 doi: 10.1111/j.1469-7580.2007.00806.x

The posterior part of the human cerebral arterial circle (CAC): arterial caliber from gestational weeks 13 to 24

Ljiljana P. Vasović,[1] Ivan D. Jovanović,[1] Sladjana Z. Ugrenović[1] and Zlatibor P. Anđelković[2]

[1]*Department of Anatomy, Faculty of Medicine, University of Niš, Serbia*
[2]*Department of Histology and Embryology, Faculty of Medicine, University of Priština-Kosovska Mitrovica, Serbia*

Abstract

Numerous studies have reported that all components of the cerebral arterial circle in the 4-month-old human fetus are more slender than adult vessels, and of equal caliber. After that period, a degree of caliber differentiation is present, especially at the level of the posterior communicating arteries. The aim of this study was to determine arterial diameters in the posterior part of the fetal cerebral arterial circle from the 4th month (IV) to the 6th (VI). One hundred and seventy-two fetal cerebral arterial circles were examined by means of a surgical microscope. It was determined that average diameters of the left (right) pre-communicating parts of the posterior cerebral artery ranged from 0.30 ± 0.03 (0.29 ± 0.02) mm in month IV, to 0.36 ± 0.04 (0.36 ± 0.03) mm during month V and up to 0.55 ± 0.22 (0.50 ± 0.18) mm in month VI. The average diameters of the left (right) posterior communicating artery ranged from 0.24 ± 0.02 mm (0.25 ± 0.02) in month IV, to 0.30 ± 0.03 mm (0.29 ± 0.05) during month V and up to 0.38 ± 0.08 (0.44 ± 0.10) in month VI. Gender differences between posterior cerebral artery and posterior communicating artery diameters were not significant. Average posterior cerebral artery diameters were significantly larger than posterior communicating artery diameters in months IV and V, but not in month VI. It was established that caliber differentiation in the posterior part of the cerebral arterial circle began from gestational month IV, and that gender differences in arterial diameters were not significant until month VI of gestation.
Key words artery; CAC; diameter; human fetus; posterior part.

Introduction

The basilar artery from the vertebral system divides into right and left posterior cerebral arteries (PCAs). Bilaterally, these arteries are connected with the posterior communicating artery (PCoA) from the internal carotid artery (ICA). The pre- and post-communicating parts of the PCA can be differentiated towards the point of the PCoA junction. Each cerebral part of the ICA distributes an anterior cerebral artery (ACA). The anterior communicating artery that unites the ACAs and divides ACA at pre-communicating and post-communicating parts completes the cerebral arterial circle (CAC) (Marinković et al. 2001).

In studying the normal development and congenital malformations of the cerebral arteries, a variety of diagnostic procedures have been used in fetuses and infants: anatomical microdissections (Seydel, 1964; Dovguiallo & Pekar, 1966; Lazorthes et al. 1971; Milenković et al. 1985; Van Overbeeke et al. 1991; Vasović et al. 2002), histological examinations (Fujimoto, 1996; Napoli et al. 1999), classic or 3-D magnetic resonance (MR)-angiographic studies (Jeanmart, 1974; Malamateniou et al. 2006), and transcranial Doppler (Wladimiroff et al. 1986; Van den Wijngaard et al. 1989; Fong et al. 1999; Komwlaisak et al. 2002; Konje et al. 2005; Tontisirin et al. 2007). In a study of human fetuses of different gestational ages, Jeanmart (1974) found similar patterns of vessel variation in cerebral arteriographs of the youngest fetuses compared to more mature fetuses and infants. In their investigation of the flow velocity waveform in the ICA, thoracic aorta, and umbilical artery in human fetuses, Wladimiroff et al. (1986) emphasized that the velocity profile in the ICA is a critical component in the qualitative assessment of cerebral blood flow. Napoli et al. (1999) examined the basilar and middle cerebral arteries in order to investigate potential mechanisms responsible for delayed atherogenesis in fetuses. Malamateniou et al. (2006) recently determined the normal range for gestational age of the descending aorta, the umbilical, middle cerebral and renal artery diameters.

Milenković et al. (1985) and Van Overbeeke et al. (1991) performed anatomical studies of the arterial diameters of the vessels of the fetal CAC many years ago. The aim of this paper was to report new research on pre-communicating part of the posterior cerebral artery (PCA-P1 or P1) and PCoA diameters in human fetuses and thereby update the state of knowledge in this field.

Correspondence
Dr L. P. Vasović, MD, PhD, Department of Anatomy, Faculty of Medicine, Blvd 'Dr Zoran Đinđić' 81, 18000 Niš, Serbia.
T: +381 18 570029; F: +381 18 238770; E: wassa@ptt.yu

Accepted for publication *8 August 2007*

Materials and methods

The research was carried out at the Department of Anatomy of the Faculty of Medicine in Niš. We used 172 fetal brains (100 male and 72 female), aged from 13 to 24 weeks of gestation (gestational age here is reported from the estimated date of conception). They were selected from 200 fetuses whose vessels had been injected with hydrosoluble solutions of Micropaque and latex (Vasović, 1990). All fetuses were obtained medicolegally from the Clinic of Gynecology and Obstetrics. Documentation for the obtained fetuses did not include restricted information on possible reasons for abortion. Macroscopic examination did not reveal any congenital malformations. The ages of the individual fetuses were determined according to Patten's scale (Patten, 1948). All external diameter measurements of the left and right pre-communicating parts of posterior cerebral arteries (lP1/rP1) and posterior communicating arteries (lPCoA/rPCoA) (Fig. 1) were performed using an ocular micrometer mounted on an operative microscope with a lens magnification of 10×. Calibration of the ocular micrometer was performed using an objective micrometer (1:100).

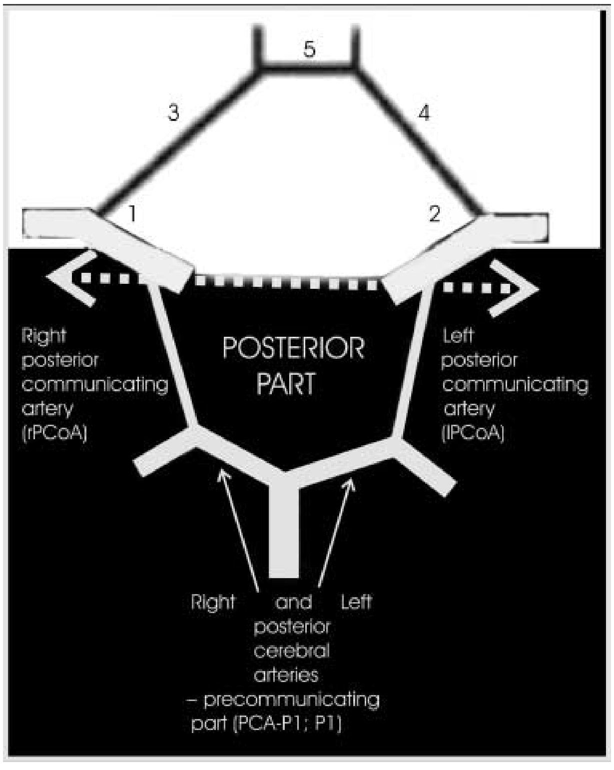

Fig. 1 Normal vascular components of the CAC. Vascular components of the posterior CAC are identified; vascular components of the anterior CAC are labeled by numerals (1 = right internal carotid artery, cerebral part, choroidal and communicating subparts, rICA-C4*; 2 = left ICA-C4*; 3 = right anterior cerebral artery, pre-communicating part, ACA-A1; 4 = left ACA-A1; 5 = anterior communicating artery).

Statistical analysis was performed with NCSS-PASS (2004–2005) statistical software (http://www.ncss.com/), which accompanied the textbook of Dawson & Trapp (2004). We compared the P1 and PCoA external diameters during gestation on both the left and right sides. Left–right asymmetry was also assessed by comparing the P1 and PCoA external diameters on the left with the external diameters of these blood vessels on the right side, for every evaluated gestational month. Comparisons were made between male and female fetuses to demonstrate sexual differences. Finally, the P1 and PCoA external diameters were also compared. Significance of differences between the compared morphometric parameters was assessed by application of Student's *t*-test. In cases of abnormal distribution of morphometric parameters, the nonparametric Mann-Whitney U test was used to assess the significance of differences between the medians (Dawson & Trapp, 2004).

Results

General data

Diameter values (minimum, maximum and average) of the P1s and PCoAs in fetuses from gestational weeks 13 to 24 are given in Table 1. Figure 2 shows CACs in the 4th (IV) and 6th (VI) months, in fetuses of both genders.

Comparison of the P1 and PCoA average diameters

We established that the left P1 average external diameters were 0.30 ± 0.03 mm during month IV, 0.36 ± 0.04 mm during month V and 0.55 ± 0.22 mm during month VI of the gestational period. There was a significant increase ($P < 0.05$) in the left P1 diameters during months V and VI compared to the values during month IV. This increase was mainly the result of a significant increase in male fetus diameters during gestation. There was also an insignificant increase in the P1 diameter on the left side in female fetuses (Table 2, Fig. 3a).

Right P1 diameters ranged from 0.29 ± 0.02 mm during month IV, to 0.36 ± 0.03 mm during month V, and 0.50 ± 0.18 mm during month VI. There was a significant increase in the P1 diameter, in both male and female fetuses, during month V and in female fetuses only, during month VI. That resulted in a significant increase in total average diameters during months V and VI (Table 2, Fig. 3b).

Left PCoA average diameters ranged from 0.24 ± 0.02 mm during month IV, to 0.30 ± 0.03 mm during month V and 0.38 ± 0.08 during month VI. There was a significant increase in the left PCoA diameter during months V and VI compared to month IV, the result of the increase of diameter in male fetuses. There was also an increase in the left PCoA diameter in female fetuses, but this was not significant (Table 2, Fig. 3c).

Table 1 Diameter values (minimum, maximum and average) of the P1 s and PCoAs in fetuses from the 13th to 24th weeks of gestation

		Left/Right PCA-P1 min–max (average)		Left/Right PCo Amin–max (average)	
Week* (CRL**, mm)	No (♂ + ♀)	♂	♀	♂	♀
13th (91–93)	4 + 0	0.2–0.3 (0.27)		0.1–0.3 (0.20)	
		0.2–0.3 (0.27)		0.1–0.3 (0.20)	
14th (105–107)	10 + 6	0.1–0.4 (0.26)	0.2–0.3 (0.25)	0.1–0.3 (0.21)	0.1–0.3 (0.21)
		0.2–0.4 (0.28)	0.2–0.3 (0.25)	0.1–0.4 (0.27)	0.1–0.4 (0.25)
15th (119–121)	11 + 6	0.2–0.4 (0.30)	0.2–0.4 (0.31)	0.1–0.3 (0.22)	0.1–0.4 (0.26)
		0.2–0.4 (0.31)	0.2–0.4 (0.28)	0.1–0.4 (0.26)	0.2–0.3 (0.26)
16th (132–134)	25 + 13	0.2–0.5 (0.33)	0.2–0.4 (0.33)	0.1–0.5 (0.27)	0.1–0.4 (0.23)
		0.2–0.4 (0.32)	0.2–0.4 (0.30)	0.1–0.4 (0.25)	0.1–0.4 (0.25)
17th (147–)	11 + 14	0.2–0.4 (0.32)	0.2–0.5 (0.33)	0.1–0.4 (0.29)	0.1–0.5 (0.34)
		0.2–0.4 (0.33)	0.2–0.6 (0.33)	0.1- 0.4 (0.28)	0.2–0.5 (0.35)
18th (160–)	10 + 7	0.2–0.6 (0.41)	0.1–0.4 (0.31)	0.1–0.5 (0.28)	0.1–0.5 (0.25)
		0.2–0.6 (0.41)	0.1–0.4 (0.31)	0.1–0.4 (0.23)	0.1–0.4 (0.24)
19th (173–)	6 + 6	0.2–0.5 (0.36)	0.2–0.6 (0.38)	0.1–0.5 (0.26)	0.1–0.4 (0.31)
		0.3–0.5 (0.36)	0.2–0.6 (0.36)	0.1–0.6 (0.33)	0.1–0.4 (0.21)
20th (185–)	13 + 4	0.2–0.7 (0.41)	0.3–0.4 (0.35)	0.1–0.5 (0.31)	0.3–0.5 (0.35)
		0.3–0.6 (0.42)	0.3–0.4 (0.35)	0.1–0.7 (0.34)	0.1–0.5 (0.32)
21st (197–)	3 + 5	0.3–0.7 (0.53)	0.3–0.5 (0.42)	0.3–0.5 (0.40)	0.2–0.5 (0.34)
		0.2–0.4 (0.30)	0.3–0.5 (0.44)	0.4–0.8 (0.56)	0.2–0.6 (0.32)
22nd (208–)	5 + 9	0.3–0.5 (0.40)	0.3–0.5 (0.36)	0.2–0.7 (0.40)	0.1–0.5 (0.33)
		0.4–0.6 (0.46)	0.2–0.6 (0.37)	0.2–0.7 (0.36)	0.3–0.5 (0.38)
23rd (219–)	2 + 0	0.7–1.0 (0.85)		0.4–0.6 (0.50)	
		0.6–1.0 (0.80)		0.4–0.7 (0.55)	
24th (230)	0 + 2		0.6–1.0 (0.80)		0.2–0.3 (0.25)
			0.2–1.0 (0.60)		0.3–0.6 (0.45)

*Ageing according to Patten (1948).
**Crown-rump length.

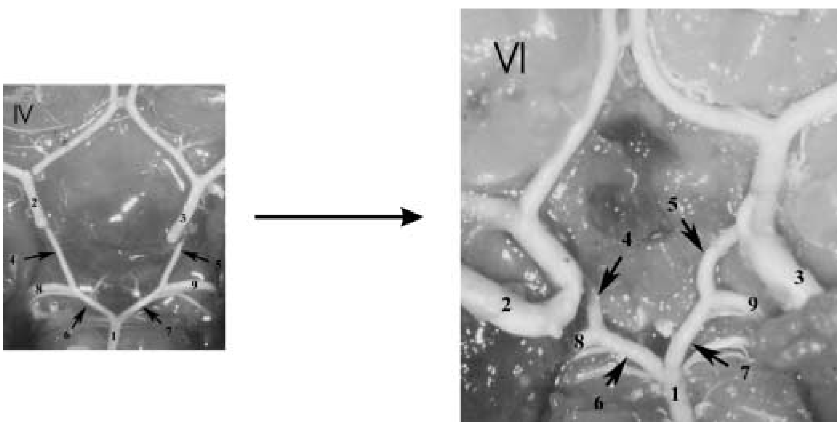

Fig. 2 Fetal CACs from months IV to VI. Some of the carotid and vertebrobasilar system arteries are identified (1 = basilar artery; 2 = right internal carotid artery, cerebral part, communicating and choroidal subparts (month IV) and right internal carotid artery, cerebral part and partially cavernous part (month VI); 3 = left carotid artery, cerebral part, communicating and choroidal subparts (month IV) and left internal carotid artery, cerebral part and partially cavernous part (month VI); 4 = right posterior communicating artery; 5 = left posterior communicating artery; 6 = right posterior cerebral artery, pre-communicating part; 7 = left posterior cerebral artery, pre-communicating part; 8 = right posterior cerebral artery, post-communicating part; 9 = left posterior cerebral artery, post-communicating part). Vascular components of the posterior CAC are labeled by numerals 4–7.

We detected a significant increase in the right PCoA average diameters during months V and VI. Values ranged from 0.25 ± 0.02 mm during month IV, to 0.29 ± 0.05 mm during month V and 0.44 ± 0.10 mm during month VI. The increases in average diameters of the right PCoA, during month VI, were significant for both male and female fetuses (Table 2, Fig. 3d).

The average P1 diameters on the left side were larger in female fetuses during month IV, and in male fetuses during months V and VI, while average diameters on the

Table 2 Average external diameter of the left and right PCA-P1 and PCoA during months 4 (IV) to 6 (VI) of the gestational period

Gestational age (month)	PCA-P1 left side (mm)						PCA-P1 right side (mm)						PCoA left side (mm)						PCoA right side (mm)					
	♂		♀		Total		♂		♀		Total		♂		♀		Total		♂		♀		Total	
	$\bar{D}$	SD	$\bar{D}$	SD	$\bar{D}$	SD	$\bar{D}$	SD	$\bar{D}$	SD	$\bar{D}$	SD	$\bar{D}$	SD	$\bar{D}$	SD	$\bar{D}$	SD	$\bar{D}$	SD	$\bar{D}$	SD	$\bar{D}$	SD
IV	0.29	0.03	0.30	0.05	0.30	0.03	0.30	0.02	0.28	0.03	0.29	0.02	0.23	0.03	0.24	0.03	0.24	0.02	0.24	0.02	0.26	0.01	0.25	0.02
V	0.38*	0.04	0.35	0.03	0.36*	0.04	0.38*	0.04	0.34*	0.02	0.36*	0.03	0.29*	0.02	0.32	0.04	0.30*	0.03	0.30*	0.05	0.28	0.06	0.29*	0.05
VI	0.59*	0.23	0.51	0.25	0.55*	0.22	0.52	0.25	0.47*	0.12	0.50*	0.18	0.43*	0.056	0.33	0.07	0.38*	0.08	0.49*	0.11	0.39*	0.06	0.44*	0.10

$*P < 0.05$.
$\bar{D}$ – average external diameter.

right were larger in male fetuses from months IV to VI (Table 2, Fig. 3a,b), although these differences were not statistically significant. Left PCoA average diameters were larger in female fetuses during months IV and V, while the values were larger in male fetuses during month VI. The right PCoA average diameters were larger in male fetuses from months IV to VI (Table 2, Fig. 3c,d). However, these differences were not significant.

The average P1 diameters were significantly larger than the PCoA diameters, during months IV and V, both on the left and right sides. These values also appeared larger during month VI on both sides, but the differences were not significant (Fig. 4a,b). The differences were the result of the significantly larger average diameters of the P1 compared to PCoA in male fetuses, both on the left and on the right sides during months IV and V (Fig. 5a–d). However, these differences were not significant during month VI in male fetuses and from months IV to VI in female fetuses.

Figure 6 presents examples of ‘ideal’ (a) and ‘average’ (b) posterior parts of the CAC, according to the relationship between P1 and PCoA average diameters in human fetuses from months IV to VI. There were bilaterally larger P1 diameters compared to PCoA, in both examples. However, the P1 diameters were equal and larger than the PCoAs which were also equal, in the first example, while in the second example, their diameters were slightly unequal (see also Table 2).

Discussion

Looking at a range of classic and more recent investigations into CAC angioarchiotecture reveals a series of theories, each one replacing earlier ideas. We suppose that current ideas, based on new data, as well as on our morphological data, provide the most convincing theories so far.

Lavieille et al. (1966) quoted the ancient embryologists who described a caudal branch of the primitive ICA appearing in embryos at 20 mm, incorporated into the PCA and PCoA. Marinković et al. (2001) quoted embryological data that the primitive PCA appears in embryos at 12.5 mm and that the PCoA was not completed until embryos reached 50 mm in length. The arterial walls of a 7-week-old embryo were composed of a single layer of endothelial cells, while in a 9-week-old embryo, the walls of the cerebral arteries consisted of an inner tunica intima, a central tunica media, and an outer tunica adventitia (Fujimoto, 1996).

Van Overbeeke et al. (1991) described diameters of the CAC vessels from gestational weeks 12 to 16 as ranging from 0.1 to 0.15 mm. According to these data, we expected that the P1 and PCoA calibers would be equal in the 13th week. However, only about one third of examined fetuses, of both male and female gender, during the period from gestational weeks 13 to 16 fit bilaterally into this ‘rule’ while one third fit unilaterally. Secondly, the caliber of P1 was 0.3 mm on the left and 0.29 mm on the right side

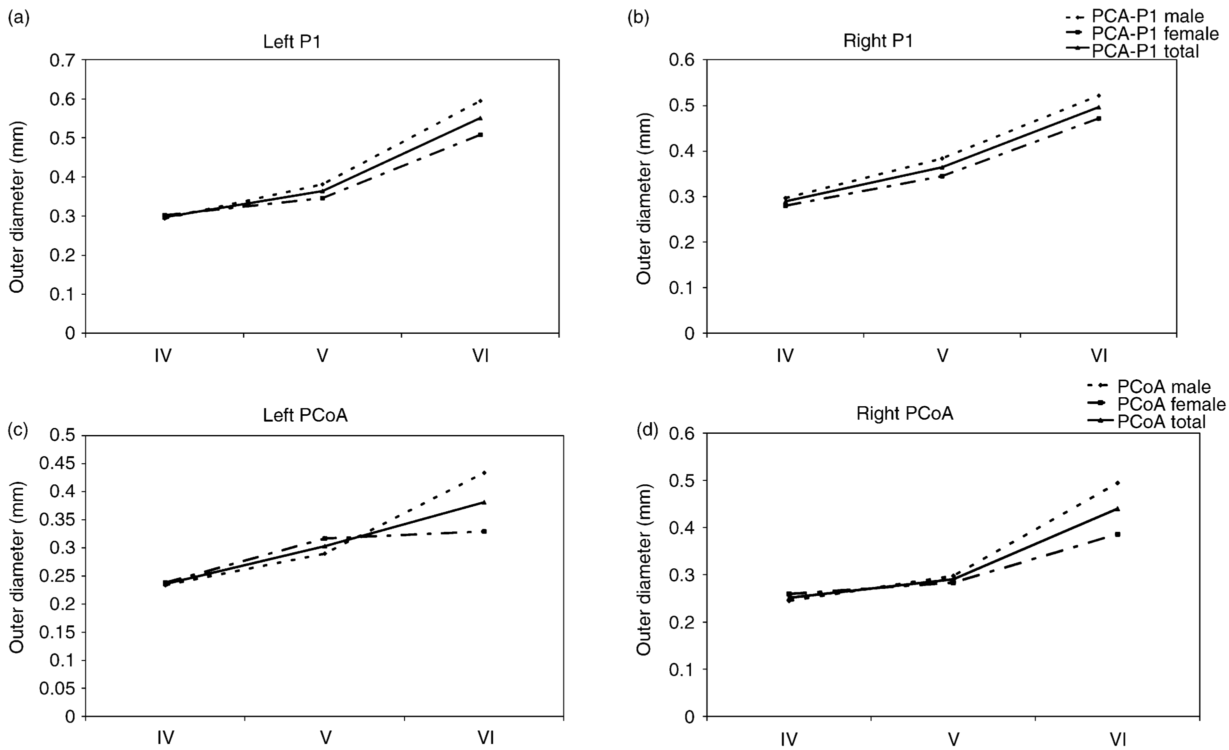

Fig. 3 Average external diameters of vascular components in the posterior CAC: Left PCA-P1 (a), right PCA-P1 (b), left PCoA (c) and right PCoA (d), in fetuses of both genders during the gestational months IV, V and VI.

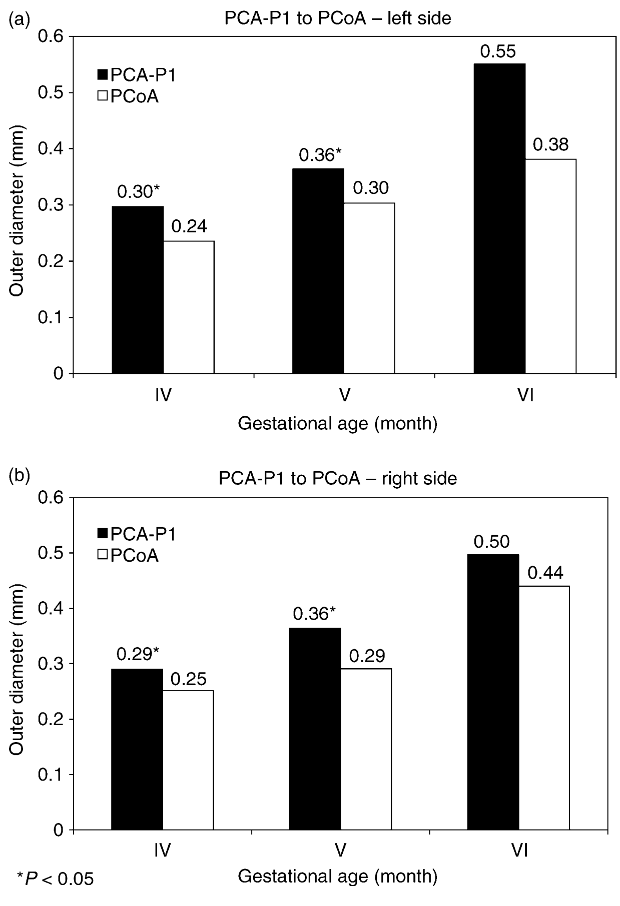

Fig. 4 Average external diameters of the PCA-P1 and PCoA on the left (a) and right (b) sides during gestational months IV, V and VI.

during month IV, while the PCoA diameter was 0.24 mm on the left and 0.25 mm on the right side.

Dovguiallo & Pekar (1966) noted that the average width and length of the P1, between months IV and V, were 5.3 mm and 24.8 mm, respectively, on the right, and 4.5 mm and 26.7 mm, respectively, on the left side. They also reported that the width and length of the PCoA were 4 mm and 67 mm, respectively, on the right and 4.08 mm and 68.2 mm, respectively, on the left side. These measurements were made at the base of the brain under a magnifying glass in 100 fetuses that were not classified by gender, and whose ages ranged from IV to X months. There were no data about the magnification of the eyepiece used, and no indication if the actual measurements might be less by a factor of 10 or 20. Thus direct comparisons to our data are not possible. Nevertheless, the authors noted larger PCA width on the right than on the left side, which is not in agreement with our data. However the average left and right PCoA calibers in month V were almost equal in Dovguialo and Pekar's report (1966), which is in agreement with the present results.

Van Overbeeke et al. (1991) reported that the caliber of the P1 and PCoA in fetuses after the 16th week of gestation ranged from 0.15 to 0.2 mm. The same authors did not note any sex differences between the right and left

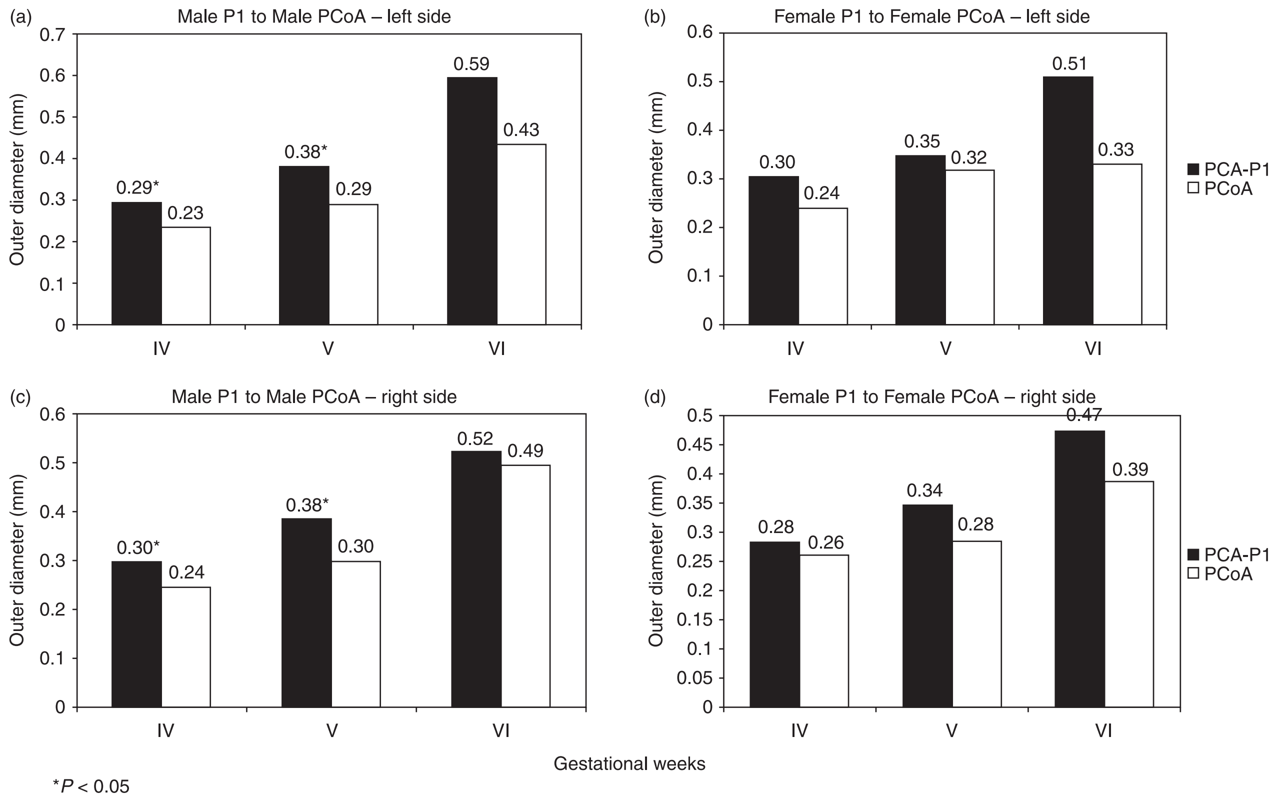

Fig. 5 Average diameters of the PCA-P1 and PCoA, on the left and right sides, during gestational months IV, V and VI, in male (a, b) and female (c, d) fetuses.

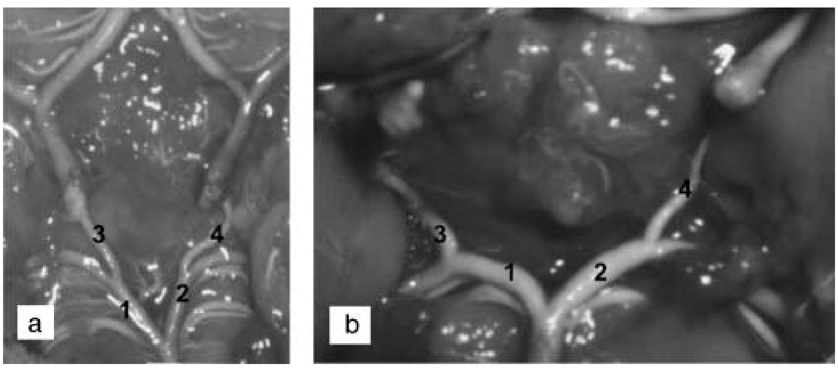

Fig. 6 Cases showing bilaterally larger diameters of P1 (1 and 2) in relation to the right (3) and left (4) PCoAs. The P1 diameters were equal or larger than the PCoAs, which were also equal in the first model, and slightly unequal in the second model.

sides, nor that the PCoA was larger than the P1, or that it was a 'striking characteristic' of those CACs. The author's conclusions were rather ambiguous; they noted that 73% of the fetuses had a posterior part of the CAC of the transitory type, in which the P1 and PCoA were of equal diameter, while only 9% were of the fetal type, in which the PCoA was larger than the P1. The average month V arterial caliber values in our study were 0.36 mm for P1, and 0.29 mm for PCoA on the right side, and 0.36 mm for P1 and 0.30 mm for PCoA on the left side. The average month VI arterial caliber values measured were 0.50 mm for P1, and 0.44 mm for PCoA on the right side, and 0.55 mm for P1, and 0.38 mm for PCoA on the left side. Dovguiallo & Pekar (1966) noted that the average P1 width and length between months VI and VII were 5.8 mm and 22.4 mm, respectively, on the right and 6.09 mm and 21.5 mm, respectively, on the left side, and the average PCoA width and length were 4.2 mm and 57.7 mm, respectively, on the right and 4.1 mm and 62.3 mm, respectively, on the left side. It may be confirmed that there is concordance if laterality in the CAC's posterior part is taken into account.

We detected a significant increase of the left P1 caliber in male fetuses from months V to VI, compared to that of the right P1, in month V in fetuses of both genders, and in month VI in female fetuses. The P1 average diameters were significantly larger than those of the PCoA in months

IV and V, on both the left and right sides. The values were also larger in month VI on both sides, but those differences were not significant. In contrast to our results, Dovguiallo & Pekar (1966) reported that the diameters of the PCoAs increased more slowly and regularly than the larger cerebral arteries.

Milenković et al. (1985) studied CACs of fetuses from gestational weeks 20 to 40, and noted that PCoA diameters ranged from 0.1 to 0.7 mm (0.34 mm, average) and diameters of the P1 ranged from 0.1 to 0.8 mm (0.51 mm, average). Due to having a lower number (26) of fetuses that were older than 20 weeks, for our research, we can suppose that while the range of these blood vessels calibers may remain similar after the 24th week, the number of cases with larger caliber values may change.

Feng et al. (1997) revealed an almost linear function of the peak velocity for the anterior, middle and posterior cerebral arteries with increasing gestational age from the 22nd to the 41st week. In addition, after an investigation of the middle cerebral artery and ascending and descending aortas normograms, Konje et al. (2005) reported an initial rise to a peak between 30 and 32 weeks followed by a gradual return to values at 38 weeks that were similar to those at 24 weeks' gestation. However, in their earlier work, Konje et al. (2000) established a significant correlation between gestational age and the diameter of the middle cerebral artery, ascending and descending aortas, and renal arteries. The rate of increase in vessel diameters was found to be steady throughout gestation, with maximal measurements for the vessels obtained at 38 weeks' gestation. Fukuda et al. (2006) emphasized that the energy requirements of fetal and neonatal brains were low, especially in premature infants, because of nonoxidative glucose metabolism. These authors also reported that total brain tissue volume increased linearly after the 29th gestational week.

In France, three sonograms are performed during a normal pregnancy. Usually, these scans are done at about 12, 22, and 32 weeks of pregnancy (Manson & Dillon, 2006). Thus, the present measurements taken from the 13th to 24th week gestation coincide with the time of prenatal sonograms but not with the diameter values that were not documented by previous authors.

The most intriguing finding of Feng et al. (1997) was a difference in total peak flow velocity between the left and right intracranial vessels. Van den Wijngaard et al. (1989) described a decrease in pulsatility in the internal carotid, middle cerebral, posterior, and anterior cerebral arteries, during the third trimester of gestation. Komwlaisak et al. (2002) endorsed use of the middle cerebral artery as the vessel of choice for assessing fetal cerebral circulation. However, Fong et al. (1999) reported a low positive predictive value of the pulsatility index of the middle cerebral artery for adverse perinatal outcomes, especially when the first Doppler ultrasound examination was performed at less than 32 weeks of gestation.

Van Overbeeke et al. (1991) found differences between the neonatal and the adult P1 and PCoA in the CAC. Malamateniou et al. (2006) noted that PCA diameters were 0.893 mm in premature infants and 0.867 mm in full-term infants. These authors also noted that there were no laterality or sex differences for PCAs in premature or full-term newborns. The sex differences in the vessels measured in our study, as well as in the study of Tontisirin et al. (2007), are likely derived from inherent sex differences in cerebral metabolic rates and/or estimated cerebrovascular resistance. Seydel (1964) determined that the most significant differences between adult and fetal diameters were in the posterior part of the circle, where the P1 shows a relatively smaller average diameter (34% of the diameter of the ICA) than that described for adult specimens (47%) while the PCoAs were of similar diameter (~0.27 mm) in both adults and fetuses.

Though pronounced inter-individual variability of the CAC, including the posterior CAC, is apparently normal (Vasović et al. 2002), it is our view that the relationships between the P1 and PCoA diameters present prenatally will not change during postnatal life unless some pathological lesions appear. Types of posterior arterial patterns in the CAC, according to the data summarized in Table 1, will be described in another paper (L. P. Vasovic, I. D. Jovanović, S. Z. Ugrenović, Z. P. Anđelković, unpubl. data).

Note

All clinics and departments, as part of the Faculty of Medicine in Niš, Serbia, have integrated professional cooperation. There was internal ethical control over fetal material used in the 1983–1990 time period. The Council for Postgraduate Study of our Faculty of Medicine gave permission to investigate the fetal material.

References

Dawson B, Trapp RG (2004) *Basics & Clinical Biostatistics*, pp. 134–161. New York: McGraw-Hill.

Dovguiallo ND, Pekar RA (1966) Growth of vessels of Willis circle in the second half of the intrauterine life (In Russian). *Arhiv Anat Gist Embriol* **3**, 87–90.

Feng IT, Raynor BD, Fiano K, Emory KE (1997) Doppler velocimetry of the fetal circle of Willis: a longitudinal study. *J Matern Fetal Invest* **7**, 133–138.

Fong KW, Ohlsson A, Hannah ME, et al. (1999) Prediction of perinatal outcome in fetuses suspected to have intrauterine growth restriction: Doppler US strudy of fetal cerebral, renal and umbilical arteries. *Radiology* **213**, 681–689.

Fujimoto K (1996) 'Medial defects' in the prenatal human cerebral arteries. An electron microscopic study. *Stroke* **27**, 706–708.

Fukuda S, Kato T, Kakita H, et al. (2006) Hemodynamics of the cerebral arteries of infants with periventricular leukomalacia. *Pediatrics* **117**, 1–8.

Jeanmart L (1974) Study of the cerebral vascularization of the human fetus by transumbilical angiography. *Angiology* **25**, 334–349.

Komwlaisak R, Saksiriwuttho P, Ratanasiri T, Kleebkaow P, Seejorn K (2002) Pulsatility indeks of the middle cerebral artery in normal fetuses. *J Med Assoc Thai* **87**, S34–S37.

Konje JC, Abrams K, Bell SC, de Chazal RC, Taylor DJ (2000) The application of color power angiography to the longitudinal quantification of blood flow volume in the fetal middle cerebral arteries, ascending aorta, descending aorta and renal arteries during gestation. *Am J Obstet Gynecol* **182**, 393–400.

Konje JC, Abrams KR, Taylor DJ (2005) Normative values of Doppler velocimetry of five major fetal arteries as determined by color power angiography. *Acta Obstet Gynecol Scand* **84**, 230–237.

Lavieille J, Choux M, Sedan R (1966) Étude anatomo-radiologique de l'artère communicante postérieure. *Neurochirurgie* **12**, 717–731.

Lazorthes G, Gouazé A, Santini JJ, Lazorthes Y, Laffont J (1971) Le modelage du polygone de Willis. Rôle des compressions des voies arterielles d'apport dans les mouvements de la colonne cervicale et de l'extrémité céphalique. *Neurochirurgie* **17**, 361–378.

Malamateniou C, Counsell SJ, Allsop JM, et al. (2006) The effect of preterm birth on neonatal cerebral vasculature studied with magnetic resonance angiography at 3 Tesla. *NeuroImage* **32**, 1050–1059.

Manson F, Dillon KC (2006) *First-trimester Examination*. Available from http://www.thefetus.net/page.php?id=1847.

Marinković S, Milisavljević M, Antunović V (2001) The arteries of the cerebrum and spinal cord. *Anatomical and Clinical Characteristics* (in Serbian), pp. 13, 14, 116, 117. Beograd: Bit inženjering.

Milenković Z, Vučetić R, Puzić M (1985) Asymmetry and anomalies of the circle of Willis in fetal brain. Microsurgical study and functional remarks. *Surg Neurol* **24**, 563–570.

Napoli C, Witzum JL, De Nigris F, G Palumbo G, D'Armiento FP, Palinski W (1999) Intracranial arteries of human fetuses are more resistant to hypercholesterolemia-induced fatty streak formation than extracranial arteries. *Circulation* **99**, 2003–2010.

Patten MB (1948) *Human Embryology*, p. 184. Philadelphia: Blakiston.

Seydel HG (1964) The diameters of the cerebral arteries of the human fetus. In *Abstract of Anat Rec* **150**, 79–88.

Tontisirin N, Muangman SL, Suz P, et al. (2007) Early childhood gender in anterior and posterior cerebral blood flow velocity and autoregulation. In *Abstract of Pediatrics* (doi:10.1542/peds.2006-2110; published online February 5).

Van den Wijngaard JAGW, Groenenberg IAL, Wladimiroff JW, Hop WCJ (1989) Cerebral Doppler ultrasound of the human fetus. *Br J Obstet Gynecol* **96**, 845–849.

Van Overbeeke JJ, Hillen B, Tulleken CAF (1991) A comparative study of the circle of Willis in fetal and adult life. The configuration of the posterior bifurcation of the posterior communicating artery. *J Anat* **176**, 45–54.

Vasović L (1990) *Morphological characteristics of the cerebral arterial circle in different origin of the vertebral arteries (in Serbian)*. Thesis of University Faculty of Medicine of Niš.

Vasović L, Milenković Z, Pavlović P (2002) Comparative morphological variations and abnormalities of circles of Willis: a minireview including two personal cases. *Neurosurg Rev* **25**, 247–251.

Wladimiroff JW, Tonge HM, Stewart PA (1986) Doppler ultrasound assessment of cerebral blood flow in the human fetus. *Br J Obstet Gynecol* **93**, 471–475.