ORIGINAL ARTICLE

Circle of Willis Collateral During Temporary Internal Carotid Artery Occlusion II: Observations From Computed Tomography Angiography

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ABSTRACT: ***Introduction:*** The Circle of Willis (CoW) is the most effective collateral circulation to the brain during internal carotid artery (ICA) occlusion. Carotid stump pressure (CSP) is an established surrogate measure of the cerebral collateral circulation. This study aims to use hemodynamic and computed tomography angiography measurements to determine the strongest influences upon the dependent variable, CSP. These findings could help clinicians noninvasively assess the adequacy of the collateral circulation and facilitate surgical risk assessment in an outpatient setting. ***Methods:*** CSP and mean arterial pressure were measured during carotid endarterectomy or during carotid balloon test occlusion in 92 patients. Intracranial arterial diameters were measured on computed tomography angiography at 16 different locations. Univariate and multivariate analyses were used to determine the key factors associated with CSP. In a subgroup of individuals (n = 27) with severe (>70% North American Symptomatic Carotid Endarterectomy Trial) contralateral stenosis or occlusion, the same analysis was performed. ***Results:*** The contralateral anterior cerebral artery proximal to anterior communicating artery (A1) of the CoW had the strongest influence upon CSP, followed by the mean arterial pressure, the contralateral ICA diameter, and the anterior communicating artery diameter ($R^2 = 0.364$). In the subgroup with high-grade contralateral ICA stenosis, the ipsilateral posterior communicating artery exerted the strongest influence ($R^2 = 0.620$). ***Conclusions:*** During ICA occlusion, the anterior CoW dominates in preserving collateral flow, especially the contralateral A1 segment. In individuals with high-grade contralateral carotid stenosis, the posterior communicating artery calibre becomes a dominant influence. The most favourable anatomy consists of large contralateral A1 and anterior communicating arteries, and no contralateral carotid stenosis.

RÉSUMÉ: Circulation collatérale dans le cercle artériel de Willis pendant une occlusion temporaire de la carotide interne. 2: observations à l'angiographie par tomodensitométrie. ***Contexte:*** Le cercle artériel de Willis (CAW) est la circulation collatérale la plus efficace du cerveau pendant une occlusion de la carotide interne (CI). La pression dans le moignon carotidien (PMC) est une mesure substitutive de la circulation collatérale cérébrale. Le but de cette étude était d'utiliser les mesures hémodynamiques et celles de l'angiographie par tomodensitométrie pour déterminer les facteurs qui influencent le plus la variable dépendante, la PMC. Ces observations pourraient aider les cliniciens à déterminer de façon non effractive si la circulation collatérale est adéquate et faciliter l'évaluation du risque chirurgical en externe. ***Méthodologie:*** La PMC et la pression artérielle moyenne ont été mesurées chez 92 patients pendant l'endartérectomie carotidienne ou pendant l'épreuve de tolérance à l'occlusion de la carotide par ballonnet. Les diamètres artériels intracrâniens ont été mesurés par angiographie par tomodensitométrie à 16 points différents. Les facteurs clés associés à la PMC ont été déterminés au moyen d'analyses uni et multivariées. Nous avons effectué les mêmes analyses chez un sous-groupe d'individus (n = 27) présentant une sténose controlatérale sévère ou une occlusion (*North American Symptomatic Carotid Endarterectomy Trial* > 70%). ***Résultats:*** L'artère cérébrale antérieure controlatérale située à proximité de l'artère communicante antérieure du CAW exerçait la plus forte influence sur la PMC, suivie de la pression artérielle moyenne, du diamètre de la CI controlatérale et du diamètre de l'artère communicante antérieure (R^2 = 0,364). Chez le sous-groupe de patients présentant une sténose de haut degré de la CI controlatérale, c'était l'artère communicante postérieure homolatérale qui exerçait la plus grande influence (R^2 = 0,620). ***Conclusions:*** Pendant une occlusion de la CI, le CAW antérieur est le facteur dominant pour la préservation du flux collatéral, particulièrement le segment A1 controlatéral. Chez les individus ayant une sténose carotidienne controlatérale de haut degré, c'est le calibre de l'artère communicante postérieure qui exerce une influence dominante. Les caractéristiques anatomiques les plus favorables sont une A1 controlatérale et des artères communicantes antérieures de gros calibre ainsi que l'absence de sténose de la carotide controlatérale.

Keywords: Carotid stenosis, carotid endarterectomy, carotid stump pressure, circle of Willis, cerebral collateral circulation

doi:10.1017/cjn.2016.10 Can J Neurol Sci. 2016; 43: 538-542

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Received May 19, 2015. Final Revisions Submitted August 28, 2015. Date of Acceptance December 12, 2015.

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The Circle of Willis (CoW) is the most effective collateral blood supply to the brain.[1-3] Blood flow directed at one side can be recruited to the contralateral side through the anterior Circle. This consists of the proximal anterior cerebral artery segments (A1's) and the anterior communicating artery. In addition, collateral flow can be recruited from the posterior Circle, which consists of the P1 segments of the posterior cerebral arteries and the posterior communicating arteries.[4] Secondary collaterals require time for recruitment and play a less important role in acute ischemia[4]; these include but are not limited to pial collaterals and extracranial-intracranial anastomoses via the ophthalmic or meningeal arteries.

It is well-known that numerous anatomical variations of the CoW exist.[1-3,5] A complete Circle only exists in approximately 50% of the population.[1,3,5-7] This has an impact on the capacity to supply blood to an affected vascular territory at times of stress. One iatrogenic source of such stress is cross clamping of the internal carotid artery (ICA) during carotid endarterectomy (CEA).

During CEA, surgeons frequently measure the carotid stump pressure (CSP), which is the residual back-pressure in the ICA following temporary occlusion of the common and external carotid arteries (CCA and ECA). CSP is an established surrogate measure of cerebral collateral circulation during CEA[8-10] as well as some neurointerventional procedures.[11] The CSP reflects the arterial pressure on the side of the CoW ipsilateral to major arterial occlusion, and it is used as an indirect measure of ischemic tolerance. Although other monitoring techniques including transcranial Doppler (TCD), near-infrared spectroscopy (NIRS), or somatosensory evoked potential (SSEP) are also widely used, in one comprehensive study with patients undergoing awake CEA, these performed equally (NIRS) or slightly worse (TCD, SSEP) than CSP.[12] A low stump pressure of 25 mmHg or less is recognized as a risk for intraoperative stroke.[10,13] Correspondingly, on angiography, poor collateral circulation is associated with a greater risk of stroke, both short term in CEA patients, and long term in medically managed patients.[14]

Currently there is no patient-specific method to predict the adequacy of the cerebral collateral circulation using computed tomography angiography (CTA) data. The present study examines anatomical measurements of the luminal diameters of the CoW and neck vessels on CTA along with the CSP measured at surgery. This was then used to determine which arterial components of the CoW have the most influence on CSP. These findings will provide clinicians with an additional tool to noninvasively assess the adequacy of cerebral collateral circulation before an intervention, and may help with patient consultation in clinic as well as intraoperative decision-making (e.g. shunt use).

Methods

Angiographic and hemodynamic data were collected according to the Canadian Tri-Council policy statement on ethical conduct for research involving the secondary use of data originally collected for health care purposes. Ninety-two patients were included over a 4.5-year period. CSP was measured either intraoperatively during CEA or intraprocedurally during carotid balloon test occlusion.

CSP Measurement

All patients undergoing CEA had symptomatic high-grade ICA stenosis of at least 70% according to the North American Symptomatic Carotid Endarterectomy Trial (NASCET) criteria.[15] Carotid surgeries were performed after informed consent and under general endotracheal anaesthesia. During CEA, the carotid exposure is performed to fully expose the CCA, ECA, and ICA. Once all vessels segments are skeletonized and mobilized, the CCA and ECA are cross-clamped temporarily. Systemic mean arterial pressure (MAP) is obtained immediately before cross-clamping. A 25-gauge sterile butterfly needle is then introduced into the lumen of the ICA just proximal to the carotid plaque. The needle is connected to an arterial-line setup with rigid tubing and calibrated pressure transducer. The CSP is allowed to stabilize for a few seconds before recording.

The CSP was also recorded for neurointerventional procedures that required balloon occlusion of the ICA. All patients gave informed consent. A balloon is introduced via a 6-Fr femoral sheath and a 6-Fr guiding catheter. Once the balloon is inflated and contrast injection confirms ICA occlusion, the pressure at the tip of catheter is measured via a calibrated arterial line setup and recorded as the CSP. MAP is obtained via the same catheter immediately before balloon inflation.

Luminal Diameter Measurements

All patients underwent CTA of the head and neck before either CEA or neurointerventional procedure to fully characterize the vasculature of the neck and the CoW. The luminal diameters of 16 vascular segments of the CoW and of the neck were measured on CTA (Figure 1). The measurements were performed on axial source images by an experienced neuroradiologist (AL).

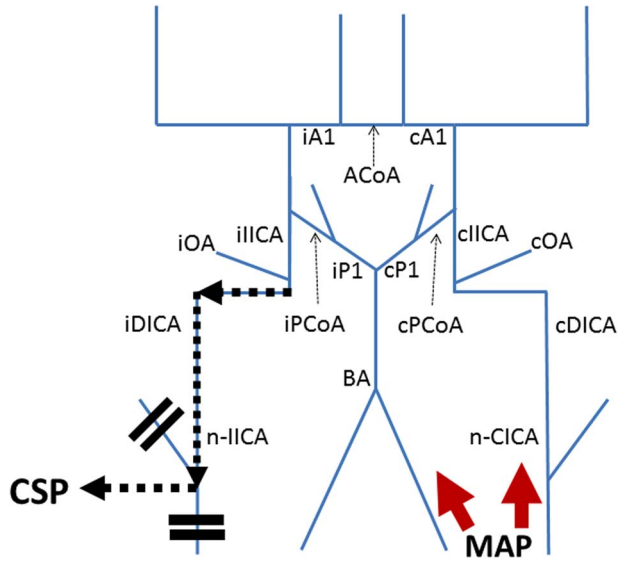

Figure 1: *Locations of 16 vascular segments measured on CTA in 92 patients. (Anterior circle) ACoA: anterior communicating artery; cA1: contralateral A1; iA1: ipsilateral A1. (Posterior circle) cPCoA: contralateral posterior communicating artery; cP1: contralateral P1; iPCoA: ipsilateral posterior communicating artery; iP1: ipsilateral P1. (Additional intracranial) BA: basilar artery; cOA: contralateral ophthalmic artery; cIICA, contralateral intracranial internal carotid artery; iIICA: ipsilateral intracranial internal carotid artery; iOA: ipsilateral ophthalmic artery. (Neck segments) cDICA: contralateral distal cervical internal carotid artery; iDICA: ipsilateral distal cervical internal carotid artery; n-CICA: narrowest contralateral internal carotid artery; n-IICA: narrowest ipsilateral internal carotid artery.*

https://doi.org/10.1017/cjn.2016.10

Table 1: Results of descriptive statistics and univariate and multivariate analyses

	Descriptive Statistic		Logistic Regression		
Variable	**Mean**	**SD**	**Univariable**	**Stepwise* Multivariable**	**Multivariable – Interactions***
Carotid stump pressure (mm Hg)	48.7	15.5			
Contralateral A1 (mm)	1.54	0.61	<0.0001	<0.0001	NS
MAP (mm Hg)	89.0	12.0	0.0037	0.0032	Significant (p = 0.041)
Contralateral ICA narrowest diameter	3.17	2.15	0.0015	0.0053	NS
Anterior communicating (mm)	1.02	0.42	0.0073	0.0066	Significant (p = 0.041)
Ipsilateral A1 (mm)	1.43	0.52	0.5300	NS	NS
Basilar artery	2.70	0.64	0.0928	NS	NS
Ipsilateral posterior communicating (mm)	0.72	0.55	0.2668	NS	NS
Ipsilateral P1	1.64	0.56	0.1876	NS	NS
Contralateral posterior communicating (mm)	0.65	0.59	0.5311	NS	NS
Contralateral P1 (mm)	1.50	0.61	0.0872	NS	NS
Ipsilateral ophthalmic	0.86	0.27	0.3716	NS	NS
Contralateral ophthalmic	0.83	0.28	0.8064	NS	NS

NS: not significant; SD: standard deviation.
*All variables left in the model are significant at the 0.0500 level. No other variable met the 0.0500 significance level for entry into the model.

Statistical Analysis

Statistical analyses were performed by an independent biostatistician (L. Stitt) using the SAS System (the REG procedure). To ensure reliable arterial diameter measurements, intrarater reliability was assessed in 22 cases using intraclass correlations for test-retest reliability. Next, univariate analysis examining MAP and the 16 arterial segments was performed, with tests for normality, treating CSP as the dependent variable. For multivariate analysis, three models were run, one with all variables forced in, followed by stepwise analysis using both forward and backward methods, with entry and removal at the 0.05 level. Analysis was performed on both the whole group (n = 92) as well as on the subgroup (n = 27) of individuals with high-grade (>70% NASCET) contralateral ICA stenosis.

Results

CSP was reasonably well distributed with no deviation from normality. The mean CSP was 48.7 ± 15.5 mmHg (mean ± standard deviation). Mean systemic pressure was 89 ± 12 mmHg. Diameter results for individual artery segments are presented in Table 1. Univariate analysis showed that the contralateral A1 was the strongest factor influencing CSP. MAP, the narrowest diameter of the contralateral ICA, and the anterior communicating artery were also significant. On multivariate analysis, variance factors were all below 2. Both forward and backward methods yielded the same result. The final model included contralateral A1, MAP, anterior communicating artery, and contralateral ICA diameter ($R^2 = .364$) (Table 2). A possible interaction of these four main effects was assessed using stepwise methods, leaving the variables as continuous. The interaction of MAP and anterior communicating artery diameter proved to be significant (p = 0.041). The final model included the four main effects plus the interaction ($R^2 = 0.394$). Results are illustrated in Figure 2.

For the subgroup of patients with high-grade (>70% NASCET) contralateral carotid stenosis, stepwise regression with forward and backward elimination also yielded identical results. Three explanatory variables met the entry criteria in the model. These were: MAP, contralateral A1 artery, and ipsilateral posterior communicating artery (Figure 3). These three variables accounted for 62% of the observed variation in CSP (Table 3).

Discussion

The most favourable condition for adequate collateral flow during acute ipsilateral ICA occlusion likely occurs in a patient

Table 2: Summary of stepwise regression for N = 92 circles ($R^2 = 0.3636$)

	Parameter Estimate	Standard Error	F Value	Pr > F
Intercept	−10.70783	10.79394	0.98	0.3239
MAP	0.35732	0.11211	10.16	0.0020
Contralateral A1	8.15356	2.23686	13.29	0.0005
Anterior communicating	8.91322	3.20085	7.75	0.0066
Contralateral narrowest ICA	1.87794	0.63946	8.62	0.0042

https://doi.org/10.1017/cjn.2016.10

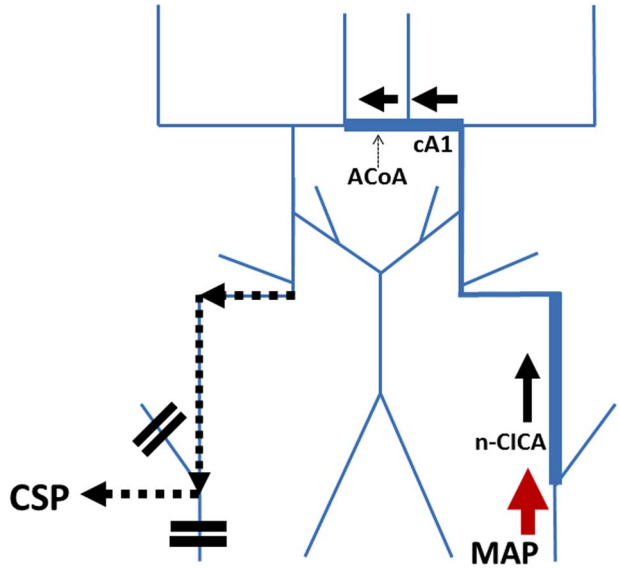

Figure 2: *Vascular segments with statistically significant association with CSP in 92 patients using univariable and stepwise multivariable logistic regression. ACoA: anterior communicating artery; cA1: contralateral A1; n-CICA: narrowest contralateral internal carotid artery.*

with a large contralateral A1 and decent (>1 mm diameter) anterior communicating artery. These conditions can reassure clinicians by providing a quantitative estimate of the collateral circulation in the event of cross-clamping of the ipsilateral ICA. On the other hand, in patients with contralateral carotid stenosis (≥70% by NASCET[15] criteria (high-grade stenosis) or CTA vessel diameter measurements ≤1.4 mm),[16] the role of the ipsilateral posterior communicating artery is quantitatively much more significant in protecting the hemisphere against hemodynamic ischemia. Quantitative assessment can be obtained by constructing a simple linear equation using the intercept and

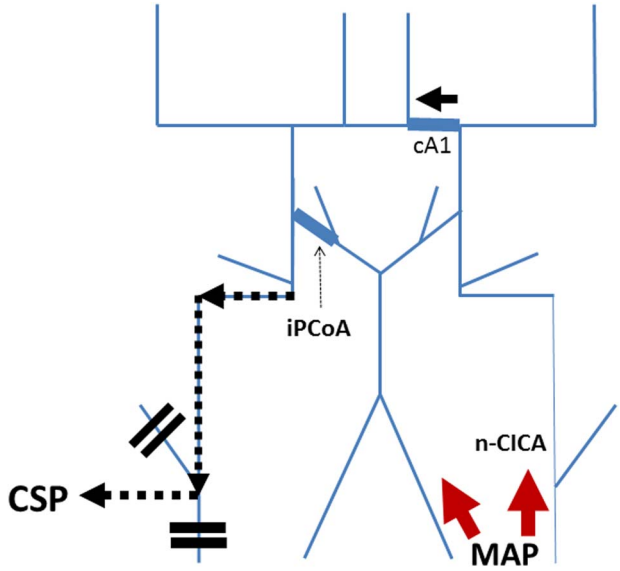

Figure 3: *Vascular segments with statistically significant association with CSP in 27 patients with high-grade contralateral carotid stenosis. cA1: contralateral A1; iPCoA: ipsilateral posterior communicating artery.*

Table 3: Summary of stepwise regression for subgroup of 27 patients with high-grade contralateral carotid stenosis ($R^2 = 0.6201$)

Variable	Parameter Estimate	Standard Error	p Value
Intercept	−11.1392	12.7476	0.391
MAP	0.3573	0.1325	0.013
Contralateral A1	8.3467	2.7083	0.005
Ipsilateral posterior communicating	14.0248	3.1207	<0.001

parameter estimates presented in Tables 2 and 3 to estimate the CSP. The results of our study are in keeping with the simulation study by Alastruey et al.[17] In their study, the authors constructed a one-dimensional fluid dynamic "circuit" model of the CoW using averaged vessel measurements. Their simulation used conservation of mass and momentum equations while accounting for nonlinear vessel wall compliance, the non-Newtonian behavior of blood, and pulse-wave propagation. Similar to our study, they demonstrated that the anterior circulation plays a greater role than the posterior circulation during acute unilateral carotid occlusion. The model assumed a normal contralateral ICA. It was concluded that ipsilateral carotid occlusion with a contralateral aplastic A1 presents the worst scenario with a reduction of ipsilateral MCA flow rate by almost 40%.

Our study provides insight into the determinants of CSP and cerebral collateral circulation via the CoW. These findings can be used before a planned surgical or endovascular intervention, to assist in preprocedural risk assessment. This has been the practice at our institution. Individuals with anatomically robust Circles appear unlikely to require a shunt during CEA, although further study is needed to confirm this. Individuals with severe contralateral stenosis or occlusion and poor posterior communicating anatomy may be at especially high risk of hemodynamic impairment during carotid clamping. Because stroke outcome is the most meaningful dependent variable after carotid surgery, further study should evaluate the relationship between vessel sizes, intraoperative monitoring, and clinical outcome.

Conclusion

In general, the strongest single vessel predictor of CSP and hence the adequacy of the collateral circulation is the calibre of the contralateral A1 segment of the anterior cerebral artery. A dominant contralateral A1 and a patent anterior communicating artery are required to conduct flow from the opposite hemisphere. In patients with high-grade contralateral ICA stenosis, the posterior circulation exerts a greater influence. These results can be incorporated into preprocedural risk assessment and planning for CEA. Clinical judgement and the use of additional monitoring technologies such as SSEP, electroencephalogram, TCD, and NIRS remain of overall importance in assessing for ischemia during endarterectomy.

Disclosures

BHW received funding from the University of Western Ontario MSc. Medical Biophysics.

https://doi.org/10.1017/cjn.2016.10

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Acknowledgements

The authors thank Larry Stitt for assistance with statistical analysis.

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https://doi.org/10.1017/cjn.2016.10