Mean Arterial Pressure Required for Maintaining Patency of Extracranial-to-Intracranial Bypass Grafts: An Investigation With Computational Hemodynamic Models—Case Series

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BACKGROUND: Maintaining flow in a newly established high-flow bypass into the intracranial circulation may be threatened by low blood pressure.
OBJECTIVE: To identify mean arterial blood pressure below which early graft failure may ensue.
METHODS: Computational fluid dynamic blood flow simulation and Doppler ultrasound–derived velocities were combined to study 12 patients with common carotid–to–intracranial (internal carotid artery in 9 and middle cerebral artery in 3) arterial brain bypass with interposition of the saphenous vein. Patients underwent carotid duplex and high-resolution computed tomography angiography to obtain the necessary data. A mean time-averaged pressure gradient across both anastomoses of the graft was then calculated.
RESULTS: The bypass graft mean blood flow ± SD was 180.3 ± 76.2 mL/min (95% confidence interval: 132-229). The mean time-averaged pressure gradient ± SD across the bypass graft was 10.2 ± 8.7 mm Hg (95% confidence interval: 4.6-15.7). This compared with a mean pressure gradient ± SD on the contralateral carotid of 21.7 ± 13.8 mm Hg. From these data, the minimum mean ± SD systemic pressure necessary to maintain graft flow of at least 40 mL/min was 61.6 ± 2.31 mm Hg, and the mean peak wall shear stress ± SD at the proximal anastomosis was 0.8 ± 0.7 Pa (95% confidence interval: 0.3-1.2).
CONCLUSION: Early postoperative mean arterial pressure less than approximately 60 mm Hg may induce blood flow in the bypass to decrease to less than 40 mL/min, a flow below which low shear stress may lead to early graft occlusion.

KEY WORDS: Blood pressure, Brain, Computational fluid dynamic, EC-IC bypass, Occlusion, Surgery

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Early graft failure in high-flow extracranial-to-intracranial (EC-IC) bypass with interposition venous grafts may be precipitated by low flow rates through the bypass graft.[1-5] Sundt and Sundt[1] estimated that vein grafts require a minimum flow rate of 40 mL/min to maintain a good patency rate. This flow rate will be dependent on both the radius of the conduit and the pressure gradient through which the blood flow passes across both anastomoses. Because of anesthesia and intensive care management, the pressure gradient can vary considerably during the early life of the graft when suture lines are most thrombogenic. The aim of this study was to use a combination of data derived from computational fluid dynamic studies and carotid duplex ultrasound from clinical cases of common carotid–to–intracranial arterial bypass with interposition of the saphenous vein to estimate the minimum mean arterial pressure (MAP) that would maintain graft flows of at least 40 mL/min.

ABBREVIATIONS: CCA, common carotid artery; **CFD,** computational fluid dynamics; **CI,** confidence interval; **ECA,** external carotid artery; **EC-IC,** extracranial-to-intracranial; **ICA,** internal carotid artery; **MAP,** mean arterial pressure; **TAV,** time-averaged flow velocity; **WSS,** wall shear stress

PATIENTS AND METHODS

We retrospectively reviewed the pre- and postprocedural 3-dimensional computed tomography (CT) angiography data. Twelve patients with high-flow

EC-IC bypasses with venous conduits were analyzed. Nine patients had common carotid artery (CCA) to intracranial internal carotid artery (ICA) bypass and 3 had CCA to middle cerebral artery bypasses. We recorded demographic, clinical indications, diagnosis, and treatment-related information. This study was approved by the university human research ethics committee and was performed in accordance with institutional ethics committee guidelines. The medical imaging data of color-coded duplex sonography and CT angiography of the 12 patients were collected. Our methods and the computational hemodynamic analysis system were described in detail and validated in vivo and in vitro in our previous studies.[6,7] In brief, the bilateral CCA, external carotid artery (ECA), and ICA along with the bypass conduit were examined with a 9-MHz linear array transducer of a computed sonography system (GE LogiQ E9, Milwaukee, WI, USA) to determine time-averaged flow velocity (TAV). This was performed after an initial 10 minutes of rest with subjects in a supine position with head slightly elevated and turned to the contralateral side by 10 to 30 degrees. Flow volume measurements were taken at 1 to 2 cm below the carotid bulb in the CCA and 1 to 2 cm above the carotid bulb in the ECA and ICA or bypass anastomosis junction. The luminal diameter was determined on the B-mode image of the vessels as the distance between the internal layers of the parallel walls. The mean of 3 measurements was evaluated at the same site. The angle of insonation was 60 degrees.

The TAV values were set as inflow boundaries condition in computational fluid dynamics (CFD) modeling. The intravascular flow volume in each vessel or bypass graft was then calculated as the product of TAV and the cross-sectional area (A) of the circular vessels according to the formula flow volume = TAV × A mL/min. For CT scanning, medical imaging data CT angiography for the cerebrovascular bypass patients was performed with a helical CT scanner (GE Medical Systems, Rydalmere, NSW, Australia) with multidetector row capability. The data were obtained using a section thickness of 0.625 mm and a table speed of 9 mm/s. Zero-degree table and gantry tilt were used. Sections in DICOM (Digital Imaging and Communication in Medicine) format were acquired with a 512 × 512 matrix. Scanning was started from the arch of the aorta and continued parallel to the orbitomeatal line to the level of circle of Willis during intravenous injection of contrast material at the rate of 3.5 mL/s. To allow for the creation of a 3-dimensional bypass geometry and volume rendering, a validated thresholding technique for regional segmentation and lumen cross-sectional contour was conducted in MIMICS (Materialise Interactive Medical Images Control System) (version 14.0; Materialise, Leuven, Belgium). The luminal surface of the vascular anastomosis in the EC-IC bypass was extracted in the format suitable for volume mesh generation used for fluid dynamic calculations. The optimum number of grid nodes, with best accuracy and optimum computing time, were carried out using ANSYS workbench (version 13.0; ANSYS, Inc., Towanda, Pennsylvania) on a high-performance workstation with a double 3.46-GHz central processing unit (8 cores) and 64-GB RAM memory. More than 500 000 elements were used for the entire bypass calculation. This included 100 000 elements applied in prism boundary calculation, which helped to derive wall shear stress (WSS) within boundary layers responsible for friction leading to the pressure gradient in the graft. It should be noted that 100 mm of the artery section was extruded in the outer normal directions for all boundaries. This allows the formation of a velocity profile at the inlet, and full recovery of the pressure wave at the outlet edge.[6] CFD was performed with an assumption of a laminar, homogeneous, incompressible blood flow with solid-vessel vein graft and nonslip and nonpenetration constraints at the wall. With the addition of real-time mean pulsatile velocities derived from Doppler ultrasound, it was possible to evaluate the inlet and outlet flow boundary conditions, the results of blood flow pattern and distribution, and pressure gradient across the patient-specific brain bypass. Kinetic energy, including the pressure gradient and energy dissipation within the vascular graft, was similarly computed across the same cut plane by deriving the positive inbound velocities.

The blood flow performed by the computational analysis system of equations is the Navier-Stokes equation and continuity equation that describe the most general movement of fluid medium.[7,8] Because of the relatively large size of the vessels examined (compared individual blood cells) and the large shear rates in arteries, the blood flows were assumed to be Newtonian with constant viscosity and density (assumed 1060 kg/m^3). The body forces of blood were omitted. An average Reynolds number of 200 to 300 was used as this is within the range of normal blood flow in humans. The energy loss (for our purpose, the mechanical energy consumed in moving the blood through conduits) is of critical importance in determining the pressure gradients necessary to overcome the resistance to provide the observed flow. Energy loss between inlet and outlet used to evaluate the cardiac workloads was calculated by the equation, which is expressed as:

$$\mathrm{EL} = \sum\nolimits_{\mathrm{inlet}}\left(\mathrm{P_{inlet}} \cdot \mathrm{Q_{inlet}} + \frac{1}{2}\mathrm{m} \cdot \mathrm{v}_{\mathrm{outlet}}^{2}\right) - \sum\nolimits_{\mathrm{outlet}}\left(\mathrm{P_{outlet}} \cdot \mathrm{Q_{outlet}} + \frac{1}{2}\mathrm{m} \cdot \mathrm{v}_{\mathrm{outlet}}^{2}\right),$$

where Q = flow (m^3/s), m = mass flow (kg/s), v = velocity (m/s), P = pressure (N/m^2).

For our patients, assumptions were made regarding the pressure distal to the anastomosis from data collected from the literature regarding normal capillary flow.[9] A distal mean systemic pressure at the arterio-capillary junction of 45 mm Hg was chosen based on pressure modeling work in the human circulatory system.[9] The hemodynamic characteristics of brain bypass blood flow patterns were also quantified along with their possible association with perioperative clinical decisions. General patient information and the characteristics of the brain bypass are summarized in Table 1.

Statistic Studies

The program GraphPad Prism (version 5.03) was used for statistical analysis. All measured values are expressed as the mean ± SD. The Student *t* test was used to reveal any difference in blood flow between pre- and post-bypass surgery in both the ipsilateral and contralateral carotid arterial systems. Vessel cross-sectional area correlation of flow volume parameters was evaluated with Spearman rank correlation coefficient. The level of statistical significance was set at $P < .05$ for all tests.

RESULTS

Blood Flow Volume, Velocity, and Cross-Sectional Area of Bypass Graft

In all 12 patients, the ipsilateral and contralateral extracranial vessels were examined postoperatively (24 vessels). Only 4 patients had preoperative extracranial imaging available for analysis (8 vessels). Carotid Doppler volumetric examination revealed

TABLE 1. Demographic Features and Location of Intracranial Pathology Treated With Extracranial-Intracranial Interpositional Saphenous Venous Grafting Brain Bypass[a]

Age, y/Sex	Treated Pathology	Proximal Anastomosis	Distal Anastomosis	Bypass Flow Volume, mL/min	Mean Velocity (PSV), cm/s	Maximum WSS, Pa		Pressure Gradient Difference, mm Hg		Mean Blood Flow Velocity at 40 mL/min on Bypass Segment, cm/s	Max WSS at 40 mL/min BF, Pa	Minimum MAP Required to Deliver BF of 40 mL/min on Bypass Segment, mm Hg
						Bypass Ipsilateral	Normal Contralateral	Bypass Ipsilateral	Normal Contralateral			
63/F	Left intracavernous aneurysm	CCA	Intracranial ICA	250.6	45.1	26.5	NA	12.33	16.80	3.6	0.9	53.3
62/M	Left cavernous sinus meningioma	CCA	M1 segment of MCA	41.0	6.4	49.8	NA	30.58	35.80	3.1	0.62	52.6
56/F	Left paraclinoid aneurysm	CCA	Intracranial ICA	159.7	36.6	19.5	NA	7.52	11.26	4.6	0.28	52.3
36/F	Left ICA traumatic pseudoaneurysm	CCA	Intracranial ICA	238.3	28.1	18.2	21.0	2.11	1.52	2.4	0.46	51.2
35/M	Right ICA false and dissecting aneurysm	CCA	Intracranial ICA	170.4	37.4	12.8	17.0	3.70	14.44	2.1	0.30	48.5
47/M	Right ICA dissecting aneurysm	CCA	Intracranial ICA	146.6	29.4	25.4	17.5	20.42	38.38	4.0	0.47	53.4
45/F	Right cavernous meningioma	CCA	MCA	98.8	49.9	2.3	15.5	14.53	47.38	10.1	2.98	56.1
63/F	Left ICA aneurysm	CCA	Intracranial CCA	222	55.5	5.0	6.38	2.13	15.21	5.0	0.78	49.1
28/F	Right ICA giant aneurysm	CCA	M1 segment of MCA	324.2	90.5	17.5	28.9	3.23	9.96	5.6	1.27	51.8
32/M	Left traumatic dissecting ICA aneurysm	CCA	Intracranial ICA	126.3	24.3	22.0	15.2	9.04	34.66	3.8	0.56	49.5
46/M	Left intracavernous aneurysm	CCA	Intracranial ICA	225.5	59.9	7.2	18.7	2.77	18.10	5.3	0.80	49.4
55/M	Left traumatic dissecting ICA aneurysm	CCA	Intracranial ICA	160.5	28.4	9.6	13.1	13.54	17.6	3.5	0.10	52.5

[a]PSV, peak systolic velocity; WSS, wall shear stress; MAP, mean arterial pressure; BF, blood flow; CCA, common carotid artery; ICA, internal carotid artery; NA, not available; M1, M1 segment of middle cerebral artery; MCA, middle cerebral artery.

a mean blood flow velocity to deliver an average of bypass blood flow of 180.3 ± 76.2 mL/min at a velocity of 20.5 ± 10.8 cm/s (95% confidence interval [CI]: 13.7-27.3). Mean ± SD values for volumetric assessment for bilateral extracranial vessels of CCA, ICA, ECA, and bypass grafts are summarized in Table 2. No statistical difference was found in each carotid vessel group between the preoperative and postoperative period.

The mean vein graft diameter was 4.5 ± 0.8 mm. There was a positive correlation ratio of volume flow with cross-sectional area assessment of bypass graft and ECA (bypass flow/ECA flow vs bypass cross-sectional area/ECA cross-sectional area) (Spearman rank correlation coefficient; $r = 2.0$, $P < .05$). There was an average doubling of flow volume after surgery at any given cross-sectional area. The coefficient of volume per cross-sectional area of ICA/ECA was noted to decrease from 1.2 to 0.9 after bypass surgery. However, there were no statistically meaningful differences in these changes.

Pressure Gradient, WSS of the Bypass Graft

CFD-derived time-averaged pressure gradient across the ipsilateral (to the bypass) ICA was 28.2 ± 6.9 mm Hg before the bypass, decreasing to 10.2 ± 8.7 mm Hg (95% CI: 4.6-15.7) after bypass surgery. This difference was significant. In addition, there was significant pressure gradient difference between ipsilateral and contralateral carotid system after surgery (Figure 1). The mean maximum WSS at the heel region of proximal anastomosis (CCA to vein graft) was 17.9 ± 12.7 N/m^2 (Pa) (95% CI: 9.8-26.1). There was no statistically significant difference in WSS between the ipsilateral and contralateral carotid systems after bypass surgery (Figure 2).

Maximum WSS, Blood Flow Velocity, and MAP in a Simulation Bypass Model at a Blood Flow of 40 mL/min

Bypass model simulation at a blood flow of 40 mL/min disclosed a mean maximum WSS at the heel region of the proximal anastomosis (CCA to vein graft) of 0.8 ± 0.7 N/m^2 (Pa) (95% CI: 0.3-1.2) (Figure 3) with a mean blood flow velocity across the vein graft of 4.4 cm/s (95% CI: 3.1-5.8). On computational hemodynamic simulation, the minimum MAP required to

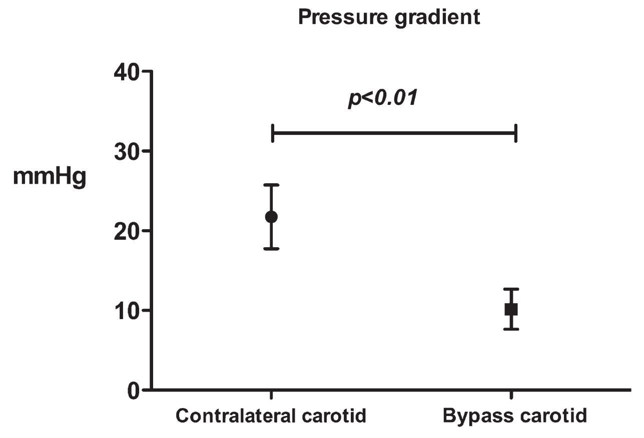

FIGURE 1. *Pressure gradient between contralateral and bypass carotid after surgery.*

deliver a 40-mL/min blood flow within the bypass graft from the CCA donor site was 51.6 ± 2.31 mm Hg (n = 12).

DISCUSSION

CFD technology as a tool for studying patient-specific hemodynamic characteristics has increased in popularity. CFD has also been used for predicting cerebral aneurysmal rupture risk,[10-12] in-stent thrombosis mechanism,[13] and arteriovenous fistula hemodynamic alteration in dialysis patients.[14] We have used this technique to evaluate brain bypass.[8] In the treatment of complex intracranial arterial diseases, various interposition venous conduit bypass operative strategies, techniques, and approaches have been described to replace the diseased intracranial artery and maintain brain blood flow.[2-5,15] The intraoperative parameters such as graft diameter and length are of utmost relevance in surgical planning to ensure a good clinical outcome. Both the radius and the length of graft are critical to the impedance of graft flow and graft maintenance. Our goal to deliver the appropriate flow with the least amount of energy loss (encouraging the selection of interposition saphenous veins with large diameters) along with graft sustainability must include consideration of the flow velocity

TABLE 2. Bilateral Flow Volumes in Extracranial Arteries Before and After Bypass Procedures[a]

	Ipsilateral Diseased Side (mL/min ± SD)		Contralateral Normal Side (mL/min ± SD)	
Vessels	Preoperatively	Postoperatively	Preoperatively	Postoperatively
CCA	244.6 ± 123	308.4 ± 99.7	279.6 ± 56	343 ± 66.9
ICA	178.4 ± 112	NA	211.8 ± 70	242.1 ± 92.9
ECA	90.3 ± 31	101 ± 50.2	86.5 ± 42	106.1 ± 48.3
Bypass graft	NA	180.3 ± 76.2	NA	NA

[a]CCA, common carotid artery; ICA, internal carotid artery; NA, not available; ECA, external carotid artery. Values are mean ± SD.

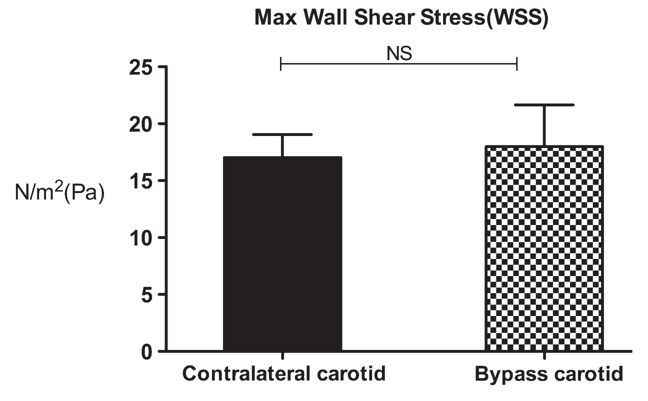

FIGURE 2. *Wall shear stress between contralateral and bypass carotid after surgery. NS, not significant.*

that minimizes thrombogenicity at vulnerable locations (eg, suture lines) as well as minimizing diameter changes at the proximal and distal anastomoses to reduce flow turbulence.[16] In addition to the long-term goal of graft viability and sustainability, there is the short-term hurdle immediately after surgery of the critical importance of the pressure gradient for flow. In our study, we set out to investigate the minimum MAP for EC-IC bypass surgery with interposition of a saphenous graft by using patient-specific CFD models. We investigated vein bypass to the anterior circulation because it has a greater risk of failure than superficial temporal middle cerebral artery bypass graft.[17,18]

Blood Flow Volume, Velocity, and Cross-Sectional Area of a Bypass Graft

Our data suggested a positive correlation ratio of volume with cross-sectional area assessment of a bypass graft to the ECA (bypass flow/ECA flow vs bypass cross-sectional area/ECA cross-sectional area) (Spearman rank correlation coefficient; $r = 2.0$, $P < .05$), with an average doubling of flow volume after surgery at any given cross-sectional area. With a greater wall dispensability and capacitance of the bypass conduit, greater blood flow volumes would be expected to be delivered via the bypass into the ipsilateral hemisphere compared with the preoperative diseased artery (in cases in which there is an unhealthy arterial wall of the ICA being superseded). Carotid Doppler volumetric examination revealed that the blood flow of the bypass graft was 180.3 ± 76.2 mL/min at a mean velocity of 20.5 ± 10.8 cm/s. However, there is great variation in results of similar studies and great variation in graft patency (including study with Excimer Laser Assisted Non-occlusive Anastomosis). Our flow results are high compared with the vein bypass series of Eguchi[5] in which mean bypass flow was 109 mL/min (n = 59) when measured with a magnetic flow meter intraoperatively. In the Mayo Clinic series,[17] mean graft flow rates at surgery were 100 mL/min for anterior circulation saphenous vein bypass grafts and 110 mL/min for posterior circulation grafts. However, in the Mayo Clinic series, this flow increased to greater than 200 mL/min in some grafts at follow-up. Jafar et al,[18] for some cases, reported intraoperative blood flow measurement in saphenous vein bypass grafts in excess of 250 mL/min. Such variations may be explained by patient selection, the circumstances in which measurements were recorded, and differences in techniques used to measure the blood flow.

On the contralateral carotid system, the coefficient of volume per cross-sectional area of ICA/ECA, measured by color-coded duplex ultrasound, was noted to decrease from 1.2 to 0.9 after bypass surgery. This result is not entirely unexpected where bypass flow is substantially greater than normal ICA flow. The interpretation of this result is that the average bypass flow in our series contributed to the contralateral circulation.

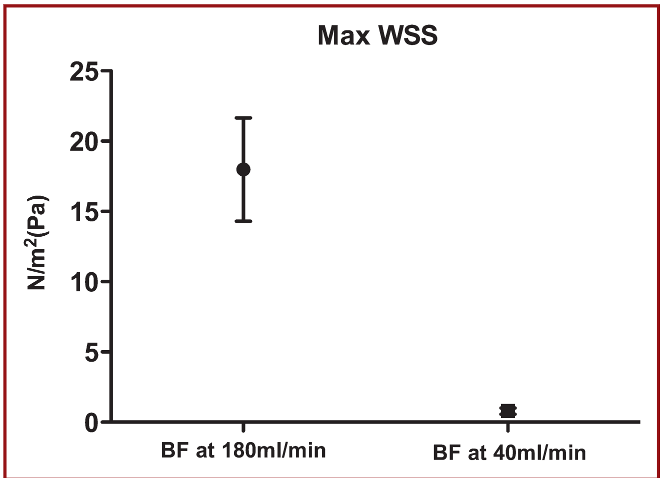

FIGURE 3. *Wall shear stress (WSS) of ipsilateral (bypass) proximal carotid anastomosis at blood flow (BF) of 180 mL/min and 40 mL/min.*

Pressure Gradient and WSS at a Bypass Graft

Case selection influences the pressure gradient across the anastomosis sites. These pressure gradients determine the blood flow rate and velocity of flow. This velocity of flow has a direct relationship to WSS within the vein graft conduit. WSS must fall within a critical normal range; outside this range, occlusion is likely to occur. It has been documented that intimal hyperplasia or atherosclerotic plaque usually arises in areas where flow separation occurs with low WSS (typically <0.4 Pa).[19,20] This is most likely to be at the arterial bifurcation and the toe and the heel of the anastomosis. WSS depends on the geometry of anastomosis (recipient vessels radii), blood flow velocity, and pressure gradient across the bypass construct. Areas of normal or above normal shear (>1 Pa) induce an atheroprotective endothelial phenotype.[21,22] In our study, the estimated peak value for WSS at the heel junction of the donor CCA proximal anastomosis was 17.9 ± 12.7 Pa (95% CI: 9.8-26.1), which is considered sufficient to prevent disruption of the endothelium dysfunction and thus prevent atherosclerosis formation.[20]

In addition, the significant pressure gradient difference between the ipsilateral and contralateral carotid systems after surgery (Figure 1), with a lower resistance to flow in the bypass venous conduit, would help to explain the increase in bypass blood flow above that in the preoperative ICA. This finding also supports the previous interpretation that the average bypass flow in our series contributed to the contralateral circulation.

Maximum WSS and Optimum MAP in a Bypass Model Simulation at Blood Flow of 40 mL/min

Sundt and Sundt[1] estimated that vein grafts require a minimum flow rate of 40 mL/min to maintain high-flow bypass patency. Our data suggested that at a blood flow rate of 40 mL/min, the bypass model predicts an estimated WSS at the heel region at the proximal anastomosis of 0.8 ± 0.7 Pa. Above these values, the hemodynamic environment is conducive to long-term patency. Our simulation indicated that WSS was reduced with decreasing flow rates. At lower flow rates, low WSS (<0.4 Pa) may lead to endothelial dysfunction, inhibition of nitric oxide synthase, greater endothelial cell cycling, and increased apoptosis.[20-22]

We also investigated the MAP requirement to maintain the patency of the graft. Although the focus must be on the long-term patient outcome, the maintenance of acute postoperative flow is critical to prevent occlusion (such as thrombosis commencing at the suture line). Sundt and Sundt[1] reported that graft flow of 40 mL/min was the minimum required to prevent early postoperative occlusion. This is supported by our CFD analysis. If we assume that the mean systemic pressure at the arteriocapillary junction is 45 mm Hg,[9] our computational modeling suggests that a graft flow of 40 mL/min requires a mean CCA pressure of 51.6 ± 2.31 mm Hg. Data also suggested that CCA pressure is approximately 10 mm Hg lower than the radial artery pressure in the supine position during surgery.[22] Therefore, our model predicts an MAP less than approximately 60 mm Hg in the immediate postoperative period may predispose to early occlusion.

Limitations

For computational simplicity, the assumptions that the vessels are rigid tubes have been applied. However, Bergel[23] demonstrated that for an arterial pressure less than approximately 100 mm Hg, the elastic modulus of the carotid artery would be 0.65 MPa. This value is consistent with Torii's study,[24] in which, for a similar blood pressure and arterial elastic module, the impact on the arterial radius was minimal and may not be of significance. Furthermore, the aim of the current study was to compare the pressure gradient between the ipsilateral and contralateral carotid systems to determine MAPs below which early graft failure may ensue. Therefore, it is reasonable to assume that the effect of vessel elasticity would have a minimal impact on the analysis of our findings.

Disclosures

Dr Sia receives a scholarship from the University of Malaya. The authors have no personal financial or institutional interest in any of the drugs, materials, or devices described in this article.

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COMMENTS

The authors generate a hypothesis about mean arterial pressures (MAPs) below which early graft failure may ensue. This proposition was primarily derived from computational blood flow simulation and Doppler ultrasound–derived velocities in cases with common carotid–to–intracranial internal carotid or –middle cerebral artery bypass. But there are no data to validate the premise that such MAP, vs any other threshold, is in fact "required" for bypass patency.

No one would suggest a study deliberately dropping MAP below various thresholds to prove such an hypothesis, given the consensus common sense (about which there is no equipoise) that maintaining good perfusion is good for the patency of any graft. But it is unclear why a given MAP and not any other should be taken at face value in view of the current analysis.

The authors acknowledge numerous limitations and biophysical assumptions inherent to such modeling, most of which have not been validated. Furthermore, it is unclear whether the same threshold would apply to other types of bypasses, including the more common STA-MCA revascularization, and what would be the impact of antiplatelet therapy, intravascular volume, hematocrit levels, and other factors.

Such modeling is mathematically elegant, and it seems to support a general premise that perfusion is important for graft patency. But it truly does not present a novel concept, nor convincingly support or refute a specific hypothesis in this regard.

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The study by Sia et al is a nice piece of work showing the potential of state-of-the-art computational tools to understand the effect of treatment based on personalized data. The authors present a study on extracranial-to-intracranial bypass graft performed using CFD in a case series. The study is based on 12 cases, 9 common carotid artery–to–internal carotid artery and 3 internal carotid artery–to–middle cerebral artery bypasses. The authors concluded that postoperative MAP below 60 mm Hg may lead to a negative outcome (bypass flow <40 mL/min and early occlusion). This work provides proof and verification, based on fluid mechanics, of the existing literature[1] on the use of CFD in patient-specific models with personalized flow boundary conditions, something that has tremendous potential in terms of treatment planning and outcome. Although there is still active discussion on the clinical value of such tools and whether their output can be trusted,[2,3] this work represents an additional example of how CFD can provide useful insights into the physics behind disease and treatment evolution, and, in the future, these might become part of routine clinical practice. Hemodynamic alterations due to bypass are hard to predict, are usually explored in situ during the intervention, and are influenced by different factors, such as graft diameter and length. These parameters have been properly studied here. Still, the large variability in flow rates (180.3 ± 76.2 mL/min) and velocities (20.5 ± 10.8 cm/s) found in this study suggests that there is now a "one size fits all" recipe, a fact also supported by previous literature. The use of preoperative planning tools based on patient-specific anatomy and boundary conditions could play a key role in treatment planning. Reduced dimensionality models[4] bring a solution to excessive computational cost and parameterization of full 3-dimensional CFD models, preserving a highly accurate representation of flow dynamics in situation in which the local topology of the vascular network has been altered, as presented by Huberts et al[5] in the case of arteriovenous fistula. The application of reduced dimensionality models in extracranial-to-intracranial bypass has the potential to improve treatment planning and therapeutic outcome. Furthermore, the use of noninvasive imaging modalities, such as Doppler ultrasound, for the acquisition of boundary conditions might make in the near future the use of such personalized models during the intervention a reality.

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