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Some variations of the circle of Willis, important for cerebral protection in aortic surgery — a study in Eastern Europeans

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Abstract

Background: During unilateral selective cerebral perfusion (SCP), via canulation of the brachiocephalic trunk, the brain receives blood only through the right common carotid artery and the right vertebral artery. For perfusion of the contralateral (left) hemisphere it is counted on the competence of the circle of Willis (CoW). It is well known that variations of CoW are present in more than 50% of the people. Furthermore, these variations usually affect more than one vessel of the circle. The aim of the present work was to study the variations of CoW, which could have an impact on cerebral blood supply during unilateral SCP. **Methods and materials:** We study 112 CoWs obtained from cadavers via routine dissection in the Department of Forensic Medicine of Medical University, Sofia. The external diameter of both vertebral arteries and all arteries that form CoW was measured with a caliper-gauge. **Results:** We identify the variations of CoW such as significant hypoplasy and/or lack of a branch of the circle. Bearing in mind the characteristics of the blood flow during unilateral SCP some of these variations were classified as significant during unilateral SCP. They were subdivided into groups according to most probable stroke site after unilateral SCP. **Conclusions:** Because of the high percent of the variations, hemodynamically significant during unilateral SCP, a suggestion for routine preoperative CT-angio of CoW could be made. Furthermore, an intraoperative follow-up with NIRO, transcranial Doppler, EEG, and so forth could also be recommended.

Keywords: Cardiac surgery; Vessels; Variations; Cerebral protection

1. Introduction

Cerebral protection (CP) is a key issue during aortic arch surgery [1,2]. Such is required in patients with DeBakey type I aortic dissections, either acute or chronic [1]. The major goal of CP is to guarantee the optimal ratio between the blood supply and the metabolic demands of the brain [1]. At recent moment several methods for CP are in clinical use, namely: deep hypothermic circulatory arrest [3], retrograde cerebral perfusion [4], and selective cerebral perfusion (SCP) [5]. The latter could be subdivided into unilateral SCP, performed with arterial canulation of brachiocephalic trunk, or some of its branches and bilateral SCP, performed with canulation of both brachiocephalic trunk and left common carotid artery [1,2].

During unilateral SCP the brain receives blood only through right common carotid artery and right vertebral artery (VA). The assumption for protective effect of unilateral SCP is based on the understanding that collateral circulation, mainly through arterial circle of Willis (CoW), is sufficient to maintain adequate perfusion in the contralateral (left) hemisphere. According to the literary data some variations of CoW exist in at least 50% of the people [6–15]. The major disadvantage of most of these studies is the fact that they study the variations of CoW for each segment separately [6–9,14]. It is important to emphasize that the variations of CoW usually affect more than one segment of the circle [10–13,15,16]. Furthermore, the hemodynamics during unilateral SCP is quite specific, and for this reason, the presence of such variations could lead to significant deterioration of the blood supply in some brain areas during unilateral SCP and thus vitiate its protective effect.

According to the best of our knowledge only six studies investigate the variations of CoW as a whole — Riggs and Rupp [10], Fisher [11], Lazorthes et al. [12], El Khamlichi et al. [13], Eftekhar et al. [15], and Papantchev et al. [16]. Only

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one of these studies raises the question about CoW variations and their influence during unilateral SCP [16]. However, this study is theoretical and has not been supported by any clinical or morphologic material [16]. In this respect a morphologic study of CoW variations, hemodynamically significant during unilateral SCP, is generally absent. The aim of the present study was to describe the variations of CoW, which could vitiate its protective effect.

2. Material and methods

For the period May 15, 2005–August 12, 2006, 112 CoWs were examined in the Department of Forensic Medicine of Medical University, Sofia. All CoWs were obtained from cadavers via routine dissection. All subjects had died from natural or violent death and were candidate for autopsy for medico-legal reasons. The medico-legal office and local Ethic Committee approved this study.

In the course of the study 13 CoWs were excluded because the morphology of the circle was affected by cranial trauma, cerebral hemorrhage, cerebral neoplasm, or headshot. All other 99 CoWs were included. The CoWs were carefully dissected and the external diameter of following vessels was measured with caliper-gauge: internal carotid artery (ICA), precommunicating (A1) segment of anterior cerebral artery (ACA), medial cerebral artery (MCA), precommunicating (P1) segment of posterior cerebral artery (PCA), anterior communicating artery (ACoA), posterior communicating artery (PCoA), and intracranial segment of both vertebral arteries. All vessels with diameter under 1 mm were classified as hypoplastic [15]. The threshold of 1 mm was chosen in order to be consistent with all other major morphologic studies of the CoW reported in the literature [10–13,15]. We chose to measure the external diameter of the vessels for the same reason. All data were collected in a database. A digital photo of each circle was taken for further analysis.

3. Results

Bearing in mind the characteristics of the blood flow during unilateral SCP some variations that could vitiate its protective effect were identified. For classification of these variations we used the classification proposed earlier in the literature [16]. This classification divides CoW into six types according to most probable stroke site after unilateral SCP (Fig. 1).

Type Ia includes all brains with hypoplastic of either left PCoA or both PCoA [16]. In this group the most probable stroke site after unilateral SCP would be in the basin of left MCA. The blood supply of this basin during unilateral SCP would be exclusively from the right ICA and the only communication with it would be through the ACoA (Figs. 1A–C and 2A; Table 1). This was the most common variation. It was found in 27.3% of all CoWs (Table 1).

Type Ib includes all CoWs with hypoplastic ACoA. In this group the most probable stroke sites after unilateral SCP would be in the basins of left ACA. The blood supply of these basins during unilateral SCP would be only through left PCoA (Fig. 1D–F; Table 1). This variation was not found in present study (Table 1).

Type IIa includes all CoWs with hypoplastic ACoA in combination with hypoplastic left PCoA [16]. In this group the most probable stroke sites after unilateral SCP would be in the basins of both left MCA and left ACA. The blood supply of these basins during unilateral SCP would be extremely diminished (Figs. 1G–I and 2B; Table 1). This variation was found in 3.1% of the cases (Table 1).

Type IIb includes all CoWs with hypoplastic right VA or P1 segment of left PCA [16]. In this group the most probable stroke sites after unilateral SCP would be in the basins of both left MCA and left PCA. The blood supply of these basins during unilateral SCP would be exclusively from the right ICA and the only communication with it would be though the ACoA (Figs. 1J–L and 2C; Table 1). This variation was found in 9.1% of the cases (Table 1).

Type III includes all CoWs with hypoplastic A1 segment of the right ACA [16]. In this group the most probable stroke sites after unilateral SCP would be in the basins of both right and left ACA and left MCA. The blood supply of these basins during unilateral SCP would be exclusively from the right VA and the only communication with it would be though the left PCoA (Figs. 1M–O and 2D; Table 1). This variation was present in 3.1% of the cases (Table 1).

Type IV includes all CoWs with hypoplastic right VA and A1 segment of the right ACA [16]. In this group the most probable stroke sites after unilateral SCP would be in the basins of both right and left ACA, left MCA and left PCA. The blood supply of these basins during unilateral SCP would be totally absent (Fig. 1P–R; Table 1). This was the most severe variation described in the literature [16]. It was not found in present study (Table 1).

The total percentage of the variations of CoW significant during unilateral SCP was 42.4% (Table 1).

4. Discussion

According to our best knowledge this is the first morphologic study of the variations of CoW, which examine the entire circle and study the variations that could be hemodynamically significant during unilateral SCP. Unfortunately our present data could not be compared with other five studies of CoW as a whole [10–13,15] for two reasons.

The first is that in four of these studies, namely Riggs and Rupp [10], Lazorthes et al. [12], El Khamlichi et al. [13], and Eftekhar et al. [15], the classification of CoW's variations used was not side-oriented – in other words, it was considered irrelevant whether the affected vessels are on the left or the right side of the circle. Since the hemodynamic during unilateral SCP is specific the side-oriented study of variations of the circle is of crucial importance. For example, all CoWs with hypoplasia of the right A1 segment are classified as type III (Figs. 1 and 2). On the contrary, hypoplasia of the left A1 is not significant during unilateral SCP.

The second reason is that in all five studies no data about the variations of VA are available [10–13,15]. This fact is not surprising since the VA is not part of the CoW in the narrow sense of the word. However, the variations of VA are of great importance during unilateral SCP (Figs. 1 and 2). Thus, for classifying CoW as type IIb or type IV a hypoplastic right VA is required. Furthermore, VA variations are not uncommon; for example, it could originate from aorta, common carotid, external carotid, intercostals, or inferior thyroid artery [14].

We could compare our present findings only with a single theoretical study [16]. Present data are in good agreement with it (Table 1). Thus, CoW type Ia was the most frequent variation of all. It represents 27.3% of all variations of CoW in the present study. According to literary data its frequency is 26.6% [16]. These results are in good agreement with the literature [6—9,14]. The major reason for the high frequency of these types of CoWs is the fact that PCoA is its the most variable part [6—9,14].

During the present study CoW type IIa was found in only three brains (3.1%), while CoW type Ib was not found at all. This type of CoW was reported with frequency of 2.4% [16]. These results are not surprising, since the hypoplasia or aplasia of ACoA is quite rare [6—9,14,17,18]. Thus, in morphologic studies, Alpers et al. report the incidence of aplasia of ACoA in 2% and hypoplasia in 3% of examined brains [9], Fawcett and Blachford report aplasia of ACoA in 0.14% of examined CoWs [7], Windle found aplastic ACoA in 1.5% of studied cases [6], and finally, Adachi did not find any aplastic ACoA [8]. Hoksbergen et al., using transcranial color-coded duplex ultrasonography, found hypofunctional ACoA in 4% of the examined subjects [17], while Macchi et al., by means of magnetic resonance angiography, found hypofunctional ACoA in 5% of all examined patients [18].

In the present study we found more often CoWs type IIb (9.1% compared to 7.2%) and less often CoWs type III (3.1% compared to 7.2%) than reported in the literature [16]. Notwithstanding the fact that the subjects of the theoretical publication, with which we compare our results, were Japanese [16], it is not acquitted to interpret these differences as population related, because some recent

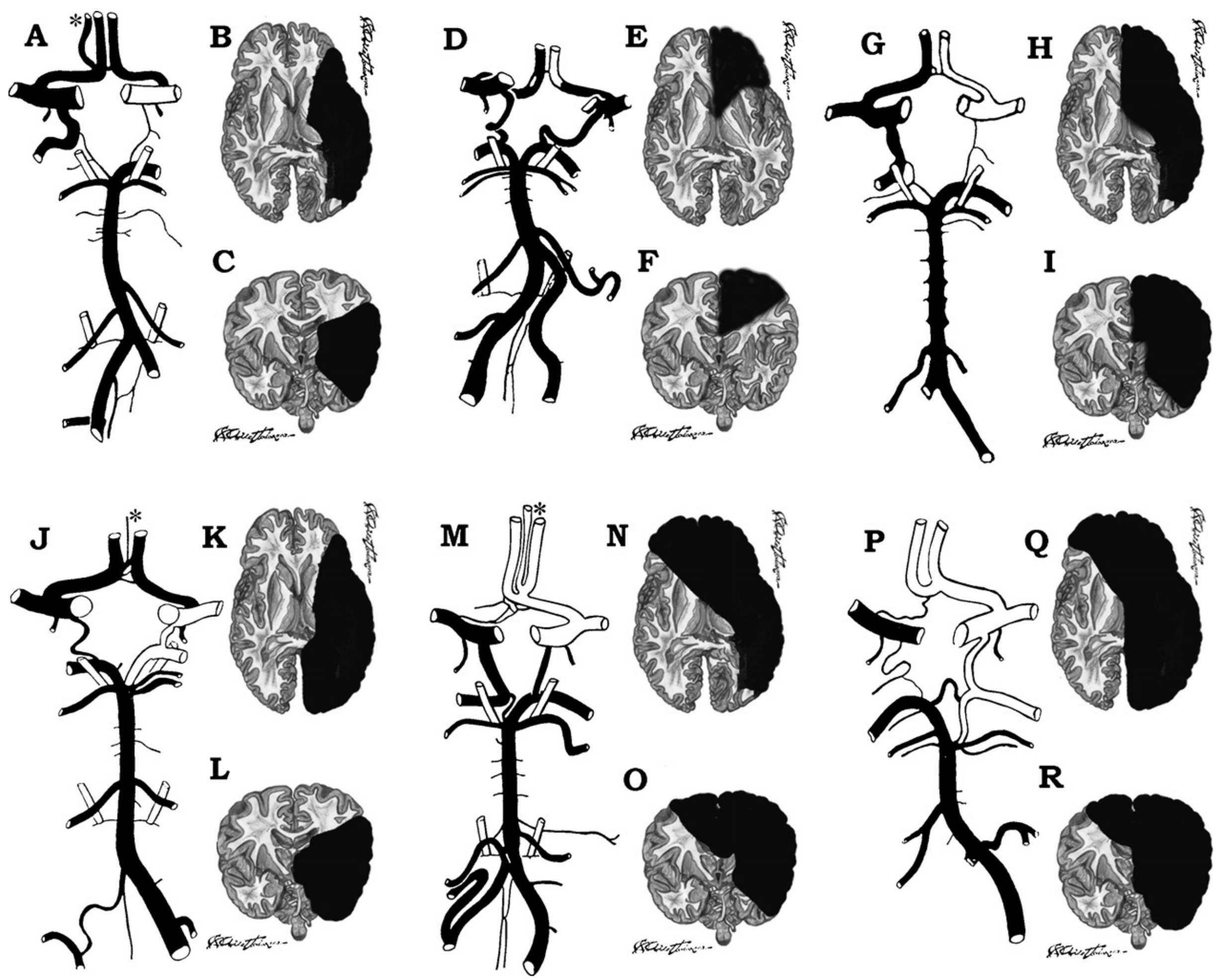

Fig. 1. Showing a schematic drawing of different types of CoW (from [16]; reprinted with permission). (A) CoW type Ia; (B) horizontal section through brain with CoW type Ia. Most probable stroke site after unilateral SCP is black; (C) frontal section through brain with CoW type Ia. Most probable stroke site after unilateral SCP is black; (D) CoW type Ib; (E) horizontal section through brain with CoW type Ib. Most probable stroke site after unilateral SCP is black; (F) frontal section through brain with CoW type Ib. Most probable stroke site after unilateral SCP is black; (G) CoW type IIa; (H) horizontal section through brain with CoW type IIa. Most probable stroke sites after unilateral SCP are black; (I) frontal section through brain with CoW type IIa. Most probable stroke sites after unilateral SCP are black; (J) CoW type IIb; (K) horizontal section through brain with CoW type IIb. Most probable stroke sites after unilateral SCP are black; (L) frontal section through brain with CoW type IIb. Most probable stroke sites after unilateral SCP are black; (M) CoW type III; (N) frontal section through brain with CoW type III. Most probable stroke sites after unilateral SCP are black; (O) horizontal section through brain with CoW type III. Most probable stroke sites after unilateral SCP are black; (P) CoW type IV; (Q) horizontal section through brain with CoW type IV. Most probable stroke sites after unilateral SCP are black; (R) frontal section through brain with CoW type IV. Most probable stroke sites after unilateral SCP are black.

publications show that there are no evidences suggesting that the distributions of the variations of cerebral arterial circle differ in different populations [15]. Most probable reason for this difference is the fact that the theoretical study '. . . was done using only illustrations, but not real brain preparations . . .' [16], so there is '. . . a real possibility for both under- and overestimation' [16].

CoW type IV was not found in the present study. Most probably, the reason for this is relatively low number of CoWs that were examined.

The collateral vessels of the brain could be subdivided into primary and secondary [14,19,20]. Primary collateral vessels form the circle of Willis, which can respond quickly to acute changes in perfusion pressure caused by occlusion of a major branch (ICA or VA) with simple reversal of flow [20]. Secondary collateral vessels such as ophthalmic artery, leptomeningeal vessels, deep vessel anastomoses, anastomoses with vessels outside the cranial cavity, and so forth require time for recruitment and are usually acquired in response to the stress of chronic hypoperfusion [14,20,21]. Lee et al. showed that the configuration of primary collateral pathways is a major risk factor for circulatory deteriorations during acute changes in hemodynamics [20]. Furthermore, these authors show that secondary collaterals are sufficient to maintain the brain perfusion only during normal conditions and not after acute changes of the hemodynamics (ICA clamping) [20]. The unilateral SCP could be compared with an acute interruption of the flow through left ICA and left VA. Thus, during unilateral SCP all blood supply for the left hemisphere will be only through the primary collaterals of CoW. If some of the variations described here is present (especially type III or IV) a massive hypoperfusion of certain parts of the left hemisphere could be expected. On the contrary, adequate volume flow in the major feeding arteries of the brain is crucial to maintaining cerebral blood flow and cerebral function [14]. The logical result will be watershed brain infarction [21]. It was shown that watershed infarctions are caused by hypoperfusion and for this reason they are also called low-flow, ischemic, or hypoperfusion infarctions [20]. The watershed infarctions could be responsible for the unfavorable motor, sensor, and/or psychical outcome in some patients after unilateral SCP [1]. However, we must emphasize that usually the infarction zone is not specific [14]. Most often the infarction foci are localized in the border zones of the big vessel basins or in the most sensitive for hypoxia zones of the cerebrum [14]. Furthermore, the clinical manifestation of watershed infarction is quite variable — from dense plegia to lack of any symptoms [14,16,21]. This could explain the relatively low percentage

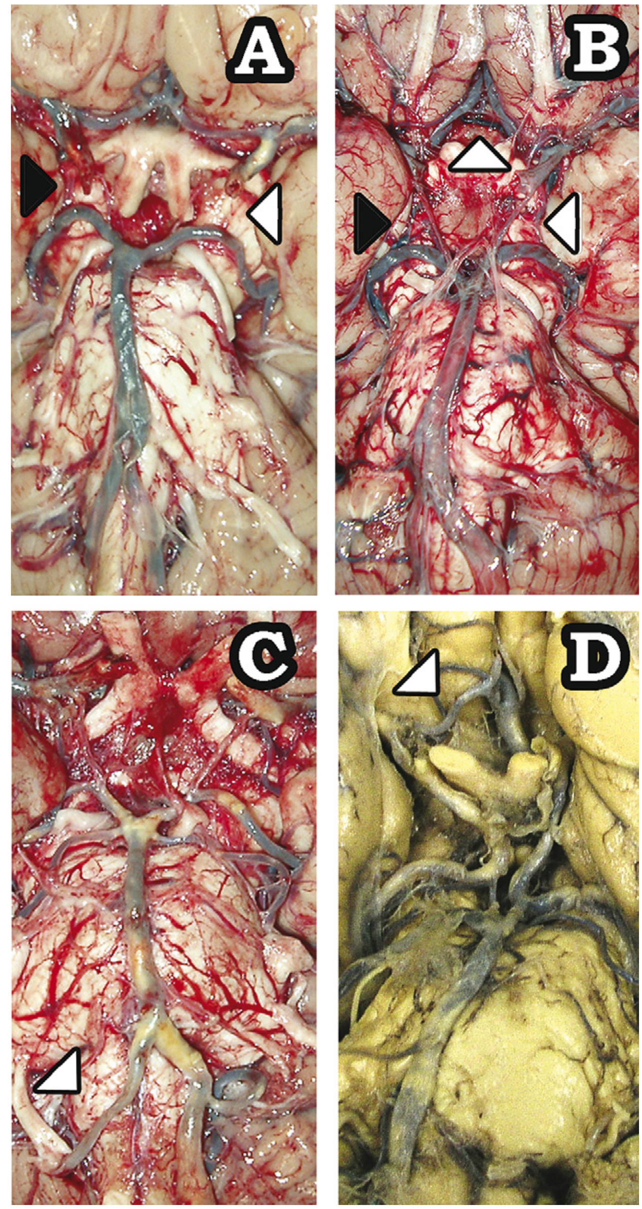

Fig. 2. Showing photos of all types of CoWs that were identified during present study. (A) CoW type Ia with hypoplastic left PCoA (white arrowhead) and normal right PCoA (black arrowhead); (B) CoW type IIa with hypoplastic ACoA and left PCoA (white arrowheads) and normal right PCoAs (black arrowhead); (C) CoW type IIb with hypoplastic right VA; (D) CoW type III with hypoplastic A1 segment of the right ACA.

Table 1
Classification of the variations of CoW, significant during unilateral SCP

Variation	Affected vessel	Most probable stroke site after unilateral SCP	Present study	Literary data ([16])
CoW type Ia	Left PCoA or both PCoA	Left MCA	27.3% (27/99)	26.6% (22/83)
CoW type Ib	AcoA	Left ACA	0% (0/99)	2.4% (2/83)
CoW type IIa	ACoA and left PCoA	Left ACA; left MCA	3.1% (3/99)	3.6% (3/83)
CoW type IIb	Right VA or left PCA (P1 segment)	Left MCA; left PCA	9.1% (9/99)	7.2% (6/83)
CoW type III	Right ACA (A1 segment)	Right ACA; left ACA; left MCA	3.1% (3/99)	7.2% (6/83)
CoW type IV	Right VA and right ACA (A1 segment)	Right ACA; left ACA; left MCA; left PCA	0% (0/99)	1.2% (1/83)
Total			42.4% (42/99)	48.2% (40/83)

of unfavorable neurological outcome after unilateral SCP compared to relatively high percentage of CoW variations. A short summary of the possible ischemia-induced clinical signs and symptoms is given in Table 2. We must also stress that usually in patients with aortic dissections, it is not possible to perform a profound neurological examination preoperatively [2]. For this reason, some minor preoperative neurological disorders are usually overlooked.

The identification of most probable stroke site was based on the Poiseulles—Hagen law (1) [16]:

$$R = 8\frac{l\eta}{\pi r^4} \quad (1)$$

where R is resistance; l is length of the pipe (vessel); η is viscosity of the fluid (blood); r is the radius of the pipe (vessel).

According to it, if the pipe's (vessel) radius decreases by 75% the resistance will rise 256 times [16]. Analogously, the decrease of the radius by 90% will result in increase in the resistance by 10,000 times [16]. The simple conclusion that could be drawn from Poiseulles—Hagen law is that small changes in the radius lead to significant increase in the resistance. Thus, hypoplastic segments of the CoW offered higher resistance than normal arteries. For this reason, during unilateral SCP the blood will follow the lowest resistance course through the normal vessels and thus it will by-pass the hypoplastic ones. This will lead to hypoperfusion in certain brain areas (Figs. 1 and 2). Another important issue is that after by-passing some CoW's vessels the length of blood's path (l value in Poiseulles—Hagen law) to certain brain areas increases. This leads to additional increase of the resistance and further reduction of perfusion of these brain areas (Figs. 1 and 2). Similar results were reported by Cassot et al. [22]. These authors used an experimental model of the cerebral circulation and showed that small changes in the diameter of ACoA (within the range of 0.4 and 1.6 mm) have a marked effect on the hemodynamics of intracerebral flows [22]. Furthermore, Kablak-Ziembicka et al., by means of transcranial color-coded duplex ultrasonography, found out that in patients with ICA occlusion the flow velocity in the contralateral MCA and ACA is significantly increased ($p < 0.001$), while the flow in the ipsilateral MCA is significantly decreased ($p < 0.001$) [23].

Since some domestic animals (usually pigs) are used routinely to study the unilateral SCP we must emphasize the fact that CoW of the animals has nothing in common with CoW of the human (Fig. 3). There are several important differences.

First, in all domestic animals (pig, bovine, goat, etc.) the ACoA is absent [24]. The only exception is the dog. This is an important fact since in human beings the ACoA is a major collateral pathway [19,23]. Thus, Hartkamp et al. showed that patients with unilateral ICA occlusion, with or without a significant contralateral ICA stenosis, have a higher prevalence of collateral flow via the anterior part of the CoW than via the posterior part, indicating that the anterior part of the circle (ACoA) is the preferred route of supply in unilateral ICA occlusion [19]. Kablak-Ziembicka et al. also show the importance of ACoA for collateral circulation of the CoW [23].

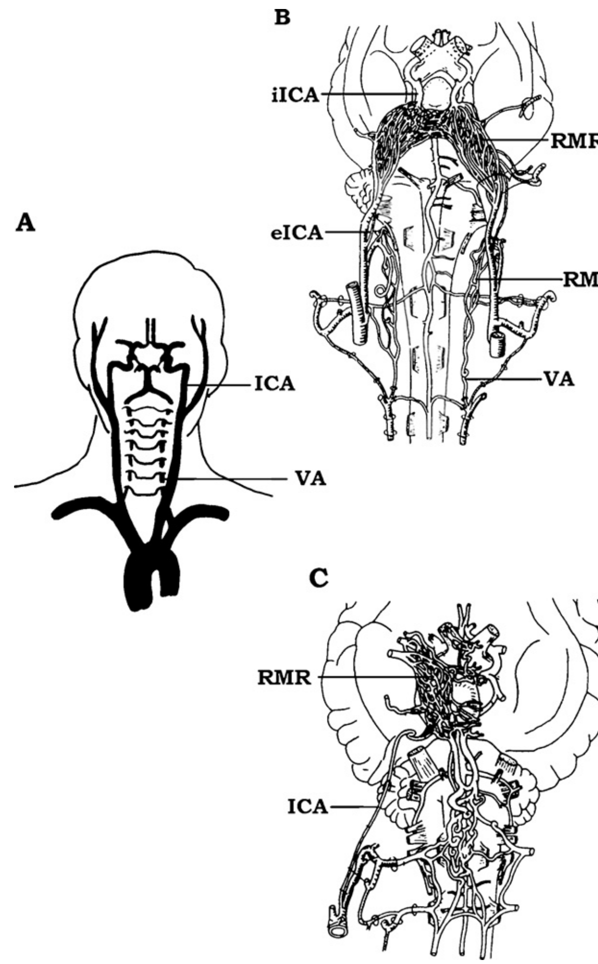

Fig. 3. Showing a schematic drawing of CoW in different species. (A) CoW in human (from [14]; reprinted with permission); (B) CoW in pig. Note the presence of both rete mirabile rostrale (RMR) and rete mirabile caudale (RMC). Note also the lack of ACoA (redrawn from [25]); (C) CoW in bovine. Note the presence of RMR and the lack of ACoA (redrawn from [25]). ICA, internal carotid artery; iICA, intracranial part of internal carotid artery; eICA, extracranial part of internal carotid artery; RMR, rete mirabile rostrale; RMC, rete mirabile caudale; VA, vertebral artery.

Secondly, in most of the domestic animals two vessel's networks called 'rete mirabile rostrale' and 'rete mirabile caudale' are present (Fig. 3). Rete mirabile rostrale is a dense network of small vessels, which is formed by branches of internal carotid artery, medial meningeal artery, rostral meningeal artery, and maxillary artery [24,25]. The small vessels of this network unite and form the intracranial part of internal carotid artery (Fig. 3). Rete mirabile caudale is a vessels network formed by VA (Fig. 3). From the physiology it is well known that such networks offered very low resistance. It also offers anastomoses with external carotid artery branches (medial meningeal artery, rostral meningeal artery, and maxillary artery).

Finally, there are variations of the CoW in all species [15]. These complicate enormously correct interpretations of the data derived form animal models.

For all above-mentioned reasons all results derived from an animal model (for example, pig) are most probably not relevant for human beings.

Table 2
Carotid and vertebrobasilar system system — supplied structures, ischemic symptoms, and syndromes (from [14]; reprinted with permission)

Artery	Supplied structures	Ischemic syndrome
Carotid system — supplied structures, ischemic symptoms, and syndromes		
Ophthalmic artery	Orbital structures	● Unilateral amaurosis
Anterior choroidal artery	Internal capsule, red nucleus, substantia nigra, optic tract, lateral geniculate body, choroidal plexuses of the third and lateral ventricles	● Homonymous hemianopsy, hemiplegia, and hemianesthesia
Posterior communicating artery (PCoA)	Optic chiasm, optic nerve, optic tract, hypothalamus, mamillar bodies, crus cerebri, thalamus, internal capsule, and subthalamic nucleus	● Visual, endocrine, or vegetative disturbances, hemiballism, decreased level of consciousness, impaired coordination, moderate contralateral hemiplegia, contralateral hemianesthesia, apathy and abulia, aphasia, memory disturbances
Anterior cerebral artery (ACA)	Caudate nucleus, internal capsule, the medial part of the frontal lobe, part of the superior margin, the posterior part of the cingulate gyrus, precuneus, and two-thirds of the superior parietal lobules	● Unilateral occlusion: contralateral hemiparesis and impaired sensation — mainly for the lower extremity, grasp reflex, indifference and lack of initiative, other frontal release symptoms ● Bilateral occlusion: clinical symptoms, which can imitate spinal trauma with paraplegia for the lower limbs, incontinence, and loss of sensation
Medial cerebral artery (MCA)	Greater part of the superolateral part of the hemisphere, caudate nucleus, genu of the internal capsule, orbital gyri, inferior frontal gyrus, inferior and middle temporal gyri, motor and premotor areas, associative areas, areas of Brocca and Wernicke	● Contralateral loss of sensation with hemiplegia — mainly for the face and upper extremity. If the dominant hemisphere is involved — aphasia is present. Often the severe brain edema and coma are present because of the extensive damage
Vertebrobasilar system — supplied structures, ischemic symptoms, and syndromes		
Vertebral artery (VA)	Deep muscles and structures of the neck (muscular branches), medulla spinalis, pia and dura mater spinalis (radicular branches, posterior spinal arteries, anterior spinal artery), cerebellar hemispheres (posterior inferior cerebellar artery), and choroidal plexus of the IV ventricle	● Vestibular and coordinative symptoms: vertigo and ataxia; vision and oculomotor disturbances — hemianopsy, cortical blindness, diplopia, myoclonus; alternating syndromes — facial and truncal hemihypesthesia, hemiparesis with nuclear and radicular lesions of the cranial nerves; bulbar symptoms; drop attacks ● Cerebellar hemisphere ischemia — a tendency for severe cerebellar edema, increasing of the intracranial pressure, and incarceration ● Isolated occlusion of the posterior inferior cerebellar artery: vertigo nystagmus, ataxia (to the side of the lesion), deviation (contralateral hypertrophy of the truncal muscles), truncal and head bending to the side of the lesion, impaired vertical perception. These symptoms are seen most often in the context of the vertebral artery lesion
Basilar artery (BA)	Internal auditory meatus, cerebellar hemispheres (anterior inferior cerebellar artery), paramedial areas of the pons, choroidal plexus of the third ventricle (superior cerebellar artery), crus cerebri (mesencephalic arteries), and areas supplied by the posterior cerebral artery	● Total occlusion: quadriplegia, diplopia, disturbances of the associate eye movements, in some cases — hemianopsy and cortical blindness, pseudobulbar syndrome, cerebellar disturbances, and locked-in syndrome ● Small lesion — a condition which imitates spinal trauma (lower limb paraplegia) with concomitant pseudobulbar symptoms ● Acute embolic incident: rapid coma, stupor or delirium, visual hallucinations with quadriplegia, and oculomotor disturbances ● Unilateral branches occlusion: contralateral hemiparesis, loss of sensation, ipsilateral ataxia and IIIrd, Vth, and VIIth cranial nerve lesions ● Isolated occlusion of the anterior inferior cerebellar artery: vestibule—ocular symptoms — vertigo, ataxia (to the side of the lesion), diplopia, or oculomotor palsy (nuclear lesion of the abducens nerve), and nystagmus ● Isolated occlusion of the superior cerebellar artery: ipsilateral ataxia, intentional tremor, Horner syndrome, tendency for severe cerebellar edema, vertigo
Posterior cerebral artery (PCA)	Thalamic nuclei, lateral geniculate body, choroidal plexus, epiphysis, mesencephalon, medial and inferior occipital areas, primary visual cortex	● Clinical signs and symptoms are rarely seen because of the well-developed collateral circulation ● Occlusion in the P_1 segment: oculomotor disturbances and thalamic lesions ● Occlusion in the P_2 segment: contralateral homonymous hemianopsy with spared macular vision, anosognosia, and alexia without agraphia (left side occlusion)

We must stress that some of the CoWs examined in the present study were affected by atherosclerosis (Fig. 2C). We did not make an approach for estimation of the degree of atherosclerosis, nor seek for a major branch occlusion. Since all autopsies were for medico-legal reasons we were not acquainted with patient's neurological history. Nevertheless, we shall offer a short discussion concerning this problem. It was shown that in 93% of the patients with asymptomatic ICA occlusion the CoW is normal [19]. On the contrary, Riggs and Rupp studied the CoW in 994 patients with previous history of neurological dysfunction and found out normal CoW in only 21% of them [10]. Furthermore, some of the risk factors for atherosclerosis (age, hypertension) are also risk factors for aortic dissection [1]. Finally, because the CT-angio is a routine diagnostic procedure for patients with aortic dissections we could recommend preoperative study of the CoW. It will show an asymptomatic occlusion or stenosis of a major branch (ICA or VA), a CoW variation, or atherosclerosis. All these data could help in choosing the most appropriate method for cerebral protection.

We must emphasize that since this study is morphologic there are some disadvantages applicable to all morphologic studies of CoW [15]. First, there is a potential minor change in the diameter of the vessels during time. Thus, the diameter of 'hypoplastic' vessels may increase with time and exceed 1 mm. Secondly, all measurements were performed 'post-mortem'. Since our results were not controlled with angiography we could never be sure that measured diameters are similar with those in living subjects. Finally, the number of examined CoW is relatively low — 99. A greater number of circles must be studied for identification of some more rare types of CoW (for example, CoW type IV).

We must stress that the methods for cerebral protection are used in patients, suffering from severe, acute, life-threatening diseases, such as DeBakey type I aortic dissections, which by themselves sometimes lead to ischemic cerebral injuries and neurological disorders before the operation. This, at its turn, imposes the use of maximally sparing methods for cerebral protection. Thus, we could say that the cerebral protection is complicated interdisciplinary problem. This imposes the combining of the efforts of specialists from different areas: cardiac surgeons, neurologists, neurosurgeons, invasive cardiologists, etc. Knowing of the variations of the cerebral vessels is a premise for the choice of the most convenient method for cerebral protection.

As a conclusion we must say that in the present work we report some variations of the CoW that could vitiate the protective effect of the unilateral SCP and could even lead to stroke. The presence of such variations could explain the unfavorable postoperative psychical, sensor, and/or motor deficits after unilateral SCP, which occurs in some patients. Because of the high percentage of these variations (42.4%) we suggest that a preoperative CT-angio of the Willis' circle should be routinely performed and/or intraoperative follow-up with NIRO, transcranial Doppler, EEG, and so forth should be carry out.

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