Does anatomical completeness of the circle of Willis correlate with sufficient cross-perfusion during unilateral cerebral perfusion?☆

Paul P. Urbanski a,*, Aristidis Lenos a, Juan C. Blume a, Volker Ziegler d, Bernd Griewing d, Rainer Schmitt c, Anno Diegeler a, Michael Dinkel b

a Department of Cardiovascular Surgery, Cardiovascular Clinic Bad Neustadt, Germany
b Department of Anesthesiology, Cardiovascular Clinic Bad Neustadt, Germany
c Department of Radiology, Cardiovascular Clinic Bad Neustadt, Germany
d Department of Neurology, Neurological Clinic Bad Neustadt, Germany

Abstract

Objectives: The aim of the study was to evaluate the role of anatomical completeness of the circle of Willis for sufficient brain perfusion during unilateral cerebral perfusion and the methodology of the preoperative and intraoperative functional assessments of adequate cross-perfusion.

Methods: This prospective observational study included all elective patients (99) who underwent elective open arch surgery (hemiarch in 74 and arch replacement in 25 patients, respectively) at our institution between September 2004 and September 2006. Preoperative neuro-vascular evaluation included color-coded duplexsonography of the extracranial arteries, cranial CT angiography, and transcranial sonography. A functional test of cerebral cross-perfusion was performed during cross-clamping of the common carotid artery during cannulation by transcranial Doppler, electroencephalography and measurement of somatosensory evoked potentials. These examinations, which were completed through measurement of arterial pressure in both radial arteries, also served as an intraoperative assessment of cerebral perfusion during surgery. During mild hypothermic (30°C) circulatory arrest with a mean duration of 18 min (range, 7–70) brain protection using unilateral cerebral perfusion was performed in all patients. Results: As assessed in preoperative CT angiography, the circle of Willis was complete in only 59 patients. Eighteen patients showed a singular abnormal location within the circle of Willis, 13 patients presented with abnormalities within the posterior communicating arteries on both sides, and 9 patients within the anterior and posterior communicating arteries. Nevertheless, functional tests during carotid artery cross-clamping as well as intraoperative cerebral monitoring including transcranial Doppler showed no pathology in any patient, and only one patient with severe aortic valve calcification suffered from embolic minor stroke after surgery. Conclusions: The anatomical status of the circle of Willis assessed with cranial CT angiography does not correlate with functional and intraoperative tests examining the cerebral cross-perfusion. The authors do not recommend cranial CT angiography as a preoperative standard examination before open arch surgery in which unilateral cerebral perfusion is scheduled.

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Keywords: Aortic arch surgery; Circulatory arrest; Brain protection; Cerebral perfusion; Circle of Willis

1. Introduction

Because deep hypothermia offers only a limited time of sufficient cerebral protection, antegrade selective perfusion is gaining increasing acceptance in aortic surgery with circulatory arrest. However, the placement of perfusion catheters into the arch arteries to perform cerebral perfusion is associated with additional manipulations on these vessels and is considered to increase the risk of several vascular or neuro-vascular injuries. This could explain why neurological complications in patients with antegrade cerebral perfusion could not be dramatically reduced when compared to deep hypothermia, especially if the circulatory arrest period is not too long [1].

Cannulation of one arch artery (innominate artery, right axillary artery, or one of the carotid arteries) for arterial return allows unilateral cerebral perfusion during circulatory arrest by simply reducing the flow in the arterial line after cross-clamping the arch branches, without additional manipulations. Even though the neurological results after use of unilateral cerebral perfusion for brain protection are very good, the role of anatomical completeness of the circle of Willis (CW) for adequate brain cross-perfusion and the methodology of its preoperative and intraoperative assessment remain unclear [2,3]. The purpose of this study was to evaluate the correlation between the anatomical...
completeness of the CW and the cross-perfusion during unilateral cerebral perfusion.

2. Material and methods

This prospective observational study included all elective patients (99) who were eligible for open aortic arch surgery on the basis of computed tomography (CT) at our institution between September 2004 and September 2006. Written informed consent was obtained from all patients. The group included 67 men and 32 women with a mean age of 65 years (range, 25–84 years). The main indication for surgery in this population was chronic degenerative aneurysm (48 patients), atherosclerotic aneurysm (3 patients), combination of both in 46 patients, and porcelain aorta in 2 patients. The detailed preoperative patient data are given in Table 1.

The cannulation of the left carotid artery for both arterial return and supplying the CW during unilateral cerebral perfusion through this artery was predetermined in all patients.

Before surgery, additional neuro-vascular examinations were performed on all patients, which included: neurological examination, color-coded duplexsonography of the extracranial vessels, and cranial CT angiography. Due to technical limitations (absence of ultrasound windows), transcranial Doppler was performed on only 88 patients. During surgery, a functional carotid occlusion test was performed during carotid cannulation and cerebral monitoring was assessed during hypothermic unilateral cerebral perfusion. Cerebral monitoring tools during surgery included arterial pressure lines in both radial arteries, electroencephalography, and measurement of somatosensory evoked potentials in all patients, as well as transcranial Doppler ultrasonography of the middle cerebral arteries, if it was feasible.

2.1. Surgical technique

The thoracic aorta and heart were exposed via median sternotomy in 98 patients, which included a left lateral extension in 1 case. Clam shell thoracotomy was performed in one patient. The technique of carotid artery cannulation has been described previously [4]. In short, the left (93) or right (1) carotid artery was prepared in 94 patients through a separate skin incision in the neck along the medial margin of the sternocleidomastoid muscle. The left carotid artery was isolated intrathoracically up to a length of 3–4 cm in five patients.

In all patients, after heparinization, the exposed segment of the carotid artery was cross-clamped, a longitudinal incision was made, and an 8 or 10 mm vascular sealed polyester graft was anastomosed to the artery with a continuous 5.0 polypropylene suture.

After connection of the arterial line and cannulation of the right atrium, cardiopulmonary bypass was started with a mean flow of 4.5 ± 0.5, range 3.5–5.8 l/min (2.4 l/min m² of body surface). During cooling, the perfusion pressure in the arterial line was limited to a maximum of 260 mmHg and amounted to 215 ± 30 mmHg on average.

Circulatory arrest for arch repair was necessary for all patients. The arch arteries were cross-clamped and unilateral cerebral perfusion was set up by simply reducing the arterial flow to a mean flow of 0.95 ± 0.2 l/min in moderate hypothermia with a mean rectal temperature of 29.8 ± 1.9 °C. By modulating the flow, the average pressure in the arterial line was maintained at about 100 mmHg (116 ± 23 mmHg), resulting in a mean pressure of 36.1 ± 10.7 mmHg and 34.2 ± 9.0 mmHg in the right and left radial arteries, respectively. The average duration of circulatory arrest and unilateral cerebral perfusion was 18 ± 10 min (range 7–70). In 26 patients this time was longer than 20 min and in 15 patients even longer than 30 min.

We administered thiopental for additional pharmacological brain protection; thus, topical cooling of the head was not performed. Acid–base balance was managed by the a-stat method. The arterial line included a Y-shaped cannula, which could be used to perfuse the other brain hemisphere for realization of bilateral cerebral perfusion during circulatory arrest, if necessary. Nevertheless, we never had to make use of this additional cerebral perfusion. After the distal aortic anastomosis had been completed, and in total or subtotal arch replacements following reimplantation of the arch arteries, this Y-shaped cannula could also be used to switch the arterial perfusion from the carotid artery to an aortic graft. It leads to an omission of re-perfusion through the carotid artery during re-warming and shortens the overall perfusion time through the carotid artery. Because this manipulation is neither complicated nor time-consuming, we employed it in all 84 patients in whom aortic grafts with side branches (‘InterGard Hemabridge’ with one side branch or ‘InterGard Aortic Arch’ with four side branches; InterVascular, La Ciotat, France) were used. The vascular graft initially anastomosed with the common carotid artery was severed near the anastomosis and oversewn during reperfusion or after terminating cardiopulmonary bypass.

The most frequent surgical procedure was ascending aortic replacement with an open distal anastomosis to the aortic arch (hemiarim replacement) followed by total or subtotal aortic arch replacement. The surgical procedures are shown in Table 2. The cardiopulmonary bypass time and

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<th>Table 1 Preoperative patient data (99 patients)</th>
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<td>Age (years)</td>
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<th>Table 2 Surgical procedures (99 patients)</th>
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<td>Hemiarth repair</td>
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<td>Total/subtotal arch replacement</td>
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<td>Aortic valve composite graft</td>
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<td>Valve-sparing root repair</td>
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* In all procedures the author’s (P.U.) single patch technique for root repair was used.
the aortic cross-clamp time including circulatory arrest were 160 ± 43 min (range 87–288 min) and 101 ± 28 min (range 54–190 min), respectively.

3. Results

Preoperative duplexsonography of the extracranial arteries showed atherosclerotic occlusion of the right internal carotid artery in one patient. Because we pre-determined cannulation of the left carotid artery in this population, this occlusion did not affect our operative strategy; however, it would have had a crucial impact on the choice of the proper side to be perfused if right-sided perfusion had been considered. On the basis of the preoperative Doppler examination of the extracranial arteries, we saw an indirect reason to switch the designated side of the perfusion from the left to right in only one case. In this patient, the left vertebral artery was occluded, and we therefore decided to cannulate the right carotid artery.

Furthermore, we found low-grade stenoses of both internal carotid arteries in one case, occlusion of the right vertebral artery in two cases, and irrelevant stenosis of vertebral arteries in eight cases. These atherosclerotic pathologies were not considered to have any consequences for the course of the intended surgery, especially for the side choice for cannulation.

The transcranial Doppler was feasible in 88 patients. Irrelevant stenosis of a middle cerebral artery was revealed in only two of them.

Cranial CT angiography was performed in all 99 patients. Only 59 of them showed no abnormalities within the CW. The patients with some abnormalities, such as hypoplasia or aplasia of the arterial components of the CW, were divided into three groups. The first group included 18 patients with one abnormal location within the CW, regardless of whether the abnormality was within its anterior or posterior part. The second group had hypoplastic or missing posterior communicating arteries on both sides, which was revealed in 13 patients. The third group, comprising nine patients, had abnormalities within the anterior and posterior communicating arteries, some of whom presented on both sides.

Carotid artery cannulation provided adequate arterial return in all patients. In no case was a switch to another cannulation site necessary for arterial return, and no complications related to the cannulation occurred. The assessment of the functional carotid occlusion test during cannulation showed no relevant alterations (decrease of somatosensory evoked potentials to less than 50%, no changes of electroencephalogram, nor ceased flow in the middle cerebral artery) in any patient.

During unilateral cerebral perfusion, the transcranial Doppler showed that the flow velocity in the contralateral middle cerebral artery varied in some cases considerably, but the flow never ceased. On average, the mean flow velocity dropped to 75%. The pressure in the radial arteries, with an average value of about 35 mmHg, was comparable on both sides. Somatosensory evoked potentials, however, were not included as a tool of cerebral monitoring because they already decreased in mild hypothermia, even significantly, without any clinical meaning. The electroencephalogram showed, already after thiopental administration, O-line or burst suppression in all patients, and therefore it was used to assess optimal reduction of cerebral oxygen consumption during the procedure.

On the basis of the findings mentioned above, we assessed sufficient cerebral cross-perfusion in all patients and did not perform additional perfusion of the contralateral carotid artery in any patient. This was the case even in patients who had an incomplete CW in whom a total or subtotal arch repair was performed; namely, in 6 of 18 patients from group 1 (33%), in 2 of 13 patients from group 2 (15%), and in 3 of 9 patients from group 3 (33%). The duration of circulatory arrest and unilateral cerebral perfusion in these 11 patients with incomplete CW and total or subtotal arch replacement was 33 ± 17 min on average and ranged from 18 to 70 min.

All patients regained consciousness postoperatively. One patient with a complete CW but with severe calcification of the aortic valve experienced focal neurological deficit after surgery, but it disappeared within 30 postoperative days; thus, the overall (permanent and temporary) focal deficit was 1%. Temporary neuropsychological dysfunction (confusion, agitation) appeared in seven patients but persisted longer than 24 h in only three patients. The postoperative cranial CT showed no pathological findings in any of them. Moreover, five of these patients had a complete CW in the preoperative imaging.

There was one death during the 30-day-period after surgery. This patient (male, 79 years) with chronic atherosclerotic aneurysm and aortic valve insufficiency died suddenly due to malignant arrhythmia resulting in cardiac arrest on the 7th day after valve-sparing ascending aorta and complete arch replacement; until then he had had an uneventful postoperative course. The autopsy showed no pathologic conditions apart from severe left ventricular hypertrophy. Three patients required prolonged primary postoperative ventilation, and two patients had to be reintubated due to respiratory insufficiency, which was the most frequent postoperative complication. Three patients required tracheotomy (one after prolonged primary ventilation and two after reintubation). Of those patients with pulmonary complications, there was one death that occurred in hospital but after the 30-day time range; it was due to multiple organ failure.

4. Discussion

Despite the very good neurological outcome after aortic surgery using unilateral cerebral perfusion in many clinical experiences [2,3,5], there are still some open questions in regard to use of this technique. The most important one is whether the anatomical completeness of the CW correlates with sufficient cross-perfusion during hypothermic unilateral cerebral perfusion.

On the basis of anatomic or angiographic studies, it has been revealed that in more than 50% of the human population several variations of the CW exist [6–9]. Insufficient cross-perfusion could be expected mainly in cases with multiple abnormalities within the CW, which were found in 30% of the patients in Macchi’s series [6] and in 23% of the patients in Hoksbergen’s series [9].
Because there are many anatomical variations of the CW, their classification into a few clearly arranged groups is hardly possible. For this reason, we divided those variations into only three groups in regard to the possible impact on the cerebral cross-perfusion. In the first group, there was only one location of an anatomical variation (hypoplasia, aplasia) within the CW. In this group an adequate collateral supply of the entire CW could generally have been expected, even if it had been supplied through the left carotid artery, i.e., through only one artery (Fig. 1). In the second group, the abnormalities existed within the posterior precommunicating (group 2a) or communicating arteries (group 2b) on both sides. In cases belonging to group 2a a sufficient supply of the posterior cerebral region could have been expected, regardless of whether the CW had been supplied from the left side (left carotid artery) or from the right side (right carotid and right vertebral arteries). However, in cases belonging to group 2b a perfusion only from the right side would offer a sufficient collateral flow (Fig. 2). In the third group, the pathologies were found in both anterior and posterior components of the CW on one or even on both sides so that an insufficient cerebral supply could have occurred during the perfusion of the left side (group 3a, Fig. 3) and in some cases (e.g., missing anterior communicating components on the right and posterior communicating components on the left or in cases with more than two abnormal locations within the CW) even during perfusion from the right side (group 3b, Fig. 4).

Because the left carotid artery is often suitable for cannulation; e.g., in acute aortic dissection in which this is the only undissected arch artery in some cases, the cannulation of the left carotid artery was predetermined in this study. Furthermore, the perfusion of the CW through only one supplying vessel would have increased the probability of finding out the impact of incompleteness of the CW on cerebral cross-perfusion, especially if the CW had been the only collateral pathway. On the basis of the anatomo-pathological findings of the CW, an insufficient cross-perfusion in our series could have been expected in 22% of the cases. In truth, it never occurred, and therefore we consider that the assessment of the true collateral
perfusion of the brain requires the use of functional tests. The Stanford group, which introduced the unilateral cerebral perfusion at the beginning of the 1980s, has already performed functional test by occluding the carotid artery with a balloon catheter during angiography [10]. It is also possible to use a less invasive carotid compression test; however, this test is associated with an increased risk of neuro-vascular injury and, therefore, should be reserved for patients needing ligation of the carotid artery; e.g., in neck dissections [11].

Thanks to our technique of common carotid artery cannulation, it is possible to perform the functional occlusion test under direct view. Although this is a cross-functional test that examines the side that is being perfused during unilateral cerebral perfusion, it gives reliable information about the potential of cross-perfusion during the complete clamping of the carotid artery. In addition, the cannulation of the carotid artery provides the possibility to choose the appropriate side for unilateral cerebral perfusion where the head supplying arteries do not have any pathology, while cannulation of the right axillary artery is always connected with perfusion of the right carotid artery independent of its actual condition.

Lacroix et al. showed that during clamping of the carotid artery in normothermia, a decrease of flow velocity in the middle cerebral artery of even more than 70% does not result in cerebral insufficient supply [12]. Therefore, we have accepted low flow velocities during the circa 8 min carotid artery occlusion test, but we saw no loss or significant decrease of somatosensory evoked potentials in any patients, which would indicate critical cerebral ischemia with high sensitivity and specificity [13]. For patients in whom the use of transcranial Doppler has not been possible, we have orientated ourselves according to the results of the somatosensory evoked potentials and the electroencephalography exclusively.

During unilateral cerebral perfusion, we also have accepted a low flow velocity, especially since the unilateral cerebral perfusion is conducted under hypothermia in which the cerebral oxygen consumption is remarkably reduced, and therefore a limited collateral perfusion can be compensated [14]. For this reason, the cooling of the patient is adapted to

Fig. 3. Cranial CT angiography (thin MIP) showing CW with abnormal anterior and posterior components belonging to group 3 (here: aplasia of the right anterior precommunicating artery and aplasia of the right posterior communicating artery, which represents group 3a). For details see text.

Fig. 4. Cranial CT angiography (thin MIP) showing CW with abnormal anterior and posterior components belonging to group 3 (here: aplasia of the right anterior precommunicating artery and hypoplasia of the right and left posterior precommunicating arteries, which represents group 3b). For details see text.
the flow velocity reduction during the occlusion test and the expected duration of circulatory arrest. Nevertheless, according to our strategy of cerebral protection, a suspension of the flow in the middle cerebral artery would have resulted in additional perfusion of the affected hemisphere, even though it was never necessary during our total experience up to present.

For patients in whom the use of transcranial Doppler has not been possible, we have orientated ourselves according to the blood pressure measurement in both radial arteries. On the basis of our earlier observations the pressure accounting about 30 mmHg in both radial arteries was considered to be sufficient for cerebral cross-perfusion from the left carotid artery (provided that the left subclavian artery is clamped) [2]. We consider the arterial pressure measurements in both radial arteries as very reliable because the radial pressure reflects the pressure in subclavian arteries, and thus in vertebral arteries, regardless of whether the pathway of cross-perfusion is the CW or extracranial collaterals. Consequently, this measurement reveals during unilateral cerebral perfusion, if only indirectly, the flow contralaterally to the cannulated carotid artery and in the vertebrobasilar supply area, since the transcranial Doppler reveals only regional flow in the single cerebral arteries. In our experience, the unilateral cerebral perfusion performed by supplying the CW through one vessel only (left carotid artery) showed even in 22 patients in whom due to incompleteness of the CW an insufficient cross-perfusion could have expected no differences in the neurovascular monitoring, including the pressure measurement in both radial arteries, when compared to the patients with complete CW. For this reason, we consider that the CW is not the only pathway for cerebral cross-perfusion, but the extracranial collateral circulation plays a meaningful role, especially in patients with an incomplete CW.

However, with the present understanding of cerebral cross-perfusion, additional neuro-vascular monitoring during unilateral cerebral perfusion would seem to be valuable. For example, cerebral monitoring can be complemented by measurement of regional cerebral saturation with a near-infrared spectroscopy, which is easy and fast to perform on all patients and can therefore be performed even in emergencies.

On the other hand, a cranial CT angiography as a preoperative diagnostic examination is associated with some negative aspects: radiation of the patient and the administration of a contrast agent increase preoperative hospital stay and cost. Because we deduce that an anatomical incompleteness of the circle of Willis does not correlate with insufficient cerebral protection during hypothermic unilateral cerebral perfusion, we abandoned the preoperative cranial CT angiography, and therefore do not recommend this examination as a standard procedure before arch surgery for which unilateral cerebral perfusion is scheduled. However, the functional carotid occlusion test and neuro-vascular monitoring during elective surgery with unilateral cerebral perfusion are, in our opinion, essential.

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References


Appendix A. Conference discussion

Dr M. Turina (Zurich, Switzerland): Thank you for this very important report. How reliable is it, on the other hand, Doppler examination in itself? The errors in Doppler have been described.

Dr Urbanski: Do you mean the transcranial Doppler?

Dr Turina: Yes.

Dr Urbanski: It is really a very important point because the transcranial Doppler examination is not always possible and when it is feasible we have observed that the flow during unilateral cerebral perfusion varies considerably, but it never ceases. For this reason, we accept even very low flow in transcranial Doppler.

But if the flow would stop, we would perform a bilateral perfusion. We have Y-shaped arterial line, and in such cases we are prepared for widening the perfusion. But this was never necessary during our overall experience with more than 300 procedures.

Dr Turina: Of course, these are relatively short times of perfusion of 18 min. So if you go into extended reconstruction of the arch, would you recommend cannulation of both carotid arteries?

Dr Urbanski: Surprisingly we saw in our aortic dissection patients for whom the time of cerebral perfusion and circulatory arrest is much longer, even 100 min or more, that unilateral cerebral perfusion under moderate hypothermia offers good cerebral protection. The neurological results of all these patients were very good.

Dr Turina: But if you give an example of a similar patient who had undergone a similar rehabilitation process, would you use transcranial Doppler, or would you use the usual methods of cerebral monitoring?
For this reason I think that the circle of Willis doesn’t play the sole role in cerebral cross-perfusion, but there are extracranial collaterals that are also important in this situation.

**Dr Y. Okita** (Kobe, Japan): We have been aware of the same problem since we have been doing the total arch replacement in such a patient. We routinely use the infrared spectroscopy on the forehead, but recently in 10 cases we put on also temporal infrared spectroscopy. We routinely perfuse three vessels, however, sometimes we find a drop in the posterior circulation. Anterior is okay.

So I think it is too early to say one perfusion is enough under 30 degrees of perfusion, even in the short period of perfusion.

**Dr S. Kucuker** (Ankara, Turkey): I would like to ask why do you prefer the left carotid artery cannulation mainly, because if you cannulate the right side, you’ll provide direct flow to the vertebral system.

**Dr Urbanski**: Yes, this is a very important point. The right side is the side of choice and we normally cannulate, of course, the right carotid artery.

But there are a lot of situations in which the left carotid artery is very suitable for cannulation, for example, in aortic dissections. And in this study we wanted to demonstrate that the left carotid artery is also a very good approach for arterial return during cardiopulmonary bypass and cerebral perfusion during circulatory arrest.

The advantage of this approach for our study was also that we had only one vessel which supplied the circle of Willis, and in 22% of the patients with incomplete circle of Willis insufficient perfusion from the left side would have been expected, and we could demonstrate that it was not the case.

But you are right, the right side is better because you have two vessels for supplying the circle of Willis.