA, significantly larger of RVA, as well as of RICA, but without such difference between males and females for LICA suggest certain impact of different variants of COW on these results.

Underestimating or denying the collateral flows are reports that the anatomical status and variations of COW (e.g. incomplete hemicircles) are without apparent disadvantages [23], do not itself determine adequacy [11], and do not correlate with functional and intra-operative tests of cerebral cross-perfusion [34]. Also, asymptomatic patients with an ICA occlusion do not have an increased collateral function of the COW [11], and the presence of asymmetric COW in more than one fourth of subjects [1, 32] indicates that these configurations represent rather one aspect of its adaptation [32].

However, prevailing evidence supports the existence of collateral or anastomotic flows via COW. Namely, the patients with ICA stenosis and with collateral flow via COW have less impaired haemodynamic parameters than those without such flow [17], and may have a compensatory increase in the peak systolic velocity and the blood flow volume in both VAs [24]. Also, in patients with cervical ICA occlusion, blood flow velocity and volume were increased in contralateral ICA, and in ipsilateral (27.5%), and in contralateral cervical VA (15%), than in controls [24]. On average 92% of the patients without border zone infarcts had Willisian collateral flow, as compared with 60% of patients with border zone infarcts [11]. Anatomic

variations of posterior communicating artery and posterior cerebral artery affected ICA flows, without a significant difference between males and females and continued to impact indexed flows in the basilar artery and ICA [1]. The anterior circle is the preferential mode of collateral supply in patients with unilateral ICA occlusion [2, 17] and an even normally larger carotid on one side related constantly with angiographic preponderance of the anterior cerebral artery on that side due to variation of COW [21]. All above findings support an old statement that COW under normal circumstances is not an equaliser and distributor of blood from different sources, but offers a potential shunt under abnormal conditions [13 cited by 28]. In this context our results contribute to estimation what means "abnormal diameters" in COW feeding vessels. In spite of all this complexities, the entire diagnosis of brain-supplying arterial stenosis is currently focused on blood flow assessment, ignoring the fact that vessels forming COW are supplied by either physiological (ICAs and VAs), or by collateral vessels [9].

Our findings of sex differences in diameters of ICA and VA strongly support the suggestion that further research of these differences and their causes is mandatory and promising in order to reduce the risk of stroke and to improve treatment outcome especially for women [9].

## CONCLUSIONS

Our findings suggest that the establishment of an simple relationship between the diameters (flows through) of ICA or VA is impossible, and is related to individual patient-specific characteristics. However, there is the possibility to investigate and define potential genetic profiles of patterns of diameters of COW inflow vessels, related to different COW configurations. The perspective methods for predicting anatomy, including COW, require complex analysis but are available [7]. Our study provides basic anatomical data which can contribute to diagnostics and treatment of impaired blood supply of the brain via COW, and to the studies of genetic associations or diversities of ICA and VA diameters, and of their relationships in health and disease.

## REFERENCES

1. Amin-Hanjani S, Du X, Pandey DK, et al. Effect of age and vascular anatomy on blood flow in major cerebral vessels. *J Cereb Blood Flow Metab.* 2015; 35(2): 312–318, doi: [10.1038/jcbfm.2014.203](https://doi.org/10.1038/jcbfm.2014.203), indexed in Pubmed: [25388677](https://pubmed.ncbi.nlm.nih.gov/25388677/).
2. Anzola GP, Gasparotti R, Magoni M, et al. Transcranial Doppler sonography and magnetic resonance angiography in the assessment of collateral hemispheric flow in patients with carotid artery disease. *Stroke.* 1995; 26(2): 214–217, doi: [10.1161/01.str.26.2.214](https://doi.org/10.1161/01.str.26.2.214), indexed in Pubmed: [7831690](https://pubmed.ncbi.nlm.nih.gov/7831690/).
3. Bender M, Olivi A, Tamargo RJ. Lulius Casserius and the first anatomically correct depiction of the circulus arteriosus cerebri (of Willis). *World Neurosurg.* 2013; 79(5-6): 791–797, doi: [10.1016/j.wneu.2011.10.044](https://doi.org/10.1016/j.wneu.2011.10.044), indexed in Pubmed: [22120555](https://pubmed.ncbi.nlm.nih.gov/22120555/).
4. Bogdanović D, Marinković S, Malobabić S. Morfološke varijacije zadnjeg segmenta Willis-ovog kruga i njihov značaj. (Morphological variations of the posterior part of circle of Willis and their significance). *Folia Anatomica Iugoslavica*, 1978; VII: 81-88. (In Serbian).
5. Chao AC, Chu WF, Mu Huo Teng M, et al. The Relationship between Carotid Artery Diameter and Percentage of Stenosis. *Neuroradiol J.* 2007; 20(1): 103–109, doi: [10.1177/197140090702000117](https://doi.org/10.1177/197140090702000117), indexed in Pubmed: [24299598](https://pubmed.ncbi.nlm.nih.gov/24299598/).
6. Dadmehr M, Behbahani FA, Bahrami M, et al. Response to Joveini (Al-Akhawayni) and the early knowledge on Circle of Willis. *Int J Cardiol.* 2017; 234: 119–120, doi: [10.1016/j.ijcard.2016.12.032](https://doi.org/10.1016/j.ijcard.2016.12.032), indexed in Pubmed: [28073657](https://pubmed.ncbi.nlm.nih.gov/28073657/).
7. Dalca AV, Sridharan R, Sabuncu MR, et al. Predictive Modeling of Anatomy with Genetic and Clinical Data. *Med Image Comput Comput Assist Interv.* 2015; 9351: 519–526, doi: [10.1007/978-3-319-24574-4\\_62](https://doi.org/10.1007/978-3-319-24574-4_62), indexed in Pubmed: [26855978](https://pubmed.ncbi.nlm.nih.gov/26855978/).
8. Eftekhari B, Dadmehr M, Ansari S, et al. Are the distributions of variations of circle of Willis different in different populations? Results of an anatomical study and review of literature. *BMC Neurol.* 2006; 6: 22, doi: [10.1186/1471-2377-6-22](https://doi.org/10.1186/1471-2377-6-22), indexed in Pubmed: [16796761](https://pubmed.ncbi.nlm.nih.gov/16796761/).
9. Elwertowski M, Leszczyński J, Kaszczewski P, et al. The importance of blood flow volume in the brain-supplying arteries for the clinical management: the impact of collateral circulation. *J Ultrason.* 2018; 18(73): 112–119, doi: [10.15557/JoU.2018.0016](https://doi.org/10.15557/JoU.2018.0016), indexed in Pubmed: [30335919](https://pubmed.ncbi.nlm.nih.gov/30335919/).
10. Ergun O, Gunes Tatar I, Birgi E, et al. Evaluation of vertebral artery dominance, hypoplasia and variations in the origin: angiographic study in 254 patients. *Folia Morphol.* 2016; 75(1): 33–37, doi: [10.5603/FM.a2015.0061](https://doi.org/10.5603/FM.a2015.0061), indexed in Pubmed: [26365867](https://pubmed.ncbi.nlm.nih.gov/26365867/).
11. Hendrikse J, Hartkamp MJ, Hillen B, et al. Collateral ability of the circle of Willis in patients with unilateral internal carotid artery occlusion: border zone infarcts and clinical symptoms. *Stroke.* 2001; 32(12): 2768–2773, doi: [10.1161/hs1201.099892](https://doi.org/10.1161/hs1201.099892), indexed in Pubmed: [11739971](https://pubmed.ncbi.nlm.nih.gov/11739971/).
12. Jensen-Urstad K, Johansson J, Jensen-Urstad M. Vascular function correlates with risk factors for cardiovascular disease in a healthy population of 35-year-old subjects. *J Intern Med.* 1997; 241(6): 507–513, doi: [10.1111/j.1365-2796.1997.tb00009.x](https://doi.org/10.1111/j.1365-2796.1997.tb00009.x), indexed in Pubmed: [10497627](https://pubmed.ncbi.nlm.nih.gov/10497627/).
13. Kamath S. Observations on the length and diameter of vessels forming the circle of Willis. *J Anat.* 1981; 133(Pt 3): 419–423, indexed in Pubmed: [7328048](https://pubmed.ncbi.nlm.nih.gov/7328048/).
14. Kamenskiy AV, Pipinos II, Carson JS, et al. Age and disease-related geometric and structural remodeling of the carotid artery. *J Vasc Surg.* 2015; 62(6): 1521–1528, doi: [10.1016/j.jvs.2014.10.041](https://doi.org/10.1016/j.jvs.2014.10.041), indexed in Pubmed: [25499709](https://pubmed.ncbi.nlm.nih.gov/25499709/).

15. Kellawan JM, Harrell JW, Roldan-Alzate A, et al. Regional hypoxic cerebral vasodilation facilitated by diameter changes primarily in anterior versus posterior circulation. *J Cereb Blood Flow Metab.* 2017; 37(6): 2025–2034, doi: [10.1177/0271678X16659497](https://doi.org/10.1177/0271678X16659497), indexed in Pubmed: [27406213](https://pubmed.ncbi.nlm.nih.gov/27406213/).
16. Klimek-Piotrowska W, Kopeć M, Kochana M, et al. Configurations of the circle of Willis: a computed tomography angiography based study on a Polish population. *Folia Morphol.* 2013; 72(4): 293–299, doi: [10.5603/fm.2013.0049](https://doi.org/10.5603/fm.2013.0049), indexed in Pubmed: [24402749](https://pubmed.ncbi.nlm.nih.gov/24402749/).
17. Kluytmans M, van der Grond J, van Everdingen KJ, et al. Cerebral hemodynamics in relation to patterns of collateral flow. *Stroke.* 1999; 30(7): 1432–1439, doi: [10.1161/01.str.30.7.1432](https://doi.org/10.1161/01.str.30.7.1432), indexed in Pubmed: [10390319](https://pubmed.ncbi.nlm.nih.gov/10390319/).
18. Krejza J, Arkuszewski M, Kasner SE, et al. Carotid artery diameter in men and women and the relation to body and neck size. *Stroke.* 2006; 37(4): 1103–1105, doi: [10.1161/01.STR.0000206440.48756.f7](https://doi.org/10.1161/01.STR.0000206440.48756.f7), indexed in Pubmed: [16497983](https://pubmed.ncbi.nlm.nih.gov/16497983/).
19. Labropoulos N, Zarge J, Mansour MA, et al. Compensatory arterial enlargement is a common pathobiologic response in early atherosclerosis. *Am J Surg.* 1998; 176(2): 140–143, doi: [10.1016/s0002-9610\(98\)00135-4](https://doi.org/10.1016/s0002-9610(98)00135-4), indexed in Pubmed: [9737619](https://pubmed.ncbi.nlm.nih.gov/9737619/).
20. Larena-Avellaneda A. „Only size (diameter) does matter“ – Stellen wir bei der asymptomatischen Karotis-interna-Stenose die richtigen Fragen? *Gefäßchirurgie.* 2017; 22(1): 6–9, doi: [10.1007/s00772-016-0239-2](https://doi.org/10.1007/s00772-016-0239-2).
21. Lehrer HZ. Relative calibre of the cervical internal carotid artery. Normal variation with the circle of Willis. *Brain.* 1968; 91(2): 339–348, doi: [10.1093/brain/91.2.339](https://doi.org/10.1093/brain/91.2.339), indexed in Pubmed: [5721934](https://pubmed.ncbi.nlm.nih.gov/5721934/).
22. Lovrenčić-Huzjan A, Demarin V, Bosnar M, et al. Color Doppler flow imaging (CDFI) of the vertebral arteries — the normal appearance, normal values and the proposal for the standards. *Coll Antropol.* 1999; 23(1): 175–181, indexed in Pubmed: [10402720](https://pubmed.ncbi.nlm.nih.gov/10402720/).
23. Musicki K, Hurst K, Molnár Z, et al. Cerebral cross-perfusion and the Circle of Willis: does physiology trump anatomy? *J Vasc Diagn Interven.* 2017; 5: 35–40, doi: [10.2147/jvd.s121839](https://doi.org/10.2147/jvd.s121839).
24. Nicolau C, Gilabert R, García A, et al. Effect of internal carotid artery occlusion on vertebral artery blood flow: a duplex ultrasonographic evaluation. *J Ultrasound Med.* 2001; 20(2): 105–111, doi: [10.7863/jum.2001.20.2.105](https://doi.org/10.7863/jum.2001.20.2.105), indexed in Pubmed: [11211130](https://pubmed.ncbi.nlm.nih.gov/11211130/).
25. Olin JW, Fonseca C, Childs MB, et al. The natural history of asymptomatic moderate internal carotid artery stenosis by duplex ultrasound. *Vasc Med.* 1998; 3(2): 101–108, doi: [10.1177/1358836X9800300203](https://doi.org/10.1177/1358836X9800300203), indexed in Pubmed: [9796072](https://pubmed.ncbi.nlm.nih.gov/9796072/).
26. Ozdemir H, Artaş H, Serhatlioğlu S, et al. Effects of overweight on luminal diameter, flow velocity and intima-media thickness of carotid arteries. *Diagn Interv Radiol.* 2006; 12(3): 142–146, indexed in Pubmed: [16972220](https://pubmed.ncbi.nlm.nih.gov/16972220/).
27. Rai AT, Hogg JP, Cline B, et al. Cerebrovascular geometry in the anterior circulation: an analysis of diameter, length and the vessel taper. *J Neurointerv Surg.* 2013; 5(4): 371–375, doi: [10.1136/neurintsurg-2012-010314](https://doi.org/10.1136/neurintsurg-2012-010314), indexed in Pubmed: [22490430](https://pubmed.ncbi.nlm.nih.gov/22490430/).
28. Rogers L. The function of the circulus arteriosus of Willis. *Brain.* 1947; 70(Pt 2): 171–178, doi: [10.1093/brain/70.2.171](https://doi.org/10.1093/brain/70.2.171), indexed in Pubmed: [20261819](https://pubmed.ncbi.nlm.nih.gov/20261819/).
29. Schimansky S, Patel S, Rahal J, et al. Extradural internal carotid artery caliber dysregulation is associated with cerebral aneurysms. *Stroke.* 2013; 44(12): 3561–3564, doi: [10.1161/STROKEAHA.113.001762](https://doi.org/10.1161/STROKEAHA.113.001762), indexed in Pubmed: [24092552](https://pubmed.ncbi.nlm.nih.gov/24092552/).
30. Spasojević G, Vujnović S, Ponorac N, et al. Sex and level differences in the diameters of extradural segment of vertebral artery: CT angiographic study. *Folia Morphol.* 2018; 77(4): 687–692, doi: [10.5603/FM.a2018.0036](https://doi.org/10.5603/FM.a2018.0036), indexed in Pubmed: [29651795](https://pubmed.ncbi.nlm.nih.gov/29651795/).
31. Stoberock K, Debus ES, Atlıhan G, et al. Gender differences in patients with carotid stenosis. *Vasa.* 2016; 45(1): 11–16, doi: [10.1024/0301-1526/a000490](https://doi.org/10.1024/0301-1526/a000490), indexed in Pubmed: [26986705](https://pubmed.ncbi.nlm.nih.gov/26986705/).
32. Stojanović N, Stefanović I, Kostić A, et al. Analysis of the symmetric configuration of the circle of Willis in a series of autopsied corpses. *Vojnosanit Pregl.* 2015; 72(4): 356–360, doi: [10.2298/vsp1504356s](https://doi.org/10.2298/vsp1504356s), indexed in Pubmed: [26040182](https://pubmed.ncbi.nlm.nih.gov/26040182/).
33. Tetiker H, Çimen M, Kosar M. Evaluation of the vertebral artery by 3D digital subtraction angiography. *Int J Morphol.* 2014; 32(3): 798–802, doi: [10.4067/s0717-95022014000300010](https://doi.org/10.4067/s0717-95022014000300010).
34. Urbanski PP, Lenos A, Blume JC, et al. Does anatomical completeness of the circle of Willis correlate with sufficient cross-perfusion during unilateral cerebral perfusion? *Eur J Cardiothorac Surg.* 2008; 33(3): 402–408, doi: [10.1016/j.ejcts.2007.12.021](https://doi.org/10.1016/j.ejcts.2007.12.021), indexed in Pubmed: [18249127](https://pubmed.ncbi.nlm.nih.gov/18249127/).
35. Usai S, Caputi L, Ciceri E, et al. Caliber fluctuations of cervical internal carotid artery and migraine with aura: a possible vasospasm detected by ultrasonographic examinations. *Headache.* 2009; 49(7): 1068–1072, doi: [10.1111/j.1526-4610.2009.01433.x](https://doi.org/10.1111/j.1526-4610.2009.01433.x), indexed in Pubmed: [19438731](https://pubmed.ncbi.nlm.nih.gov/19438731/).
36. Vasović L, Trandafilović M, Jovanović I, et al. Morphology of the cerebral arterial circle in the prenatal and postnatal period of Serbian population. *Childs Nerv Syst.* 2013; 29(12): 2249–2261, doi: [10.1007/s00381-013-2151-3](https://doi.org/10.1007/s00381-013-2151-3), indexed in Pubmed: [23702737](https://pubmed.ncbi.nlm.nih.gov/23702737/).
37. Williams MA, Nicolaides AN. Predicting the normal dimensions of the internal and external carotid arteries from the diameter of the common carotid. *Eur J Vasc Surg.* 1987; 1(2): 91–96, doi: [10.1016/s0950-821x\(87\)80004-x](https://doi.org/10.1016/s0950-821x(87)80004-x), indexed in Pubmed: [3503020](https://pubmed.ncbi.nlm.nih.gov/3503020/).
38. Windle BC. The arteries forming the circle of Willis. *J Anat Physiol.* 1888; 22(Pt 2): 289–293, indexed in Pubmed: [17231742](https://pubmed.ncbi.nlm.nih.gov/17231742/).
39. World Medical Association Declaration Of Helsinki: Ethical Principles for Medical Research Involving Human Subjects, 64th WMA General Assembly, Fortaleza, Brazil, October 2013. <https://www.wma.net/policies-post/wma-declaration-of-helsinki-ethical-principles-for-medical-research-involving-human-subjects/>.
40. Yeniçeri İÖ, Çullu N, Deveve M, et al. Circle of Willis variations and artery diameter measurements in the Turkish population. *Folia Morphol.* 2017; 76(3): 420–425, doi: [10.5603/FM.a2017.0004](https://doi.org/10.5603/FM.a2017.0004), indexed in Pubmed: [28150270](https://pubmed.ncbi.nlm.nih.gov/28150270/).
41. Zarrinkoob L, Birgander R, Eklund A, et al. Blood flow distribution in cerebral arteries. *J Cereb Blood Flow Metab.* 2015; 35(4): 648–654, doi: [10.1038/jcbfm.2014.241](https://doi.org/10.1038/jcbfm.2014.241), indexed in Pubmed: [25564234](https://pubmed.ncbi.nlm.nih.gov/25564234/).