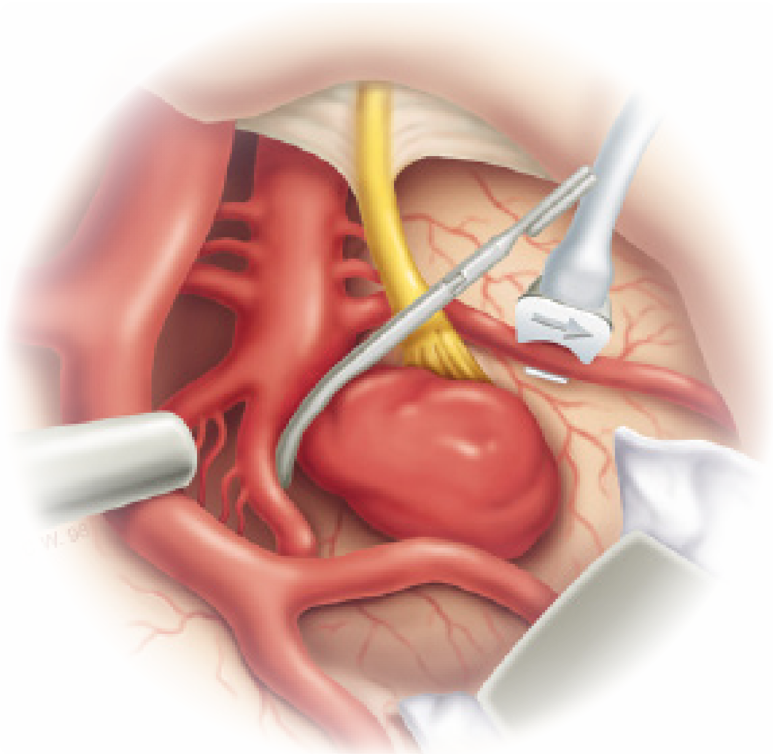
THE MEASURE OF BETTER RESULTS.

Flow-Assisted Surgical Technique (F•A•S•T) in Cerebrovascular Surgery



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Restoration and preservation of blood flow in parent vessels and distal outflow branches are critical to the functional success of aneurysm clipping and other cerebrovascular surgeries. Augmentation of flow, via an extracranial to intracranial (EC-IC) bypass, is instrumental in treating cerebral occlusive diseases. This handbook presents Flow-Assisted Surgical Technique (F•A•S•T®) during cerebrovascular neurosurgery with transit-time ultrasound flowmetry. Transonic's quantitative intraoperative measurements provide precise, non-invasive information so that the surgeon can improve outcomes.

We gratefully acknowledge the invaluable contributions of F.T. Charbel, MD, FACS, professor, head and chief of neurovascular surgery and S. Amin-Hanjani, MD, FAANS, FACS, FAHA, professor and program director, co-director of neurovascular surgery at the University of Illinois at Chicago, M. Lee, MD, clinical assistant professor of neurosurgery, Stanford University and G. Meglio, MD. Their gracious knowledge sharing has made this handbook possible.

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Flow-Assisted Surgical Technique (F•A•S•T) during Cerebrovascular Surgery

A. Introduction

The human brain weighs just three pounds (1,300 - 1,400 g) and represents two percent of one's total weight.[1] Yet, it houses one hundred billion neurons whose interactions give us the ability to sense, move, understand and create. Our brain sets us apart from other species and gives us our memories, thoughts and personalities.[2] Oxygen and nutrients are delivered to this delicate, yet incredibly complex organ through an intricate network of cerebral vessels. When delivery of vital nutrients or oxygen is threatened by problems in this cerebrovasculature, a person's life rests in the hands of highly skilled cerebrovascular surgeons who seek to revascularize parts of the brain and avert devastating consequences.

One threat to cerebral function is a cerebrovascular aneurysm, a weak spot in the wall of an cerebral artery that dilates to form a balloon-shaped defect. As the aneurysm continues to enlarge, the thin wall of the vessel can rupture, spilling blood into surrounding tissues. Consequences can be catastrophic. About 30,000 people in the United States annually experience a ruptured cerebral aneurysm and require emergency medical attention. If the aneurysm cannot be treated endovascularly, intracranial aneurysm surgery is advised. The goal of this surgery is to obliterate the aneurysm while fully preserving flow in the intracranial parent vessels and their distal branches. Failure can result in life-long disability or death.

Although aneurysms have been reported in the medical literature since the 17th century, it was not until 1931 that the first direct intracranial aneurysm operation was performed. Scottish surgeon Dr. Norman Dott wrapped an internal artery bifurcation aneurysm with muscle to prevent its rupture. The surgery's success marked the advent of modern intracranial aneurysm surgery. In 1936, Dr. Walter Dandy of Baltimore (see sidebar on the following page) trapped an aneurysm by tying off the internal carotid artery on both sides of the aneurysm. A year later he successfully clipped a posterior communicating artery aneurysm and preserved flow in the parent vessel and ushered in an era of aneurysm clipping surgery.

Occlusive cerebrovascular disease constitutes another challenge for cerebrovascular surgeons. As intracranial atherosclerotic vessels constrict, brain cells are starved for their life sustaining nutrients. Cerebral ischemia ensues which, in turn, can trigger a stroke. The surgeon attempts to augment flow to the deprived cells through revascularization and avert dire consequences.

1www.faculty.washington.edu/chudler/facts.html

2Black, K, Mann, A, Brain Surgeon, A Doctor's Inspiring Encounters with Mortality and Miracles" Wellness Central, Hachett Book Group, Inc., 2009 New York, New York

A. Introduction cont.

One strategy used to augment cerebral flow is an extracranial to intracranial bypass (EC-IC), pioneered by M.G. Yasargil at the University of Zurich and the University of Vermont (see sidebar on following page).

> *"The convergence of microneurosurgical techniques and more refined understanding of the pathophysiology of cerebral ischemic disease set the stage for the EC-IC bypass."*
> Hayden MG et al, Neurosurg Focus 2009; 26(5):E17.

By the 1960's, the introduction of the operating microscope and development of angiography began a new era for cerebrovascular surgical management. Surgeons could, for the first time, pinpoint the location of an aneurysm prior to surgery and illuminate the surgical field as they operated. With these sophisticated microsurgical instruments and techniques, cerebrovascular neurosurgeons skillfully repair complex aneurysms and difficult occlusive disease cases. At the same time, technology continues to evolve, driving ever-expanding potential for improved surgical outcomes.

The Charbel Probe® and Transonic® Surgical Flowmeter are one such advance. During intracranial surgery, the bayonet-handle Micro-Flowprobe can be used under a microscope to provide neurosurgeons with real-time, quantitative measurements of the quintessential vital sign: direct blood flow in major cerebral vessels.

Transonic® technology provides quantitative flow data without disrupting the flow of surgery. Developed in collaboration with Fady T. Charbel, M.D., F.A.C.S., (see sidebar on page 4) the Charbel Probe® provides immediate functional verification of flow preservation in parent vessels and distal outflow branches following placement

Cerebrovascular Surgery **Pioneer**

Walter Edward Dandy, M.D.

Walter Dandy was a founding father of neurosurgery. The only son of John Dandy and Rachel Kilpatrick, immigrants from Lancashire, England, and Armagh, Ireland, respectively, Dandy graduated from Johns Hopkins Medical School in 1910 and remained at that institution until his death.

Dandy's neurosurgical innovations included his 1938 description of clipping an intracranial aneurysm. This marked the birth of the sub-specialty of cerebrovascular neurosurgery and represented the first time that a vascular problem of the brain was treated successfully with a strategic surgery. This experience led Dandy, during the later years of his career, to treat other vascular cerebral problems such as arterio-venous malformations (AVMs), arteriovenous fistulas (AVFs), carotid cavernous fistulas (CCFs), and cavernous malformations.

In 1944, Dandy published a book entitled Intracranial Arterial Aneurysms in which he summarized his experiences with these treacherous and technically formidable lesions.1

[1]www.wikipedia.com

Neurosurgery's Man of the Century 1950-1999

Mahmut Gazi Yasargil, M.D.

Mahmut Gazi Yasargil, the founder of microneurosurgery, was born in 1925 in Lice, Turkey. Yasargil left his home in 1943 to continue his medical education in Germany and then to the Department of Neurosurgery, University of Zurich, Switzerland where he trained under Krayenbühl. There and at the University of Vermont, over the next 20 years, he conducted research and developed clinical applications for microsurgical techniques, performing 7,500 intracranial operations and training about 3,000 colleagues.

After retiring from the University of Zurich in 1993 Yasargil accepted an appointment as Professor of Neurosurgery at the College of Medicine, University of Arkansas for Medical Sciences in Little Rock, AK where he is still active in the practice of microneurosurgery, research, and teaching.

Hailed as one of the greatest neurosurgeons of the twentieth century, Yasargil's microsurgical techniques have transformed the outcomes of patients with conditions that were previously inoperable.[1]

[1]www.wikipedia.com

of aneurysm clips. It alerts the surgeon to compromised blood flow during aneurysm clipping and other cerebrovascular revascularization procedures, and thus spurs corrective action to avoid cerebral compromise.

Transonic® intraoperative blood flow measurements complete a flow-based surgical cycle that includes:

- Pre-operative assessment with NOVA qMRA® (Non-invasive Optimal Vessel Analysis Quantitative Magnetic Resonance Angiography);
- Intra-operative assessment with Transonic® Flow-QC® intraoperative flow measurements, complemented by indocyanine green (ICG) video angiography and/or intraoperative angiography;
- Post-operative assessment with NOVA qMRA®.

Third Edition

The intent of the cerebrovascular surgery handbook is to familiarize the neurovascular community with quantitative measurements of blood flow during cerebrovascular surgery with the Transonic® Surgical Flowmeter and Charbel Probe®. The first edition focused on flow preservation during aneurysm clipping surgery. The second edition expanded the handbook's scope to include EC-IC bypass for flow replacement/preservation during aneurysm clipping surgery and flow augmentation/revascularization for treatment of occlusive disease. This third edition now includes a new algorithm on pages 97-98 for flow measurements during arteriovenous malformation (AVM) resection surgery.

A. Introduction cont.

The handbook first reviews cerebral circulation and presents a basic overview of cerebral aneurysm and EC-IC bypass management with Flow-Assisted Surgical Technique (F•A•S•T®). Sidebars in this section provide synopses of landmark papers.

The handbook then outlines algorithms for measuring flow during surgical aneurysm management with more detailed descriptions of the more common aneurysms, and recommendations for Probe size and Probe placement during aneurysm clipping surgery. Integrated into this section are a number of case examples where flow measurements were invaluable to achieving a successful surgical outcome.

The handbook presents EC-IC bypass for flow replacement/preservation during complex aneurysm clipping surgery, or to increase cerebral flow (flow augmentation) to treat occlusive disease, including moyamoya. A landmark hemodynamic moyamoya study performed at Stanford University by Dr. Gary Steinberg and his surgical team is presented.

The handbook then presents a new algorithm on flow measurements during AVM resection surgery, compliments of Drs. A Della Puppa, O. Rustemi and R. Scienza at Padua University Hospital, Padua, Italy.

The AVM algorithm is followed by questions that are frequently asked about transit-time flowmetry and the use of the Charbel Probe®. A list of peer-reviewed publications completes the handbook.

Cerebrovascular Surgery
Flow Pioneer

Fady T. Charbel, M.D. FACS

Dr. Fady T. Charbel has pioneered quantitative measurements of cerebral flow before, during and after cerebrovascular neurosurgery.

Educated in Beruit, Lebanon, Dr. Charbel completed fellowships at Henry Ford Hospital in Detroit and McGill University, Montreal, before moving to the University of Illinois at Chicago where he became Professor and Head of the Department of Neuro-surgery and Chief of the Neurovascular Section.

As co-inventor of the Charbel Probe® (Transonic Systems Inc.®) for quantitative on-the-spot measurements of flow during cerebrovascular surgery, Dr. Charbel was named "Inventor of the Year" by his institution in 2002.

As a scientist/surgeon, Dr. Charbel also recognized the importance of knowing cerebral blood flow before and after treatment. This led to his founding of VasSol Inc. and development of NOVA qMRA®, which creates computer simulation of cerebral circulation models.

Through publications, lectures, seminars and workshops, Dr. Charbel has tirelessly championed quantitative cerebrovascular flow measurements to guide surgical management and improve outcomes.

Intraoperative Flow Measurements Help Prevent Intraoperative CVA

Stroke, a result of vascular complications, is a major cause of morbidity and mortality during and after aneurysm surgery. If an aneurysm clip occludes the parent vessel or a distal branch, the flow deficit may cause an acute intraoperative stroke (see case synopsis in sidebar).

Measuring Flow Confirms Flow Integrity in Parent Vessels and Distal Branches after Aneurysm Clipping

The basis of intracranial aneurysm surgery is identification of all proximal parent and distal vessels associated with the aneurysm and preservation of flow in these vessels after aneurysm clipping. Transonic® Flow-QC® either confirms that blood flow is indeed preserved in the these vessels, or it prompts the surgeon to correct flow deficiencies.

Offers Surgeons Peace of Mind

In addition to providing flow documentation for a patient's record, flow measurements offer the surgeon peace of mind: evidence not only of what has been done right, but evidence of what *hasn't* been done wrong.

Flow Measurements Inform Surgical Decisions

Flow measurements during aneurysm clipping or during EC-IC bypass procedures offer quantitative information about flow in cerebral vessels. During EC-IC bypass construction, flow measurements aid the surgeon as he or she chooses the most appropriate bypass conduit. They can also help predict its future patency.

Knowing Flow Saves the Day!

Giant Carotid Ophthalmic Aneurysm

A patient with a giant carotid ophthalmic aneurysm was referred to the University of Illinois at Chicago from another institution. Before clip placement, baseline flows were measured in the internal carotid artery and the anterior and middle cerebral arteries. The surgeon placed two-angle fenestrated clips across the neck of the aneurysm. After clipping, anterior and middle cerebral arterial flows returned to normal but internal carotid artery flow was only 33 ml/min. It took numerous clip reapplications coupled with intraoperative flow measurements to achieve baseline internal carotid artery flow of 66 ml/min. It was clear that, despite multiple intraoperative angiograms, complete restoration of flow in the internal carotid artery was confirmed only through intraoperative flow measurements. The post-operative angiogram confirmed excellent clipping (Complete case study on page 39).

B. Why Measure Blood Flow cont.

Flow Measurements Provide Immediate Assessment of Residual and Collateral Flow Reserve during Temporary Clipping

When temporary clips are applied to proximal and distal arteries before aneurysm clipping in order to control bleeding and avoid hemorrhage, Transonic® intraoperative flow measurements are used to assess the safety of the temporary clipping. If there is little change in flow after temporary clipping, it indicates good collateral flow. The surgeon can proceed knowing that the temporary clipping is relatively safe. If there is a reduction in flow following temporary clipping, the surgeon is alerted to the fact that there is poor collateral flow and the temporary clip time must be as brief as possible within an eleven minute window.

Flow Measurements during Flow Preservation or Flow Augmentation EC-IC Bypass Confirm That The Bypass Is Fully Functional before Leaving the OR

In cases where the surgeon elects to perform an EC-IC bypass to preserve or augment distal cerebral perfusion, intraoperative flow measurements indicate if the bypass is functioning optimally. If bypass flow is inexplicably less than free flow measured before anastomosing the bypass, the surgeon will look for technical problems and, if necessary, revise the bypass.

Conclusions

- The Charbel Probe® helps the surgeon achieve optimal clip placement to completely obliterate an aneurysm while preserving flow in parent vessels and distal branches.
- Transonic® flow data confirms the functional success of the surgery or alerts the surgeon to dangerous, flow-limiting conditions.
- Transonic® flow measurements provide invaluable quantitative flow data for the surgeon's clinical armamentarium.
- No other flow technology produces flow data so quickly and non-intrusively during surgery.

***Note to the Surgeon:* The following chapter presents basic cerebrovascular anatomy as it relates to various surgeries. The information is therefor quite familiar to you. It is included for sake of completeness and well-rounded treatment of the subject. As a surgeon, you may prefer to skip ahead to sections about techniques or applications in procedures you frequently perform.**

C. F•A•S•T in Cerebral Disease Management

Introduction

Cerebrovascular Flow-Assisted Surgical Technique (F•A•S•T®) categories include procedures to clip and obliterate aneurysms and procedures to treat cerebral occlusive disease.

1. Aneurysm Clipping Surgery:

Dr. Fady T. Charbel, professor and head of the Department of Neuro-surgery at the University of Illinois at Chicago and pioneer of the use of intraoperative blood flow measurements in cerebrovascular surgery, uses Transonic® flow measurements as part of his operative strategy to:

- Preserve Flow during clipping of aneurysms. Although most aneurysms are first considered for coiling, those that cannot be coiled are surgically clipped. When aneurysms are clipped, baseline flows are measured before clipping so that the patient can serve as his or her own control. Post-clipping flows are then compared to the patient's own baseline flows. Full preservation of flow in the cerebral arteries is the goal.
- Replace Flow during clipping of complex aneurysms where the parent vessel must be sacrificed and an EC-IC bypass is constructed.

2. EC - IC Bypass Surgery for Treatment of Cerebrovascular Occlusive Disease

The University of Illinois at Chicago neurosurgical team also uses intraoperative blood flow measurements for surgical decisions while constructing an EC-IC bypass to augment flow to treat occlusive cerebrovascular disease such as carotid artery occlusion. In these cases they use the Cut Flow Index to help determine if a bypass will be viable (see pages 16, 83 & 84).

References:

Charbel et al, "Superficial Temporal Artery - Middle Cerebral Artery Bypass," Neurosurgery, January 2005.

Amin-Hanjani S, Charbel FT, "Flow-assisted surgical technique in cerebrovascular surgery," Surg Neurol. 2007;68 Suppl 1:S4-11.

Charbel FT, Alaraj A, Amin-Hanjani S, "Advanced Strategies and Techniques for Surgical Aneurysm Treatment," 8th International Conference on Cerebrovascular Surgery, Taipai, Taiwan 2006. Medimond S.r.l. GY30R9091.

Charbel FT, Alaraj A, Amin-Hanjani S, "Surgical Treatment of Intracranial Atherosclerosis: Update on the State of the Art," 8th International Conference on Cerebrovascular Surgery, Taipai, Taiwan 2006. Medimond S.r.l. GY30R9093.

Amin-Hanjani S, Alaraj A, Charbel FT, Flow replacement bypass for aneurysms: decision-making using intraoperative blood flow measurements. Acta Neurochir (Wien). 2010 Jun;152(6):1021-32; discussion 1032.

Amin-Hanjani S, Du X, Milnarevich N, Meglio G, Zhao M, Charbel FT, "The Cut Flow Index: An Intraoperative Predictor of the Success of EC-IC Bypass for Occlusive Cerebrovascular Disease," Neurosurgery 2005; 56:75-85.

C1. Aneurysmal Disease

Cerebrovascular aneurysms are balloon-shaped defects in the cerebral arterial vasculature. Often asymptomatic, many people do not realize that they have an aneurysm until it ruptures. Statistics indicate that eighty-five to ninety percent of aneurysms are not diagnosed until after they rupture. Rupture can cause severe neurologic complications that can culminate in death. Acute bleeding or a subarachnoid hemorrhage (SAH) from a ruptured cerebral aneurysm requires emergency medical attention.

A severe, sudden headache, often described as "the worst headache of my life," signals a ruptured aneurysm. Other symptoms include nausea, vomiting, double vision and numbness in the face or arms. One of the most serious delayed complications of subarachnoid hemorrhage due to aneurysm rupture is cerebral vasospasm, a severe narrowing of the major cerebral arteries, which reduces blood flow to critical territories of the brain.

Occurrence

Intracranial aneurysms occur in 0.2 - 7.8 percent of the general population. Twenty to thirty percent of these persons have multiple aneurysms. Aneurysms are thought to occur more frequently with increasing age. SAH is reported to occur more frequently in cocaine users. Ten and one-half out of every 100,000 persons experience a ruptured aneurysm. Of the 30,000 Americans annually who experience a ruptured aneurysm, one-third survive with a good recovery. One third are disabled. The final third die.

Types of Aneurysms (Figs. C1a-d)

Aneurysms are classified by size, shape, location, origin, vessel type and whether other diseases are present. Saccular or berry aneurysms are the most common type of intracranial aneurysm (Fig. C1a). They are usually spherical and have an irregular appearance. A neck connects the aneurysm to the parent vessel.

Aneurysm Types

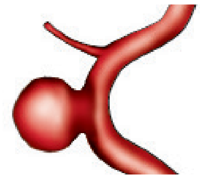


Fig. C1a: Saccular (berry) aneurysm with narrow neck.

Fig. C1b: Saccular aneurysm with a broad neck. These aneurysms do not lend themselves to coiling.

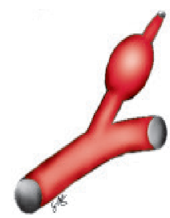
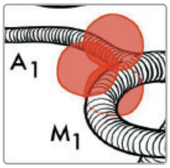


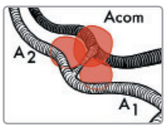
Fig. C1c: Fusiform (short section of artery bulges all the way around the vessel like a spindle).

Fig. C1d. Mycotic (rare, caused by infection).

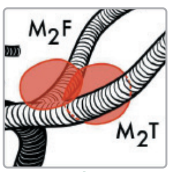
Aneurysm Sites



ICA Bifurcation Aneurysm

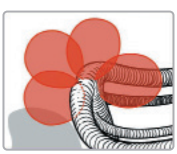


AComA Aneurysm



MCA Bifurcation Aneurysm

Figs. C2: Common anterior circulation aneurysm sites.



Basilar Artery Aneurysm

Posterior Inferior Cerebellar Artery Aneurysm

Figs. C3: Sites of common posterior circulation aneurysms.

As some aneurysms grow, the neck broadens (Fig. C1b) and can sometimes incorporate branches or perforating arteries from the parent vessel into the aneurysm. These broad base aneurysms do not lend themselves to endovascular coiling and create enormous challenges for cerebrovascular surgeons as they try to clip and obliterate the aneurysm while still preserving flow in parent and distal vessels.

Sizes of Saccular Aneurysms		
Diameter	Classification	Percentage
< 12 mm	small	79%
12 - 25 mm	large	19%
> 25 mm	giant	2%

Most intracranial saccular aneurysms which rupture have diameters of 5 to 15 millimeters.

Complex Intracranial Aneurysms

Aneurysms are categorized as "complex" due to their:

1) Location, the difficulty of surgical approach and the depth of and surrounding anatomy of the aneurysm.
2) Configuration and shape which dictates the level of difficulty encountered in its surgical management.
3) Size: as the size of large or giant (diameter > 2.5 cm) increases, the aneurysm may obscure its surrounding anatomy, develop an intraluminal thrombus, contort the parent vessel, incorporate branches into its sac and become calcified.
4) An intraluminal thrombus in the aneurysm can significantly complicate its surgical treatment. The thrombotic material often has to be removed from the sac before the aneurysm can be clipped. Sophisticated clip techniques have to be developed to obliterate these aneurysms. A calcified aneurysmal neck also creates problems and will sometimes prohibit the clip from closing completely. Various techniques must be used to prepare the neck to

accept the clip. Sometimes an EC-IC bypass is performed to ensure distal circulation and prevent ischemia.

5) Intraoperative misadventures: premature rupture of the aneurysm before its adequate surgical exposure can be catastrophic and can make a relatively straightforward surgery complex and challenging.

6) Failed prior therapy: recurrent or residual lesions from previously coiled aneurysms also creates complex surgical challenges.

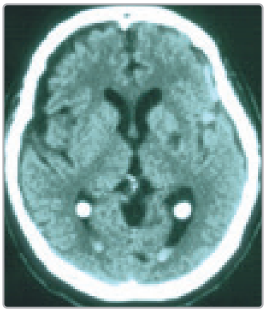
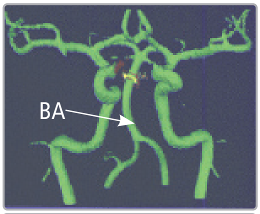


Fig. C4: MRI shows subarachnoid hemorrhage caused by rupture of left MCA aneurysm.

Other Types of Aneurysms

Other types of aneurysms are called fusiform, mycotic and traumatic. Fusiform aneurysms are spindle-like dilatations (Fig. C1c, page 8) that encompass the entire vessel with no distinguishable neck. They are rare, as are mycotic aneurysms (Fig. C1d, page 8), which result from infection. Traumatic aneurysms result from head trauma.



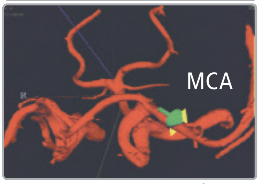


Fig. C5: NOVA qMRA® scans of cerebral circulation with volumetric flow rates calculated at arrow points: BA in top scan, Left MCA in bottom scan.

Aneurysm Sites

Aneurysms usually form where a cerebral vessel bifurcates or branches at or near the arterial forks within the Circle of Willis. They are generally found in the region of the bifurcation apex, the point of minimum curvature facing the blood flow and project in the direction that flow would take if the vessel had not divided. The flow pattern in these locations is thought to place more stress on the vessel wall and cause the dilatation.

Eighty-five to ninety percent of cerebral aneurysms occur in the anterior circulation at the following locations (Figs. C2, page 9):

a) ICA — 30%

b) AComA — 30%

c) MCA — 30%

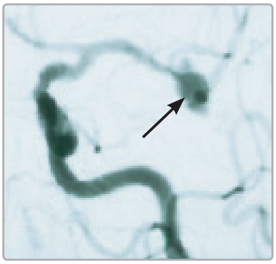


Fig. C6: Pre-operative angiogram confirms left MCA aneurysm.

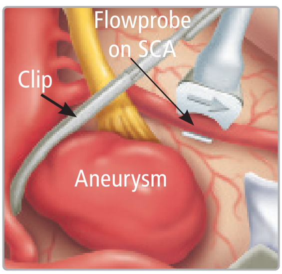


Fig. C7: The clip is shown placed around the neck of the SCA aneurysm.

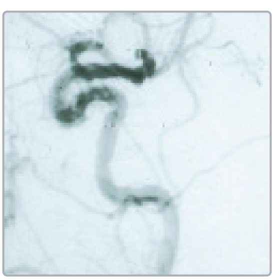


Fig. C8: Post-operative angiogram confirms preservation of flow after obliteration of MCA aneurysm.

The remaining ten to fifteen percent occur in the posterior circulation at bifurcations with the basilar or vertebral arteries (Figs. C3, page 9).

Aneurysm Causes

Intracranial aneurysms were once considered to be congenital lesions. However, since aneurysms are not seen in small children, many experts now believe that they form spontaneously later in life. They then either rupture or undergo "stabilizing changes." The causes of cerebral aneurysms continues to be investigated, but there appears to be a correlation with some diseases, such as polycystic kidney disease that exhibit unusual flow patterns at vessel bifurcations.

Diagnosis

Most aneurysms are first diagnosed by a computerized tomography (CT) scan, a non-invasive test that confirms the presence of blood in the subarachnoid space surrounding the brain, indicating that an aneurysm may have ruptured. Magnetic resonance imaging (MRI) (Fig. C4) is another method for detecting aneurysms with more detailed images than CT scans or regular X-rays. The capability of MRI is now enhanced by a new technology, NOVA qMRA®, developed at the University of Illinois at Chicago. NOVA (Fig. C5) quantifies the volumetric flow rate of vessels using a standard MRI scan. It provides physicians with a new level of flow information that they may use to diagnose and develop courses for treatment for neurovascular disease. When an aneurysm is suspected, a cerebral angiogram (Fig. C6) is performed to determine its exact size and location.

Cerebral Aneurysm Management

Treatment of cerebral aneurysms may be approached either non-invasively, or invasively. The non-invasive approach is by endovascular coiling during which a radiologist introduces a series of tiny platinum coiled

The Utility of Intraoperative Blood Flow Measurement during Aneurysm Surgery Using an Ultrasonic Perivascular Flow Probes

Amin-Hanjani S et al, University of Illinois at Chicago

Study Objective

Existing cerebrovascular intraoperative assessment strategies have possible limitations and disadvantages which may cause unfavorable aneurysm surgery outcomes. Therefor, the objective of this study is to assess the novel use of quantitative intraoperative flow measurements with the Transonic® ultrasonic Flowprobe.

Method

Intraoperative flow measurements from 103 patients with 106 aneurysms treated surgically at University of Illinois at Chicago from 1998 to 2003 were analyzed for:

- The frequency of flow compromise (flow reduction of >25% from baseline) after aneurysm clipping;
- The frequency of clip repositioning assessed and correlated with postoperative angiography and stroke;
- The frequency with which blood flow measurement averted the need for clip repositioning, when vessel compromise was suspected and assessed;
- Aneurysm features most associated with vessel compromise;
- Complications related to use of the Flowprobe.

Postoperative angiography of vessel patency was correlated with intraoperative assessment. Evidence of stroke due to large vessel occlusion and incidence of unexpected residual aneurysms seen on postoperative angiography were assessed.

Results

- 33 (31.1%) cases demonstrated a significant flow reduction after aneurysm clipping;
- Clips were repositioned in 27 (25.5%) cases, with return to baseline flow in 25 cases. Two cases indicated vessel thrombosis/dissection.
- In six cases, flow reduction was attributed to spasm and was resolved with papaverine (n = 3) or retractor repositioning (n = 3).
- In six (5.7%) cases, unnecessary clip repositioning was avoided (n = 3) or safe occlusion of the parent vessel for trapping of the aneurysm was allowed by confirming adequate distal flow (n = 3).
- Basilar, middle cerebral, anterior communicating, or carotid terminus aneurysms were more likely to be associated with flow compromise (odds ratio, 4.3; P = 0.03).
- Postoperative angiography corroborated vessel patency in all cases.

Conclusion

"Use of the ultrasonic Flowprobe provides real-time immediate feedback concerning vessel patency. Vessel compromise is easier to interpret than with Doppler, and faster and less invasive than intraoperative angiography. Intraoperative flow measurement is a valuable adjunct for enhancing the safety of aneurysm surgery."

Reference

Amin-Hanjani S, Meglio G, Gatto R, Bauer A, Charbel FT, "The utility of intraoperative blood flow measurement during aneurysm surgery using an ultrasonic perivascular flow probe," Neurosurgery. 2008; 62(6 Suppl 3):1346-53. (Transonic Reference # 7226AH)

Giant Aneurysms (diameter > 2.5 cm)

Thought to represent about 5-8% of all intracranial aneurysms. Treatment of large (2-2.5 cm) and giant aneurysms has traditionally been associated with higher morbidity and mortality than smaller aneurysms.

An aneurysm's size does not seem to influence its hemorrhage rate, and approximately 25% of patients present with subarachnoid hemorrhage. The large mass of giant aneurysms can obscure visualization, and can cause cranial nerve dysfunction, paralysis on one side (hemiparesis), seizures or headache.

Where Do Giant Aneurysms Occur?

Anterior Cerebral Circulation 80%

- 60% - internal carotid artery
- 10% - anterior communicating artery
- 10% - middle cerebral artery

Posterior Cerebral Circulation 20%

- 15% basilar artery apex
- 5% vertebral artery

References:

http://neurosurgery.mgh.harvard.neurovascular/v-s-94-1.htm

Ojemann RG et al, Surgical Management of Cerebrovascular Disease, Third edition, Williams & Wilkins, Baltimore.

wires into the aneurysm sac to induce blood clotting within the aneurysm.

When endovascular coiling is not an acceptable option, as in cases of complicated aneurysms involving perforators or other vessels, or those which have already ruptured, intracranial surgery is performed as soon as possible. Since many aneurysms are not diagnosed until after they rupture, most aneurysm surgeries are emergent rather than elective.

Microsurgical Aneurysm Clipping

Aneurysm clipping surgery seeks to clip off the aneurysm and reestablish a healthy arterial segment. To assess the aneurysm, the skull is opened (craniotomy) and the fibrous dura mater is penetrated to access the subarachnoid space and expose the major cerebral vessels and the aneurysm.

Using an operating microscope, the surgeon dissects to the site of the aneurysm in the subarachnoid space, taking care not to damage surrounding tissues, nerves and perforating vessels. The surgeon then positions one or more small clips across the neck of the aneurysm (Fig. C6, page 11). Properly placed, this stops blood from flowing into the aneurysmal sac, but leaves the parent blood vessel(s) intact.

Intraoperative flowmetry using the Charbel Probe® is instrumental in achieving this outcome. Post-operative angiography confirms successful aneurysm management (Fig. C7, page 11). During some aneurysm surgeries, the surgeon elects to apply temporary clips to the arteries proximal and distal to the aneurysm before the aneurysm itself is clipped. This technique is used to “soften” the aneurysm by reducing flow of parent vessels to the aneurysm during neck dissection. It controls bleeding and avoids hemorrhage if the aneurysm inadvertently ruptures during its permanent clipping. Temporary clips are structurally and visually different from permanent clips. Their gold tips also distinguish them from permanent clips and they have a smaller closing force in order to avoid vascular injury. In some cases involving giant aneurysms or tumors, the surgeon will occlude the parent vessel to see if there is sufficient collateral flow to allow the vessel to be permanently trapped and sacrificed (see next page).

Preservation EC-IC Bypass (Fig. C9)

While most cerebral aneurysms can be treated either by intracranial surgical clipping or coiling, some complex aneurysms do not permit complete obliteration by aneurysm clipping techniques alone. Features that may preclude aneurysm treatment by clipping or coiling include giant size; inclusion of parent vessel or perforating arteries within the aneurysm; calcification at the base of the aneurysm and/or fusiform or dissecting types of aneurysms.

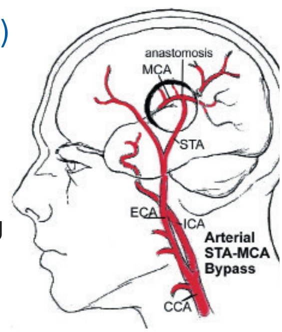


Fig. C9: Lateral view of an arterial Flow Restoration STA-MCA EC-IC Bypass. The Superficial Temporal Artery (STA) is exposed, cut and then anastomosed to the Middle Cerebral Artery (MCA) via an end-to-side anastomosis.

In these instances, a Flow Restoration EC-IC Bypass may be created to preserve flow in distal intracranial vessels. An EC-IC bypass involves taking a segment of extra-cranial donor artery (usually the STA) or a saphenous vein grafted to the carotid artery and anastomosing it to an intracranial recipient artery to preserve distal cerebral perfusion.

Vasospasm

Cerebral vasospasm (a narrowing of cerebral arteries) is a serious post-operative complication and major cause of morbidity and mortality of patients with ruptured aneurysms.

About 20% of SAH patients experience vasospasm which decreases blood flow through the cerebral arteries leading to possible ischemia and infarction (stroke) in the brain tissues the vessels supply.

Vasospasm's patho-physiology is not fully understood, but it is known to occur intraoperatively following craniotomy with aneurysm clipping or post-operatively, usually between the third and eleventh day after SAH. It rarely occurs beyond two weeks after SAH.

Increased intracranial pressure from vasospasm can cause swelling and herniation of brain tissue. It typically presents with neurologic deficits such as weakness or paralysis on one side of the body or the inability to speak (aphasia).

Reference:

http://www.theuniversityhospital.com/stroke/hemorrhagic.htm

Flow Replacement Bypass for Aneurysms: Decision-Making Using Intraoperative Blood Flow Measurements

Amin-Hanjani S et al, Dept. of Neurosurgery, University of Illinois at Chicago, Chicago IL

Study Objective

To introduce a flow replacement bypass strategy to compensate for loss of flow in the efferent vessels of the aneurysm. Direct intraoperative flow measurements are used to guide optimal revascularization by matching graft flow to demand and to immediately verify the adequacy and patency of the graft after bypass construction.

Method

The decision-making strategy was analyzed from 23 extracranial-intracranial (EC–IC) bypass cases, performed over a 6-year period, in which intraoperative flow measurements were used to determine a revascularization strategy.

Aneurysm Site	Number	Baseline Flows (ml/min)	Post-Anastomosis Flows (ml/min)
MCA	9	50 ± 25	50 ± 25
PICA	4	13 ± 7	18 ± 9
PCA	1	33	64
SCA	1	10	12

Results

- Terminal Aneurysms: Flow measurement in the affected vessel at baseline predicted the flow required for full replacement;
- Proximal Internal Carotid Artery (ICA) Aneurysms (n=8): Flow deficit from baseline; was measured during temporary carotid occlusion (26±18 cc/min, average 44% drop from baseline);
- Pre-Bypass Flow Measurement was assessed prior to bypass for superficial temporal or occipital arteries. Superficial temporal artery (STA), occipital artery (OA) or vein interposition grafts were used accordingly;
- Post-Anastomosis Flow Measurement confirmed patency and sufficient flow in all cases.

Conclusion

There are two types of decision-making challenges for revascularization of complex aneurysms: choice of a bypass and verification of bypass success. Direct intraoperative measurement of flow deficit in aneurysm surgery requiring parent vessel sacrifice can guide the choice of flow replacement graft and confirm the subsequent adequacy of bypass flow.

Reference

Amin-Hanjani S, Alaraj A, Charbel FT. “Flow replacement bypass for aneurysms: decision-making using intraoperative blood flow measurements.” Acta Neurochir (Wien) 2010;152(6):1021-32 (Transonic Reference # 7940AH)

C2. Occlusive Disease

Occlusive Diseases Management

Atherosclerosis affects hundreds of thousands of persons and is the root cause of a spectrum of arterial occlusive diseases that include cerebrovascular occlusive disease, coronary artery disease and peripheral occlusive disease.

Cerebrovascular surgeons treat cerebro-occlusive diseases by increasing flow to deprived territories with a variety of procedures and techniques that include endovascular interventions, endarterectomy and surgical reconstructions.

Three flow factors affect the outcome of a surgical revascularization. These are: the quality of inflow into the reconstruction, the amount of flow in the bypass conduit and the amount of outflow into the distal bed. Flow-guided surgery with Transonic® transit-time ultrasound technology informs the surgeon about each of these key factors.

Inflow: Intraoperative flow measurements check the quality of flow before the bypass is created.

Conduit: Intraoperative flow measurements can measure the carrying capacity of a bypass. It is a check for kinks or twists in the graft. When an autologous vein is used for a bypass graft, flow measurement will also confirm that all valves have been lysed.

Outflow: Intraoperative flow measurements provide a quantitative measurement of flow augmentation. It provides a valuable peri-operative check for technical error at anastomotic sites.

Transonic® intraoperative flow measurements are an essential quality measure whenever surgical revascularization outcomes are critical to preventing a total arterial occlusion with subsequent devastating consequences.

Augmentation EC-IC Bypass and Cut Flow Index

To evaluate the probability that an EC-IC bypass would augment flow to treat cerebral ischemia, Drs. Amin-Hanjani and Charbel introduced the concept of a Cut Flow Index. First, the free flow of the donor extracranial artery intended for use as a bypass is measured. After construction of the bypass, donor artery bypass flow is measured. The ratio of bypass flow to free flow is the Cut Flow Index. A value greater than 0.5 indicates that the bypass should be viable (see next page).

The Cut Flow Index: An Intraoperative Predictor of the Success of EC-IC Bypass for Occlusive Cerebrovascular Disease

Amin-Hanjani S et al, Dept. of Neurosurgery, University of Illinois at Chicago, Chicago IL

Study Objective
To evaluate the usefulness of intraoperative blood flow measurements in predicting bypass success (flow augmentation) after EC-IC bypass.

Method
EC–IC bypass cases (n=51) (76% males), performed over a 5-year period (1998-2003) at the University of Illinois at Chicago, were reviewed retrospectively. In all cases a Cut Flow Index (bypass flow following anastomosis in ml/min divided by "cut flow" or free flow from the cut end of the donor vessel) was calculated and analyzed for bypass patency determined by angiographic patency and NOVA qMRA, post-op bypass flow, clinical outcomes and cerebrovascular reserve.

Interpretation of Cut Flow Index
A low (<0.5) Cut Flow Index leading to poor bypass graft performance was attributed to either:
- Type 1 Error: Poor patient selection for revascularization;
- Type 2 Errors: Patient with hemodynamic compromise appropriately selected for EC-IC bypass but poor Cut Flow Index due to problems with:
  1) donor vessel;
  2) anastomosis;
  3) poor recipient vessel bed.

Conclusions
- Cut Flow Index greater than 0.5 predicted high rates of postoperative bypass patency. Intraoperative flow measurement correlated well with post-op NOVA qMRA.
- A poor Cut Flow Index (< 0.5) alerted surgeons to potential problems thus affording them an opportunity to correct the problem on-site.
- A Cut Flow Index of 1.0 indicated impaired cerebrovascular reserve in the recipient bed.
- In cases where visual inspection of the donor vessel may indicate that the conduit is too small to become a viable bypass, flow measurements can show that the vessel does, in fact, have adequate flow carrying capacity.

Reference
Amin-Hanjani S, Du X, Milnarevich N, Meglio G, Zhao M, Charbel FT, "The Cut Flow Index: An Intraoperative Predictor of the Success of EC-IC Bypass for Occlusive Cerebrovascular Disease," Neurosurgery 2005; 56: 75-85. (Transonic Reference # 2922AH)

C2. Occlusive Disease cont.

Moyamoya Syndrome

Moyamoya is a progressive disease in which the wall of the cerebral arteries around the Circle of Willis thicken, stenose and occlude. Moyamoya disease primarily affects the anterior circulation. Progressive stenosis of the proximal carotid and middle cerebral arteries can cause ischemic symptoms and strokes. Oxygen deprivation resulting from an inadequate blood supply causes typical moyamoya symptoms which include paralysis of the feet, legs or the upper extremities, headaches, vision problems, mental retardation and other problems.

Tiny collateral vessels characteristically form to compensate for the obstructed cerebral blood flow and supply oxygen to the brain. These small vessels appear as a puff of smoke on an angiogram (Fig. C10) and give the disease its name "moyamoya" which means puff of smoke in Japanese. These fragile moyamoya vessels can cause hemorrhagic strokes in adults.

The disease occurs worldwide, but moyamoya is most prevalent in Asian populations. In children it is characterized by the onset of one or more cerebral ischemic events. In adults cerebral hemorrhages occur. Indirect or direct surgical revascularization is the current treatment for moyamoya.

Moyamoya Disease Management
Indirect Revascularization

Indirect revascularization surgery, pioneered by Dr. Michael Scott, chief neurosurgeon at Boston's Children's Hospital, is termed "pial synangiosis." It takes advantage of the tendency of a child's brain to attract new blood vessels from any source. During surgery, the superficial temporal artery (STA), is excised from its surrounding tissue. A window is then cut directly into the cranium down to the thin, skin-

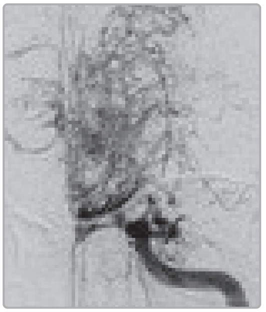


Fig. C10: Angiogram showing characteristic formation of tiny puff-like collateral vessels.

Moyamoya Syndrome

The cause is unknown. The narrowing of the brain arteries seems to be a non-specific reaction of the brain's blood vessels to a wide variety of stimuli, injuries or genetic defects. In children some of the reported causes include Asian ethnicity; neurofibromatosis, (congenital condition that causes tumors to grow on nerves); Down Syndrome; following cranial X-ray or chemotherapy treatments and surgical history of congenital heart disease. In adults, identified causes include heavy smoking, oral contraception, and cocaine abuse.

like pia mater, and the STA is sutured directly to this surface of the brain. New blood vessels sprout (synangiosis) from the donor STA and from surrounding blood vessels and increase the blood supply to the underlying brain.

Direct Revascularization with EC-IC Bypass (STA-MCA)

Direct revascularization of the anterior circulation via a STA-MCA bypass has also been shown to decrease future risk of transient ischemic attacks and ischemic strokes for moyamoya patients. In small children, the diameter of the STA is too small, so this technique is used more often in older children and adults. Dr. Gary Steinberg, neurosurgery chief at Stanford University has created bypasses in hundreds of moyamoya patients. He routinely measures blood flow as he constructs the STA-MCA bypass to augment flow to the brain territories.

A landmark hemodynamic moyamoya study published by the Stanford group in Cerebral Blood Flow Metabolism in 2011 documents the hemodynamics of 496 cerebral revascularizations performed in 292 moyamoya patients including 73 children at Stanford University over a seventeen year period (see abstract on next page).

References:

Lee M, Steinberg GK et al, "Intraoperative blood flow analysis of direct revascular-ization procedures in patients with moyamoya disease. J Cereb Blood Flow Metab. 2011 Jan;31(1):262-74.

Lee M et al, "Quantitative hemodynamic studies in moyamoya disease: a review." Neurosurg Focus 2009;26(4):E5.

Guzman R et al, "Clinical outcome after 450 revascular-ization procedures for moyamoya disease." Neurosurg. 2009 Nov;111(5):927-3

Hayden MG et al, "The evolution of cerebral revascularization surgery." Neurosurg Focus. 2009 May;26(5): E17.

Coert, BA et al, "Revasculariza-tion of the Posterior Circulation," Skull Base, 2005, 15(1):43-62.

Golby, AJ et al, "Direct and Combined Revascularization in Pediatric Moyamoya Disease," 1999;45:50-60.

Chang, SD, Steinberg, GK, "Surgical Management of Moyamoya Disease," http://www.moyamoya.com/journals/moyamoya.html

Kawaguchi, S et al, "Effect of Direct Arterial Bypass on the Prevention of Future Stroke in Patients with the Hemorrhagic Variety of Moyamoya Disease." J Neurosurg, 2000;93:397-401.

Zipfel, GJ, et al, "Moyamoya Disease in Adults: The Role of Cerebral Revascularization." Skull Base, 2005, 1:27-41.

http://www.webmd.com/hw/health guide atoz/nord617.asp

http://www.childrenshospital.org/clinicalservices/Site2156/mainpageS2156P0.html,

Intraoperative Blood Flow Analysis of Direct Revascularization Procedures in Patients with Moyamoya Disease

Lee M et al, Department of Neurosurgery, Stanford University, Palo Alto, CA

Study Objective

To analyze various hemodynamic factors in patients with moyamoya disease with attention to documentation of vessel dimension and measurement of blood flow intraoperatively, using a perivascular ultrasonic flowprobe.

Method

Hemodynamic factors were analyzed retrospectively from 1991-2008:

- 183 adults; 73 children patients with moyamoya disease or syndrome;
- 496 cerebral revascularization procedures performed in 292 patients;
- Distal STA and MCA M4 branch diameters were measured under magnification;
- Distal MCA and proximal MCA flows (to the anastomosis) were measured.

Results

- STA and proximal MCA flows were significantly lower in pediatric group.
- Proximal MCA flow was lower in patients with unilateral disease.
- STA size and flow correlated as did STA size, flow and MCA flows.
- MCA flow increased on an average of fivefold after the bypass.
- High postanastomosis MCA flow was associated with postoperative stroke (31.2 ±6.8 mL/min; P=0.045), hemorrhage (32.1±10.2 mL/min; P=0.045), and transient neurologic deficits (28.6±5.6 mL/min; P=0.047).

<table>
<tr><th>Vessel</th><th>Diameter in mm</th><th>Baseline Flows (mL/min)</th><th>After STA-MCA Bypass (mL/min)</th></tr>
<tr><td>STA</td><td>1.3 ± 0.02</td><td></td><td>22.2 ± 0.9</td></tr>
<tr><td>Distal M4 MCA</td><td rowspan="2">1.4 ± 0.02</td><td rowspan="2">4.4 ± 0.26</td><td>9.7</td></tr>
<tr><td>Proximal M4 MCA</td><td>13.4</td></tr>
</table>

Conclusions

- Revascularization surgery is the mainstay for treatment of moyamoya disease and promotes clinical benefits quicker, with low morbidity.
- Revascularization results in a four-fivefold increase in blood flow.
- STA diameter and flow are the main determinants of blood flow augmentation.

Reference

Lee M, Guzman R, Bell-Stephens T, Steinberg GK, “Intraoperative blood flow analysis of direct revascularization procedures in patients with moyamoya disease,” J Cereb Blood Flow Metab., 2011;31(1):262-74. (Transonic Reference: # 7969AH)

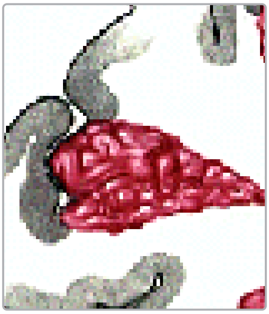


Fig. C11: Arteriovenous malformation.

Arteriovenous Malformations (AVMs)

Arteriovenous malformations are masses of abnormal blood vessels which can grow in any area of the brain. They consist of a blood vessel nidus (nest) through which arteries connect directly to low resistance veins, instead of feeding into a capillary network to perfuse the territory. It is thought that AVMs form during embryonic or fetal development or soon after birth. As a child matures into adulthood, the veins cannot handle the pressure of the arterial vessels and the AVMs might then hemorrhage.

AVMs most likely bleed between the ages of 10 - 55 where the likelihood of hemorrhaging is between 3-4% per year. After 55, the chances of bleeding rapidly diminish. Once an AVM has hemorrhaged, the risk of rehemorrhage is up to 20% the first year and decreases to 3-4% over the next few years. AVM hemorrhage usually results in limited blood loss. Only 1% of those with AVMs die as a direct result of their presence.

Most people with AVMs experience few, if any, significant symptoms. In 12% (36,000 of an estimated 300,000) of Americans with AVMs, the abnormality causes symptoms of varying severity. Loss of neurologic function depends on the both the location of the AVM and the amount of bleeding. Many patients have very small and multiple hemorrhages. The patient may convulse before even knowing of the presence of an AVM. Heart failure sometimes occurs in children with an AVM because the AVM makes the heart work beyond its capability.

Disease Management

Very small AVMs seated deep within the brain are treated by radiation. AVMs surrounded by a very discrete layer of abnormal, non-functioning brain tissue can be safely removed from the surrounding

References:

Moftakhar P et al, “Cerebral Arteriovenous Malformations. Part 1: Cellular and Molecular Biology,” Neurosurg Focus 2009; 26(5):E10.

Moftakhar P et al, “Cerebral Arteriovenous Malformations. Part II: Physiology,” Neurosurg Focus 2009; 26(5):E11.

Kirk HJ, Khurana VG et al, “Intraoperative Transit Time Flowmetry Reduces the Risk of Ischemic Neurological Deficits in Neurosurgery.” Br J Neurosurg. 2009 Feb;23(1):40-7.

brain tissue. Surgery cures the AVM by totally excising the nest of blood vessels, thus keeping them from ever recurring. Larger AVMs may be made more surgically manageable by filling the malformation with agents (coils, glues, plastic spheres, balloons) which help decrease the blood supply to the malformation prior to surgery. Finally, some AVMs are best left alone due to their size, location or behavior.

In the British Journal of Neurosurgery in 2009, Drs. Kirk and Khurana from the Department of Neurosurgery, Canberra Hospital, Canberra, Australia reported the first use of intraoperative blood flow measurement with the Transonic® flowprobe on the draining vein of an AVM to assure obliteration of the AVM.

They also cite use of the flowprobe during obliteration of a dural fistula and on tumor resection surgery (see synopsis of paper on the following pages).

F•A•S•T® Study: Intra-operative Transit Time Flowmetry Reduces the Risk of Ischemic Neurological Deficits in Neurosurgery.

Kirk et al, Department of Neurosurgery, The Canberra Hospital, Canberra, ACT, Australia

Study Objective

To assess intraoperative transit time flowmetry in terms of its indications, ease of implementation and interpretation, safety and reliability.

Method

- Twenty-eight patients (17 females, 11 males, average age 53) undergoing 30 craniotomies including 21 aneurysm clipping or explorations, 2 AVMs, 2 dural AV fistula disconnections, 2 EC-IC bypass and 3 tumor resections.
- Transit-time ultrasound flowmetry was recorded from at-risk vessels before and after surgical intervention.
- Any episodes of flow compromise or change in surgical procedure were correlated with post-operative neurological deficits and imaging.

Results

- Flowmetry led to adjustments in 27% of the surgeries (8 of the 30 cases).
- Aneurysms: inadvertent vessel occlusion, identified in 3 cases, led to immediate repositioning of the aneurysm clips. One aneurysm patient awoke with a stroke presumably from an undetected embolism.
- AVMs: markedly reduced draining vein flow rates in 2 AVM surgeries were confirmed quantitatively immediately before final surgical excision.
- AV fistulae: reduced draining vein flow rates in 2 AV fistulae surgeries were confirmed quantitatively immediately.
- In 1 EC-IC bypass patient, the measurement suggested graft vasospasm which was then successfully treated with papaverine.

Conclusions

- TTUF provides immediate feedback regarding vessel patency and clip-related arterial compromise and local vasospasm.
- TTUF was found to have a broad utility in intra-cranial surgery including AVMs, fistulae disconnections and tumor excisions. Demonstrating dramatically reduced flow in the draining veins aided confidence in surgical disconnection of the AVM or DAVF. During excision of complex tumors surrounding vascular structures,TTUF was invaluable in confirming that vessel compromise was not occurring secondary to brain retraction.
- TTUF was found to be safe, rapidly performed, easy to interpret and generally reliable. Its use contributes significantly to the safety of patients.

Reference

Kirk HJ, Khurana VG et al, "Intra-operative transit time flowmetry reduces the risk of ischemic neurological deficits in neurosurgery." Br J Neurosurg. 2009 Feb;23(1):40-7. (Transonic Reference # 7744AH)

Flowmetry in Arteriovenous Malformation (AVM) Surgery

Extracted from: Kirk HJ et al, "Intra-operative transit time flowmetry reduces the risk of ischemic neurological deficits in neurosurgery." Br J Neurosurg. 2009 Feb;23(1):40-7. Dept. of Neurosurgery, The Canbarra Hospital, Canberra, ACT, Australia

Presentation

A cerebral angiogram identified a right parietal ruptured AVM in a 51-year-old male patient. The main feeding artery of the AVM was a M4 middle cerebral artery (MCA) branch. A posterior cerebral artery also fed the AVM.

Procedure

- The right parietal dura was opened to expose the cortical surface of the AVM.
- A 2-mm flowprobe was placed around the M4 feeding artery and flow was recorded.
- Flow was then recorded from the proximal portion of the main draining vein before arterial clipping.
- A clip was placed on the M4 feeding artery of the AVM as flow was measured in the main draining vein of the AVM.

Results

- Initial flow in the M4 feeder artery was 115 ml/min, a relatively very high volume flow for a cortical artery.
- Initial flow in the main draining vein of the AVM was 54 ml/min, also a relatively very high volume flow for a cortical vein.
- After the M4 feeder artery to the AVM was clipped, flow in the main draining vein dropped to 4 ml/min.

Vessel	Pre-Clip Flow (ml/min)	Post-Clip Flow (ml/min)
M4 Feeding Artery	115	0
Draining Vein	54	4

Conclusion

The 4 ml/min flow recorded in the main draining vein following clipping of the AVM's feeding artery indicated satisfactory shut down of this main portion of the AVM before its removal. It provided the quantitative reassurance required by the surgeon that the operative goal had been achieved.

Reference

Kirk HJ, Khurana VG et al, "Intra-operative transit time flowmetry reduces the risk of ischemic neurological deficits in neurosurgery." Br J Neurosurg. 2009 Feb;23(1):40-7. Transonic Reference # 7744AH)

Intraoperative Flow Measurement by Microflow Probe During Surgery for Brain AVMs

Extracted from: Della Puppa *et al,* "Intraoperative Flow Measurement by Microflow Probe During Surgery for Brain Arteriovenous Malformations," Neurosurg 2015; Jun;11 Suppl 2:268-73.
Dept. Neurosurgery, Padua Univ. Hospital, Padova, Italy.

Objective

To test intraoperative quantitative flow measurement (FAST - Flow Assisted Surgical Technique) with a microvascular ultrasonic flow probe in brain arteriovenous malformation (AVM) surgery.

Procedure

- Retrospective analysis of data from 25 patients with brain AVMs who consecutively underwent microsurgical resection with the assistance of flow measurement by a microflow probe.
- Flow measurements were performed 203 times on 92 vessels including arterial feeders, potential transit arteries, and venous drainages of AVMs during different phases of AVM resection.

Results

Pre-resection:

- Flow data helped understand the AVM architecture and guided surgical planning and AVM resection.
- Flow data completely agreed with ICG-VA on AVM angioarchitecture.
- In seven cases, flow measurements clarified ICG-VA data for planning the surgical approach.

During resection:

- Flowmetry discriminated between deep small arterial feeders and venous drainages (76% of cases, 19/25) both superficially and deeply located, by defining the direction of flow in AVM vessels.
- Flow measurements identified transit arteries in 12% of cases (3/25) by detecting a major flow drop between 2 points of the same vessel during AVM dissection. Further dissection revealed a deep afferent artery to the nidus arising from a transit artery between the points of the two previous measurements.
- At the final stage of resection, a residual nidus was detected in 20% of patients (5/25) when the flow value of venous drainage was greater than 4 mL/min.

After resection:

- No microflow probe-induced AVM vessel injury was reported.
- Complete AVM resection was achieved in all cases with low morbidity.

Conclusions

- Intraoperative flow measurements proved to be a feasible, safe, repeatable, and reliable methodology to assist surgery in different phases of AVM resection.
- Intraoperative data changes surgical planning in 32% of cases: 12% sparing a transit artery and 20% of further final dissection of the AVM nidus before sectioning the main venous drainage.

Reference

Della Puppa A, Rustemi O, Scienza R, "Intraoperative Flow Measurement by Microflow Probe During Surgery for Brain Arteriovenous Malformations," Neurosurg 2015; Jun;11 Suppl 2:268-73. (Transonic Reference # 10288AH)

C3. Other Cerebral Morbidities cont.

Flowmetry in Dural Arteriovenous Fistula (DAVF) Surgery

Extracted from: Kirk HJ et al, "Intra-operative transit time flowmetry reduces the risk of ischemic neurological deficits in neurosurgery." Br J Neurosurg. 2009 Feb;23(1):40-7. Dept. of Neurosurgery, The Canbarra Hospital, Canberra, ACT, Australia

Presentation

A three-dimensional CT angiogram showed a fronto-ethmoidal DAVF fed by bilateral ophthalmic arteries in a 77-year-old male patient. The fistula was located in the ethmoidal dura to the left of a proximal draining vein that expands into a large venous aneurysm. The arterialized distal draining vein terminated in the superior sagittal sinus.

Procedure

- The local arachnoid was dissected to allow placement of a 2 mm flowprobe on the draining vein for a baseline flow measurement.
- When the proximal draining vein was exposed, permanent clips were placed across its origin.
- Flow was remeasured in the draining vein for a post-clip flow measurement.

Results

- Pre-clipping flow in the arterialized DAVF draining vein was 21 ml/min.
- Post-clipping flow in the DAVF draining vein was 0 ml/min.
- Blood in the vein changed from red to purple.

Vessel	Pre-Clip Flow (ml/min)	Post-Clip Flow (ml/min)
Arterialized Draining Vein	21	0

Conclusions

- The demonstration of dramatically reduced flow in the draining vein of the ethmoidal DAVF confirmed successful disconnection of the fistula and has become routine practice.
- The change in hue from red to purple after clipping the draining vein provided the surgeon with qualitative feedback as well as the quantitative feedback from flow measurement that the fistula was completely disconnected.

Reference

Kirk HJ, Khurana VG et al, "Intra-operative transit time flowmetry reduces the risk of ischemic neurological deficits in neurosurgery." Br J Neurosurg. 2009 Feb;23(1):40-7. Transonic Reference # 7744AH)

D. F•A•S•T during Flow Preservation Aneurysm Clipping Surgery

> *"One of the major risks associated with aneurysm surgery is the potential for inadvertent occlusion or compromise of the vascular branches from which the aneurysm arises, which can result in stroke."*
>
> Amin-Hanjani S, Charbel, FT, Surg Neurol. 2007; 68 Suppl 1:S4-11.

Introduction: Aneurysm Clipping Surgery

The goal of aneurysm clipping surgery is the direct or indirect hemodynamic removal of the aneurysm from the circulation. To ensure safe, consistent outcomes, Dr. Fady Charbel (University of Illinois at Chicago) advocates routine adherence to a sound surgical strategy and techniques. His surgical steps for aneurysm clipping surgery include:

1) Placement of scalp incision and craniotomy;
2) Proximal control of the aneurysm;
3) Identification of the aneurysm neck;
4) Choice of a tentative clip;
5) Distal control of the aneurysm;
6) Identification & baseline flow measurements of vessels at risk;
7) Mobilization of the aneurysm dome;
8) Clipping of the aneurysm;
9) Verification of the integrity of vessels at risk with post-clip flow measurements and intraoperative angiography or ICG;
10) Deflation of the aneurysm.

To ensure successful aneurysm clipping surgery and avoid direct or indirect vessel compromise and/or adverse hemodynamic consequences, Dr. Charbel pioneered the use of intraoperative blood flow measurements. He coined the acronym F•A•S•T® for Flow-Assisted Surgical technique. F•A•S•T® has proven to be a sound operative strategy to ensure cerebral flow preservation after aneurysm clipping.

F•A•S•T is used to guarantee flow preservation after clipping complex aneurysms. Aneurysms are generally first evaluated for treatment by endovascular coiling. However, for complex aneurysms that are unsuitable for coiling, or where coiling has been unsuccessful or the aneurysm has ruptured, obliteration of the aneurysm by clipping offers a viable alternative.

Amin-Hanjani S, Charbel FT, "Flow-assisted surgical technique in cerebrovascular surgery," Surg Neurol. 2007;68 Suppl 1:S4-11.

Case Example: F•A•S•T during Superior Cerebellar Artery (SCA) Aneurysm Clipping Surgery

Courtesy F.T. Charbel, Chair, Dept. of Neurosurgery, University of Illinois at Chicago

Introduction

When aneurysms are clipped, baseline flows are measured before clipping (See Algorithm page 31). The patient then serves as his or her own control. Post-clipping flows are then compared to the patient's own baseline flows. Preservation of flow in the distal run-off arteries and parent vessels is the F•A•S•T® goal.

Presentation

The patient presented with headaches and diplopia. Cerebral angiogram confirmed a right superior cerebellar (SCA) aneurysm. Meticulous dissection exposed the aneurysm and the SCA and the posterior cerebral artery (PCA) (Fig. D1).

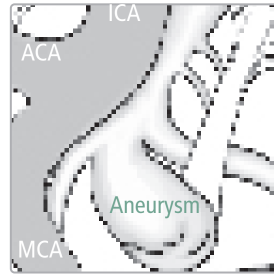


Fig. D1: Right SCA aneurysm exposed.

Baseline Flows Measured

Baseline flows were measured in the right SCA and right PCA (Fig. D2).

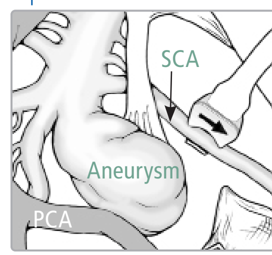


Fig. D2: Baseline flow measured in right SCA.

Aneurysm Clipped

A clip was positioned around the neck of the aneurysm (Fig. D3).

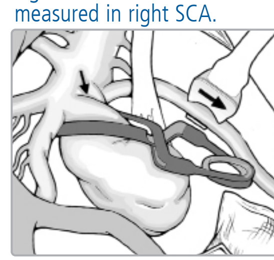


Fig. D3: Clip positioned around neck of aneurysm. SCA flow measured.

Integrity of SCA and PCA Flows Checked

The integrity of SCA and PCA flow was checked. Flow in the SCA dropped to 2-4 cc/min. The SCA was found to be partially enclosed in the clip. Flow in the PCA was recorded as 55-60 cc/min .

Clip Readjusted

The clip around the neck of the aneurysm was readjusted (Fig. D4).

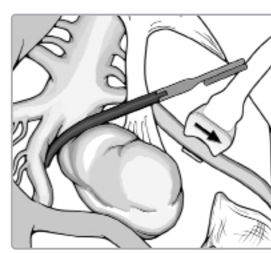


Fig. D4 Clip repositioned. SCA and PCA flow remeasured.

Flows Remeasured

Right SCA and PCA flows were rechecked. Both flows had returned to almost baseline levels (Fig. D5 on page 29).

Case Example: F•A•S•T during Superior Cerebellar Artery (SCA) Aneurysm Clipping Surgery cont.

Flow Summary ml/min				
Vessel	Probe Size (mm)	Baseline Flow	Post-Clip Flow	Clip Repositioned
SCA	2	16-18	4	15
PCA	2	34-36	55-60	40

SCA Flows PCA Flows

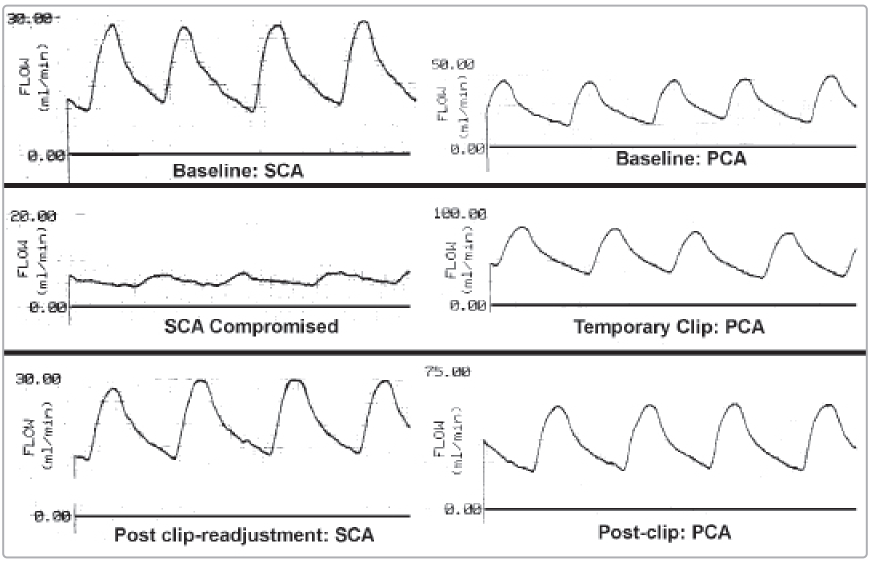


Fig. D5: SCA & PCA flow measurements taken during the aneurysm clipping surgery.

Flow-QC® Benefits

- Flow measurements alerted the surgeon to a compromise in flow in the right SCA after clipping the aneurysm.
- Flow measurements confirmed that SCA flow was fully restored to baseline after readjustment of the clip.

D2. F•A•S•T Measurement during Aneurysm Clipping Surgery

Transonic® F•A•S•T® intraoperative measurements provide neurosurgeons with immediate, quantitative flow measurements during cerebrovascular surgery. Measurements either confirm the functional success of the surgery by assuring that flow is preserved in parent vessels and distal branches or alerts the surgeon immediately to flow compromise.

Surgeons who visually inspect clip placement during intracranial aneurysm clipping surgery know that it is not always possible to see the tips of the clip or to determine if the clip has inadvertently snared vessels and occluded flow. Transonic® F•A•S•T® quickly reports the status of flow in parent and distal vessels and prompts repositioning of the clips if flows are lower than expected.

Fig. D6: Transit-Time Ultrasound Flowmetry: A non-constrictive Transonic® Flowprobe is applied around a vessel exposed during surgery to measure volume flow, not velocity. The Flowprobe consists of a Probe body which houses ultrasonic transducers and a fixed acoustic reflector. The transducers are positioned on one side of the vessel and the reflector is fixed at a position between the two transducers on the opposite side. Ultrasound couplant (saline or CSF) provides full ultrasound passage within the flowsensing window.

Non-constrictive Charbel Flowprobes® use ultrasonic transit-time principles (Fig. D6) to directly measure volume blood flow, not velocity. Available in 1.5, 2, and 3 mm sizes, the Probes are custom designed with a bayonet handle and flexible neck (Fig. D8) to measure vessel blood flow under a microscope during aneurysm and other cerebrovascular procedures. They operate with Transonic® Flowmeters/Monitors (Fig. D11) which feature:

- Bright display of mean flow, status messages and ultrasound signal quality;
- FlowSound® audible volume flow so eyes can remain focused on the surgical field;
- Integrated autoscaling for documenting flow waveforms (Fig. D7) for the case record;
- Invert button to change polarity when a flow waveform would otherwise print upside down.

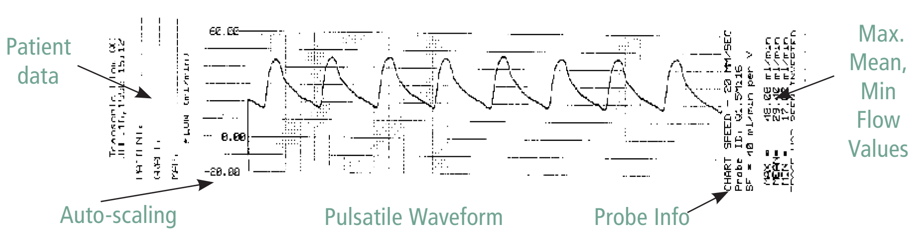


Fig. D7: Baseline flow measurement of left A2 prior to clipping an anterior communicating artery aneurysm.

Fig. D8: Charbel Probes® -MB & -MR-Series: Long bayonet-handle Flowprobes for deep intracranial surgery under the surgical microscope. A flexible neck near the Probe tip permits orienting the Probe to the vessel. -MB-S & -MR-S-Series: short bayonet handle Probes with larger flowsensing heads are designed for surface intracranial measurements such as flow preservation EC-IC bypass surgery.

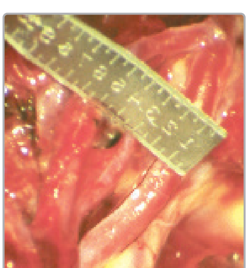


Fig. D9: Selecting Flowprobe sizes for vessels at risk.

Flow Measurement Algorithm

1. Identify Vessels at Risk

Expose and identify parent vessels and distal outflow vessels of the aneurysm.

2. Select Flowprobe Sizes

Measure the diameter of the vessels at risk with a gauge (Fig. D9) before opening the Probe package. Select Probe size(s) so that the vessel(s) will fill between 75% - 110% of the lumen of the Probe(s).

Probe Size	Nonrestrictive Vessel Range
1.5 mm	1.1 - 1.6 mm
2 mm	1.6 - 2.4 mm
3 mm	2.6 - 3.8 mm

3. Apply Flowprobe

Examine the vessel to determine the optimal position for applying the Probe. Select a site wide enough to accommodate the Probe's acoustic reflector without disrupting perforators coming off the vessel. Apply the Flowprobe so that the entire vessel lies within the lumen of the Probe and aligns with the Probe body (Figs. D13).

Bend the Probe's flexible neck segment (Fig. D12) to position the Flowprobe at the most convenient angle. As the Flowprobe is being applied to the vessel, listen to FlowSound®. The higher the pitch, the greater the flow.

Sterile saline or cerebrospinal fluid may be used to flood the Probe lumen and provide ultrasound coupling. Do not irrigate continuously because the Probe will also measure the flow of the saline. The Signal Quality Indicator (bucket display) on the front panel of the Flowmeter indicates acoustic contact. If acoustic contact falls below an acceptable minimum, an acoustic error message is displayed.

4. Measure Baseline Flows

Measure baseline flows in all vessels at risk before clipping the aneurysm. If burst suppression is being administered, baseline flows should be measured following burst suppression, since these agents will lower flows. Record the baseline flow measurements and the patient's blood pressure on the Flow Record.

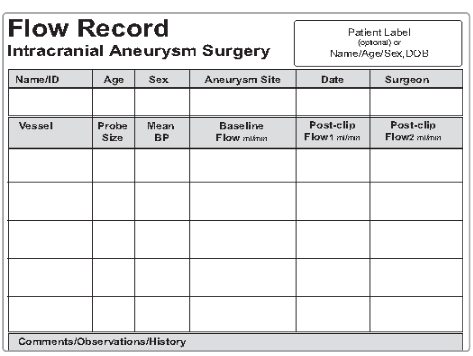
5. Document Flows

After applying the Probe, wait about 10-15 seconds for mean readings to stabilize. Document the phasic flow patterns for the case record. If flow is negative, press the INVERT button to change the polarity before printing the waveform.

6. Compare Post-Clip to Baseline Flows

After the aneurysm has been clipped, remeasure flow in each of the vessels and compare flow values with baseline flows. Each measurement should be equal to or greater than its respective baseline flow. Higher flows are expected in cases where the aneurysm has severely compromised flow. Temporary clipping can also produce hyperemia which can cause flows to be 20-30% higher than baseline flows. If post-clip flow is below baseline flow, the clip placement should be reexamined and readjusted, as necessary.

Fig. D11: FlowXL® (at top) AureFlo® (at bottomn)



Flow Record
Intracranial Aneurysm Surgery

Patient Label (optional) or Name/Age/Sex, DOB

Name/ID	Age	Sex	Aneurysm Site	Date	Surgeon

Vessel	Probe Size	Mean BP	Baseline Flow ml/min	Post-clip Flow1 ml/min	Post-clip Flow2 ml/min

Comments/Observations/History

Fig. D10: Sample aneurysm flow record for the patient's case history.

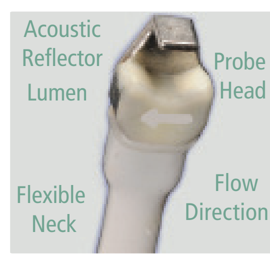


Fig. D12: The flexible neck segment between the Probe body and Probe handle may be bent to orient the Probe body as needed.

Algorithm

Fig. D13: The vessel must be aligned with the body of the Probe as shown.

Identify Vessels at Risk

↓

Select Proper Flowprobe Size

↓

Measure Baseline Flows
in all vessels at risk

↓

Measure Post-clip Flows
in all vessels at risk

↓

Compare Post-clip Flows to Baseline Flow

- **Flow equal or more than baseline** → **Flow Preserved** in vessels at risk
- **Flow less than baseline** → **Re-examine/adjust clip and remeasure flow.**

Fig. D14: Algorithm for measuring blood flow in vessels at risk during aneurysm surgery.

Review

1. Measure & record baseline flow measurements of vessels at risk.
2. Measure & record post-clip flows & compare with baseline flows. If flow is significantly lower than baseline flows, readjust clip until flow corresponds.

Key Points

1. Select appropriate size Flowprobe and apply to vessel while listening to FlowSound®.
2. Measure baseline flow(s) after burst suppression, if administered. Record blood pressure and end tidal CO_2 during initial measurements and keep these parameters constant during subsequent flow measurements.
3. Add saline as needed to obtain good ultrasonic contact. Do not irrigate continuously because the Flowprobe will also measure the flow of the saline.
4. When the flow reading is stable (10-15 seconds), press PRINT. Keep Probe steady on the vessel until the printer stops.
5. Document flows.

Flow-assisted Surgical Technique in Cerebrovascular Surgery

Amin-Hanjani S, Charbel FT, Dept. of Neurosurgery, University of Illinois at Chicago

Introduction

Cerebrovascular surgery, a technically challenging subspecialty of neurosurgery, faces increasingly complex challenges now that endovascular technologies often address the most routine pathologies. Direct vessel flow measurements intraoperatively can provide valuable data in decision-making and in direct evaluation of the success of the surgical intervention. A flow-based approach (FAST) can help to optimize neurosurgiocal interventions. This publication offers a comprehensive review of FAST for flow preservation in aneurysm clipping surgery and FAST in EC-IC Bypass surgery for flow augmentation or flow replacement.

FAST in Aneurysm Surgery

One of the major risks associated with aneurysm surgery is the potential for inadvertent occlusion or compromise of the vascular branches from which the aneurysm arises which can result in stroke.

- Use of quantitative measurements can provide a technique to reliably avert vessel compromise. Flow measurement of relevant vessels requires minimal time and little more dissection beyond that used for routine aneurysm dissection.
- The utility of FAST in Aneurysm Surgery is discussed. In 106 aneurysm clippings in 103 patients, significant flow reduction after clipping prompted clip repositioning in 27 (25.5%) cases with return to baseline flow in 25 cases.

FAST in EC-IC Bypass Surgery

Flow Augmentation Surgery:

The surgical goal is to increase flow to the ischemic hemisphere. FAST can be helpful in predicting graft patency and efficacy during flow augmentation STA-MCA bypass procedures.

- Technique is described for flow augmentation, including Cut Flow Index as a predictor of bypass success.

Flow Replacement in Planned Vessel Sacrifice:

Giant or complex aneurysms may require sacrifice of the parent vessel such as the carotid, which may result in ischemia or stroke in up to 30% of patients.

- Technique for flow replacement bypass using measurements before and after temporary occlusion to assess the potential flow deficit is described.
- FAST provides a mechanism for guiding graft selection to provide optimum revascularization strategy. Moreover, the function and adequacy of the bypass can be verified intraoperatively.

Transonic Comment

This paper offers a comprehensive summary of the benefits of direct intraoperative blood flow measurements during a number of cerebrovascular procedures.

Reference:

Amin-Hanjani S, Charbel FT, “Flow-assisted Technique in Cerebrovascular Surgery,” Surgical Neurology. 2007; 68: S1-4 - S11. (Transonic Reference # 7560AH)

D3. Anterior Cerebral Circulation: ICA, ACA & MCA Vasculatures

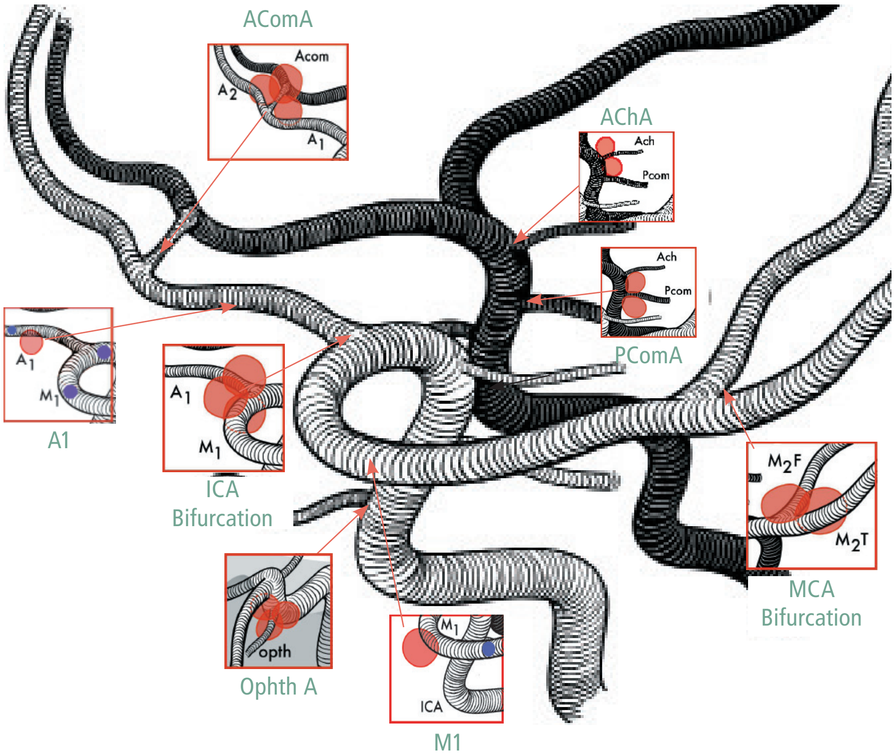


Fig. D15: Lateral view of the anterior cerebral circulation. Sites for anterior circulation aneurysms include the carotid ophthalmic artery (OpthA), Internal Carotid Artery (ICA) bifurcation , Middle Cerebral Artery (MCA) bifurcation, M1 Segment MCA, Anterior Cerebral Communicating Artery (AComA), and Posterior Communicating Artery (PComA).

Anterior Cerebral Circulation (Fig. D15)

The anterior cerebral circulation consists of the:

- Internal Carotid Artery (ICA) and its branches;
- Carotid Ophthalmic Artery (OpthA);
- Anterior Cerebral Artery (ACA) and its branches;
- Anterior Cerebral Communicating Artery (AComA) (a bridge between the two bilateral ACAs);
- Middle Cerebral Artery (MCA) and its branches;

D3. Anterior Cerebral Circulation: ICA, ACA & MCA Vasculatures cont.

- Posterior Communicating Artery (PComA) (Connecting anterior and posterior cerebral circulations).

Described are the most common aneurysm sites of the anterior circulation. These include: Internal Carotid Artery (ICA) sites with Carotid Ophthalmic Artery (OpthA) aneurysms, Anterior Choroidal Artery (AChA) aneurysms, Posterior Communicating Artery (PComA) aneurysms, and aneurysms of the ICA bifurcation.

Anterior Cerebral Artery (ACA) aneurysms sites include aneurysms of the A1 Segment and difficult Anterior Communicating Artery (AComA) aneurysms.

Middle Cerebral Artery (MCA) aneurysms that can be surgically clipped generally occur on the M1 trunk or at the MCA bifurcation. Aneurysms of the middle cerebral artery M2 ,M3 and M4 segments are uncommon and usually result from trauma or injury.

Vessel	Expected Flows (ml/min)
ICA	120-170
A1	40-60
A2	40-50
M2	80-120
M2	50-80

Morphology

Carotid ophthalmic aneurysms arise from the dorsal surface of the ICA just distal to the origin of the ophthalmic artery as the ICA enters the subarachnoid space from the cavernous sinus. Carotid-ophthalmic aneurysms generally project dorsally or dorsal-medially from the ICA toward the optic nerve.

Occurrence

Ophthalmic aneurysms are frequently large, occur predominately in women and are the aneurysms most often associated with multiple aneurysms.

Presentation

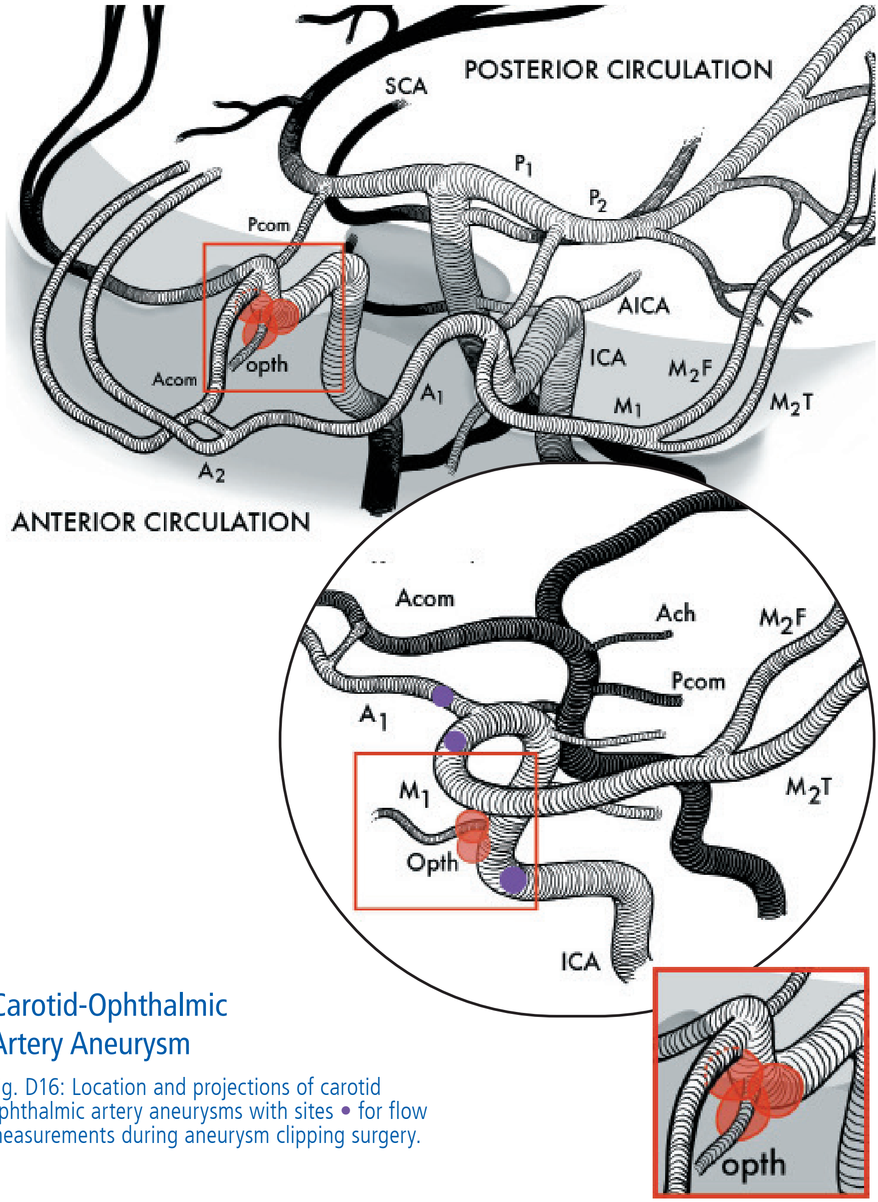
The aneurysm presents with a diminished sense of smell which often goes unnoticed by the patient. As the aneurysm enlarges the sense of smell continues to decline, accompanied by vision loss in one eye and then possible blindness in one or both eyes. Ruptured aneurysms present as subarachnoid hemorrhage (SAH) and/or vision loss.

Flow Measurement Sites (Fig. D16)

Aneurysm Site	Probe Placement	Size (mm)	Expected Flows (ml/min)
Carotid Ophthamic A (Opth)	M1	2.0	80-110
	A1	2.0	40-60
	ICA	3.0	120-170

Flow Measurement

Flow must be preserved in the ICA and M1(MCA) and A1(ACA) outlet vessels. Check M1 and A1 flows with or without temporary clipping of ICA. Care must also be taken to ensure preservation of all nearby perforators including the ophthalmic, superior hypophyseal and posterior communicating arteries. Post-clip flows are measured in the ICA, M1 of the MCA, A1 segment of the ACA and then compared to baseline flows.



Carotid-Ophthalmic Artery Aneurysm

Fig. D16: Location and projections of carotid ophthalmic artery aneurysms with sites • for flow measurements during aneurysm clipping surgery.

Case Example: Giant Carotid-Ophthalmic Artery Aneurysm

Introduction

The patient presented with SAH. The pre-op angiogram showed a giant carotid ophthalmic aneurysm (Fig. D17).

Pre-op Angiogram

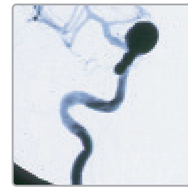


Fig. D17: Pre-op angiogram showing giant carotid ophthalmic aneurysm.

Baseline Flows

Baseline flows were measured in the MCA (45 ml/min) and ICA (60 ml/min).

Flows Rechecked after Temporary Clipping

MCA baseline flow did not change. The surgeon determined that this would be a safe temporary occlusion.

Aneurysm Clipped

Two angle fenestrated clips were placed across the neck of the aneurysm. ICA post-clip flow was 33 ml/min (Fig. D18). Multiple clip reapplications, coupled with flow measurements, were made until flow improved to an optimal value of 66 ml/min (Fig. D19).

Compromised ICA Flow

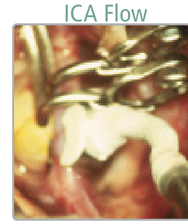


Fig. D18: Post-clip ICA flow: 33 ml/min.

Carotid-Ophthalmic Aneurysm Flow Summary (ml/min)				
Vessel	Probe Size (mm)	Baseline Flow	Post-Clip Flow	Clip Repositioned
MCA	2	45	43	44
ICA	3	60	33	66

Summary

The post-operative angiogram showed excellent clipping. Despite multiple angiographic views, it was impossible to know if the internal carotid artery was compromised. Intraoperative flow measurements provided this functional assessment.

Repositioned Clips

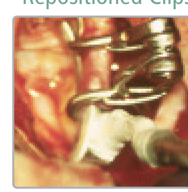


Fig. D19: Flow improved to 66 ml/min.

Flow-QC® Benefits

- Compromised ICA flow prompted the surgeon to reposition the clip until optimal ICA flow was achieved.
- Final flow measurements assured the surgeon that flow was preserved in distal conduits.
- Flow-QC measurements assisted in surgical decision making throughout the surgery.

D3a. Carotid-Ophthalmic Artery Aneurysms cont.

Flow Examples: Carotid Ophthalmic Aneurysm Cases

M1 (MCA) Baseline Flows

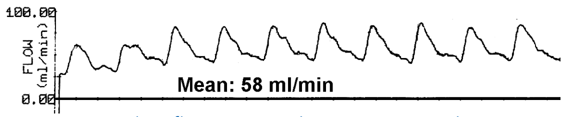


Fig. D20: Baseline flow measured in M1 segment during carotid ophthalmic aneurysm clipping. Mean baseline flow: 58 ml/min.

M1 (MCA) Baseline Flow with ICA Occluded

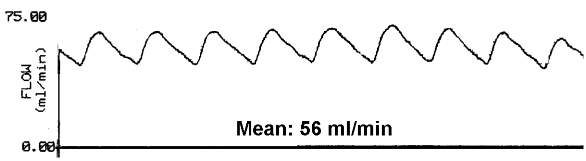


Fig. D21: Baseline flow measured in M1 segment with ICA occluded. Mean flow: 56 ml/min demonstrates good collateral flow.

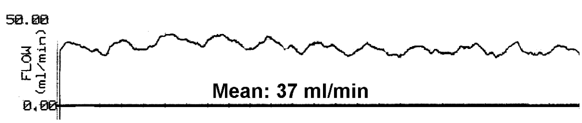


Fig. D22: Baseline flow measured in M1 segment with ICA occluded. Drop in flow demonstrates dangerous situation.

M1 (MCA) Flow after Aneurysm Clipping

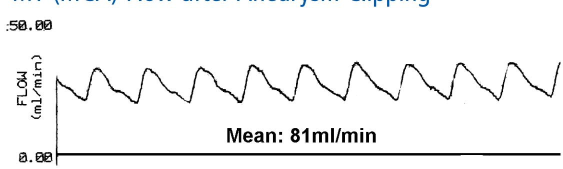


Fig. D23: M1 segment post-clip flow of 81 ml/min.

M1 (MCA) Flow after Clip Readjustment

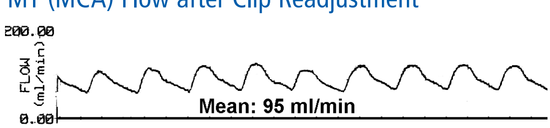


Fig. D24: M1 segment post-clip flow of 95 ml/min after readjustment of clip in carotid-ophthalmic surgery.

Morphology

The anterior choroidal artery (AChA) arises from posterior-lateral wall of the internal carotid artery (ICA) 2.5 mm distal to the origin of posterior communicating artery (PComA). The AChA usually arises as a single trunk and may occasionally arise from the PComA or ICA bifurcation. Multiple trunk AChA arteries have been reported in approximately thirty percent of cases. The artery courses along the optic tract and ultimately terminates in the choroid plexus of the lateral ventricle.

Occurrence

Anterior choroidal artery aneurysms account for four percent of all intracranial aneurysms.

Presentation

Subarachnoid hemorrhage, third-nerve palsy presents with large or giant AChA aneurysms. There may be interchangeability of brain regions supplied by the AChA or PComA. If the PComA is small, the AChA may take over and supply its region of the brain. Alternately, if the AChA is small, the PComA may supply its region. This variability may account for the unpredictable consequences associated with AChA occlusion: from little clinical consequence to hemiplegia and hemianopsia.

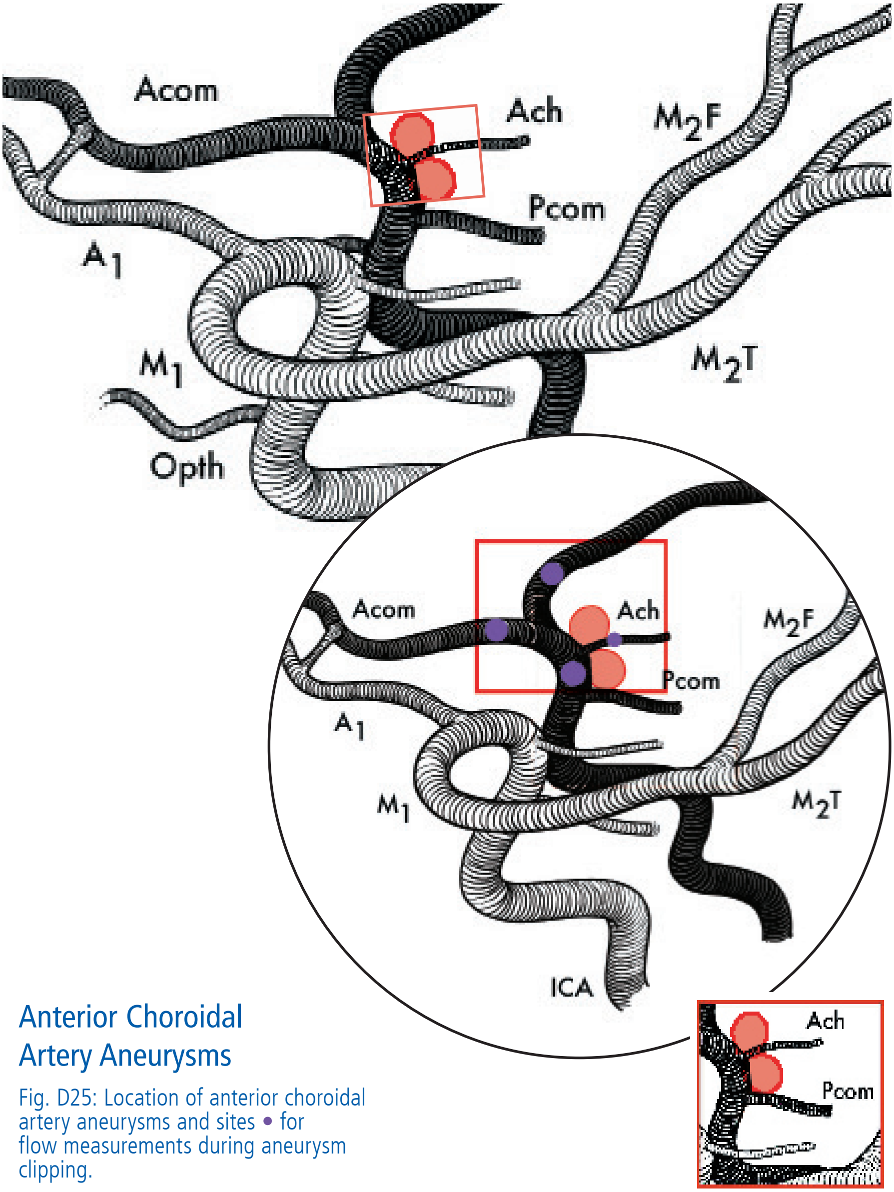
Flow Measurement

Flow preservation is particularly important in the distal anterior choroidal artery as well as M1(MCA), A1(ACA), and internal carotid artery. Post-clip flows are measured in the AChA, M1 segment (MCA), A1 segment (ACA), and internal carotid artery and are then compared to baseline flows.

Flow Measurement Sites (Fig. D25)

Aneurysm Site	Probe Placement	Size (mm)	Expected Flows (ml/min)
Anterior Choroidal A (ACh)	M1 (MCA)	2.0	80-120
	A1 (ACA)	2.0	40-60
	ICA	3.0	120-170
	AChA	1.5	20-60

D3b. Anterior Choroidal Artery Aneurysm cont.



Anterior Choroidal Artery Aneurysms

Fig. D25: Location of anterior choroidal artery aneurysms and sites • for flow measurements during aneurysm clipping.

Morphology

The posterior communicating artery (PComA) arises from the postero-lateral wall of the internal carotid artery (ICA) within the subarachnoid carotid cistern. It first runs medially to the oculomotor nerve and then turns posterior to join the posterior cerebral artery to complete the circle of Willis. Larger PComA arteries are found more often in children than in adults suggesting that the vessel size may diminish with age. If the PComA fails to get smaller, the ICA then supplies the posterior cerebral circulation through this fetal-type PComA.

Occurrence

Twenty-five to thirty percent of intracranial aneurysms occur at the ICA and PComA junction, making this site the second most common aneurysm location after anterior communicating artery.

Presentation

PComA aneurysms are associated with subarachnoid hemorrhage (SAH) and/or a third-nerve palsy involving the extra-oculomotor muscles innervated by the oculomotor nerve and pupil.

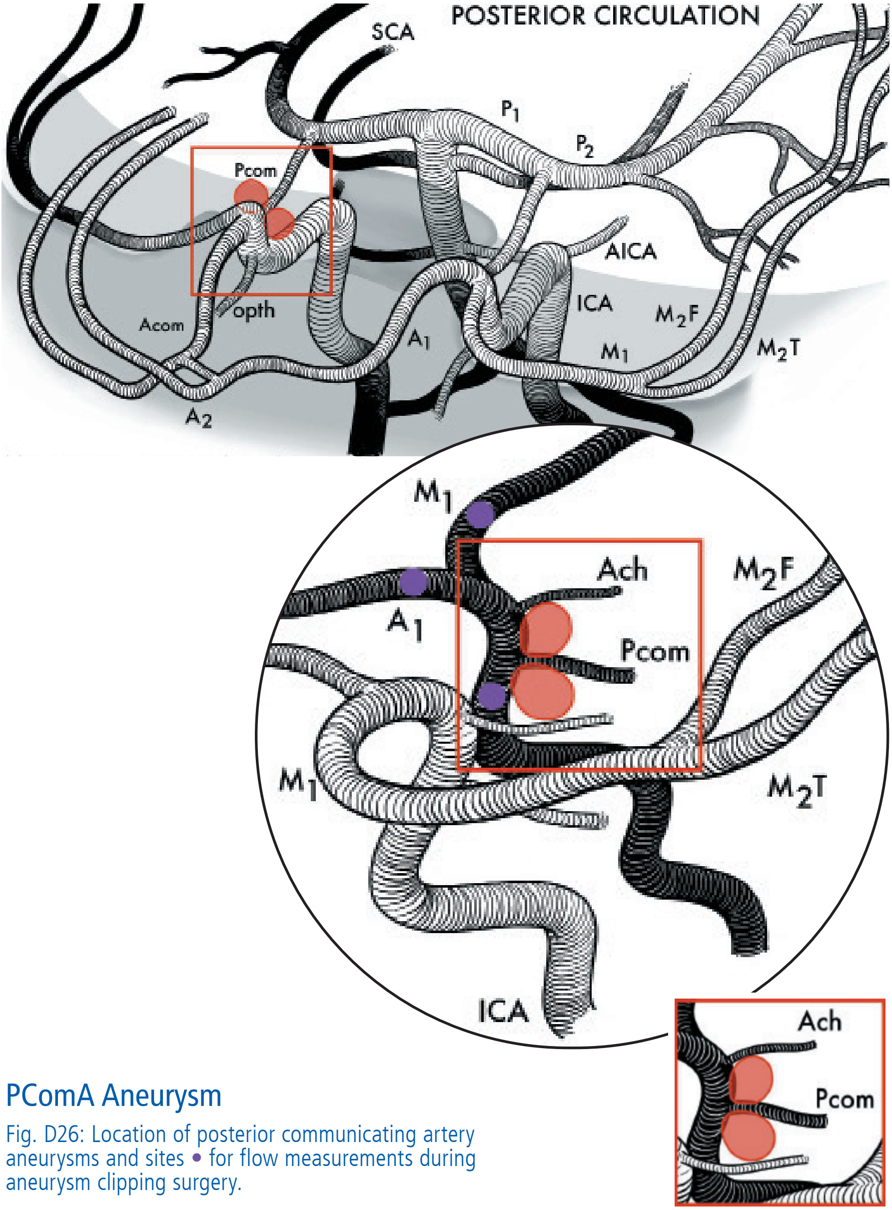
Flow Measurement

Flow must be preserved in the ICA and M1 (MCA) and A1 (ACA) outlet vessels. Care is also taken to ensure preservation of all nearby perforators. Flow is measured in the ICA, M1, A1 and compared to baseline flows. PComA aneurysms are the one site where the Flowprobe might not be used because the surgeon may only choose to expose the ICA and the aneurysm.

Flow Measurement Sites (Fig. D26)

Aneurysm Site	Probe Placement	Size (mm)	Expected Flows (ml/min)
Posterior Communicating A (PCom)	ICA	3.0	100-170
	M1 (MCA)	2.0	80-120

D3c. Posterior Communicating Artery (PComA) Aneurysms cont.



PComA Aneurysm

Fig. D26: Location of posterior communicating artery aneurysms and sites • for flow measurements during aneurysm clipping surgery.

Morphology

The internal carotid artery bifurcates into the anterior cerebral artery (ACA) and middle cerebral arteries (MCA) just after the origin of the Anterior Choroidal artery (AChA).

Presentation

Internal carotid artery bifurcation aneurysms exhibit no particular clinical features. Subarachnoid hemorrhage occurs in 95% of cases. Large or giant internal carotid artery bifurcation aneurysms may cause aphasia and hemiparesis.

Occurrence

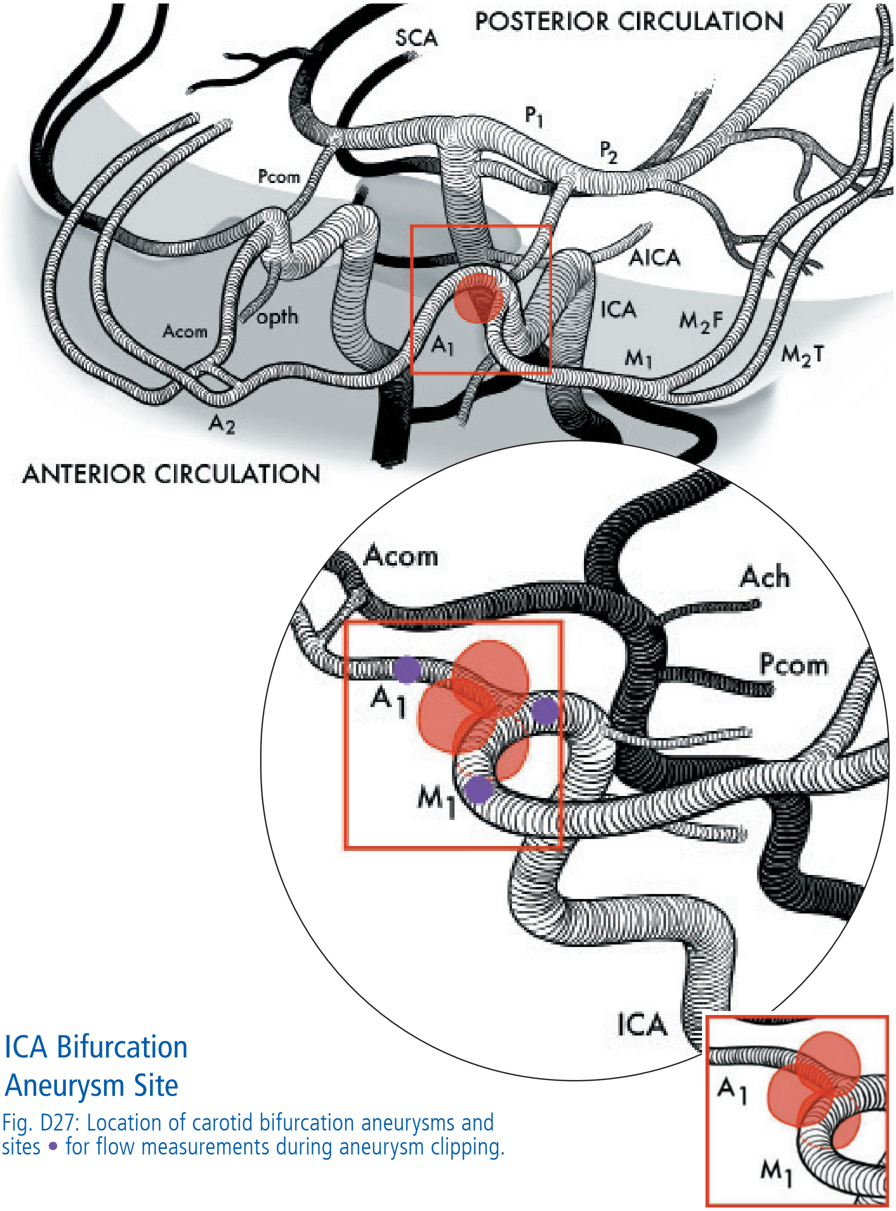
Internal carotid artery bifurcation aneurysms account for five to fifteen percent of all intracranial aneurysms. They can project from the superior, inferior or lateral surfaces of the bifurcation.

Flow Measurement

Flow must be preserved in the M1 (MCA) and A1 (ACA) outlet vessels. Post-clip flows are measured in the M1 segment of the MCA, and/or A1 segment of the ACA and are then compared to baseline flows. Flow in the ICA can also be checked.

Flow Measurement Sites (Fig. D27)

Aneurysm Site	Probe Placement	Size (mm)	Expected Flows (ml/min)
Carotid Bifurcation (ICA)	M1	2.0	80-120
	A1	2.0	40-60
	ICA	3.0	120-170



ICA Bifurcation Aneurysm Site

Fig. D27: Location of carotid bifurcation aneurysms and sites • for flow measurements during aneurysm clipping.

Case Examples: ICA Aneurysms

Case # 1

ICA Aneurysm Flow Summary (ml/min)			
Vessel	Probe Size (mm)	Baseline Flow	Post-Clip Flow
Left M1	2	45	65
Left A1	2	16	30

Introduction

A 46-year-old patient presented with SAH. A left ICA bifurcation aneurysm was diagnosed.

Baseline Flows

Baseline flows were measured in the left M1 MCA and left A1 ACA. Flow in the M1 segment measured 45 ml/min. Flow in the A1 segment measured 16 ml/min indicating some compromise due to the aneurysm.

Aneurysm Clipped & Flow Remeasured

M1 and A1 segment flows were rechecked after aneurysm clipping. Flows in both segments improved. Post-clip M1 flow was 65 ml/min. Post-clip A1 flow increased from 16 to 30 ml/min.

Case # 2

ICA Aneurysm Flow Summary (ml/min)			
Vessel	Probe Size (mm)	Baseline Flow	Post-Clip Flow
Left M1	2	57	45
Left A1	2	41	37

Introduction

A 63-year-old patient presented with SAH. A left ICA bifurcation aneurysm was identified.

Baseline Flows

Baseline flows were measured in the left M1 segment of the MCA and left A1 segment of the ACA. Baseline flow in the M1 segment measured 57 ml/min. Flow in the A1 segment measured 41 ml/min.

Aneurysm Clipped & Flow Remeasured

Left M1 and A1 segment flows were rechecked after aneurysm clipping. Post-clip M1 flow was 45 ml/min. Post-clip A1 flow was 37 ml/min. Both were acceptable values to the surgeon.

Flow-QC® Benefits

- Post-clip flow measurements assured the surgeon that flow was preserved in distal arterial vessels.
- Flow-QC® measurements assisted the surgeon in defining the operative strategy in both internal carotid artery aneurysm clipping cases.

D3e1. Anterior Cerebral Artery (ACA) Aneurysm: A_1 Segment

Morphology

The first segment (A1) of the anterior cerebral artery (ACA) lies between the ACA's point of origin at the ICA bifurcation and the anterior communicating artery (AComA). This A1 segment measures 12.7 mm long. Its diameter is about 2.6 mm. Numerous perforators arise from both the A1 and A2 segments. The recurrent artery of Heubner arises near or at the A1 and A2 segments boundary and then courses along the A1 segment.

Presentation

Subarachnoid hemorrhage (SAH)

Occurrence

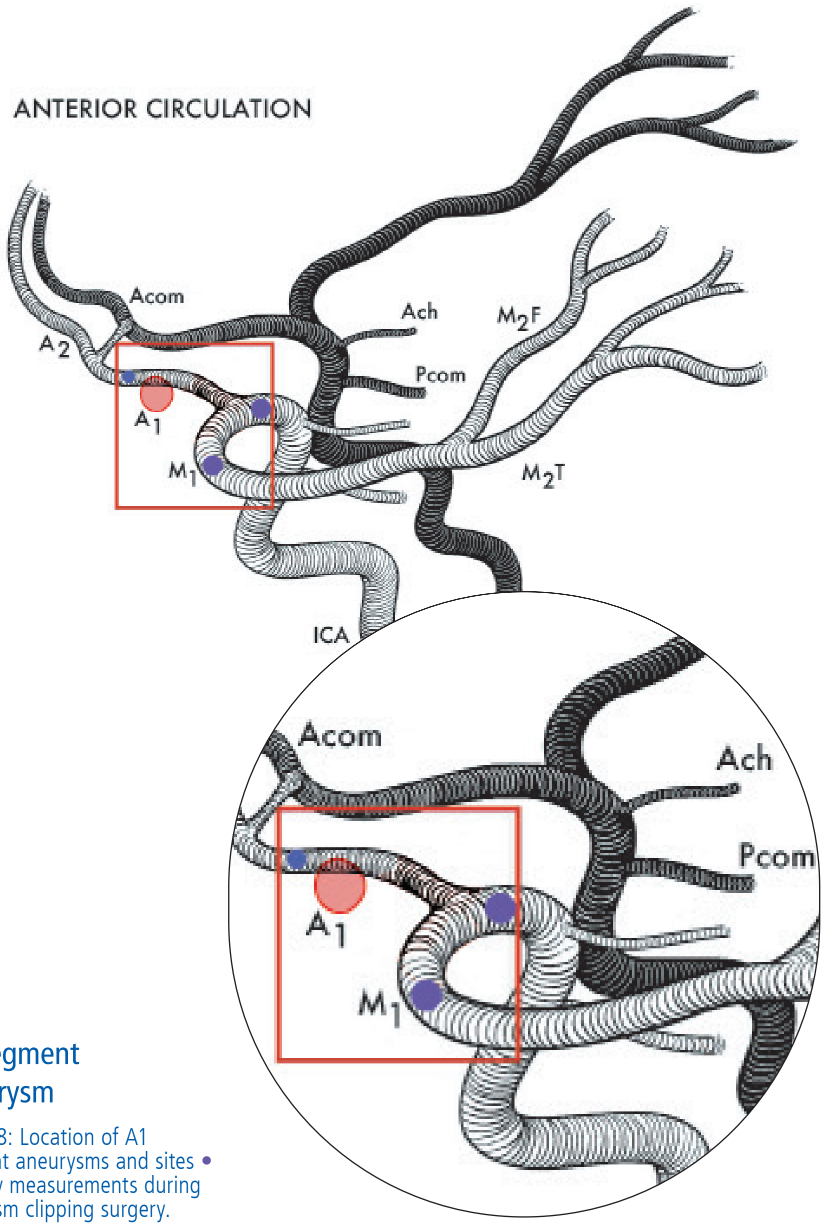
A1 segment aneurysms are rare and represent less than two percent of all aneurysms. Aneurysms can arise anywhere between the bifurcation and the AComA complex.

Flow Measurement

Flow must be preserved in the ICA and M1 of the middle cerebral artery (MCA) and A1 (ACA) outlet vessels. Post-clip flows are measured in the ICA, the M1 segment, and the distal A1 segment and are then are compared to baseline flows.

Flow Measurement Sites (Fig. D28)

Aneurysm Site	Probe Placement	Size (mm)	Expected Flows (ml/min)
Anterior Cerebral A (A1 Segment)	ICA	3.0	120-170
	M1 (MCA)	2.0	80-120
	A1 (distal)	2.0	40-60



A1 Segment Aneurysm

Fig. D28: Location of A1 segment aneurysms and sites • for flow measurements during aneurysm clipping surgery.

D3e2. Anterior Communicating Artery (AComA) Aneurysm

Morphology

The anterior communicating artery (AComA) is a small bridge artery that connects the bilateral anterior cerebral arteries (ACAs). The AComA marks the origin of the A2 segments of the anterior cerebral artery. It is between 0.3 and 7.0 mm long and presents many variations in different individuals.

Occurrence

AComA aneurysms are among the most common aneurysms and represent about 30% of ruptured aneurysms. Many AComAs have a large dominant A1 segment with a hypoplastic contralateral A1 segment. The larger A1 segment feeds the aneurysm and both A2 segments. Also aneurysms with an large third A2 segment occur. An aneurysm may project from any side of the AComA: superior, inferior, anterior and posterior. Therefore, every AComA aneurysm clipping surgery is challenging and requires a custom approach.

Presentation

Patients with AComA aneurysms commonly present with subarachnoid hemorrhage (SAH) and visual disturbances. Following SAH, diabetes or hypothalamic dysfunction may be observed. Interventricular hemorrhage, hydrocephalus and hematomas may also occur.

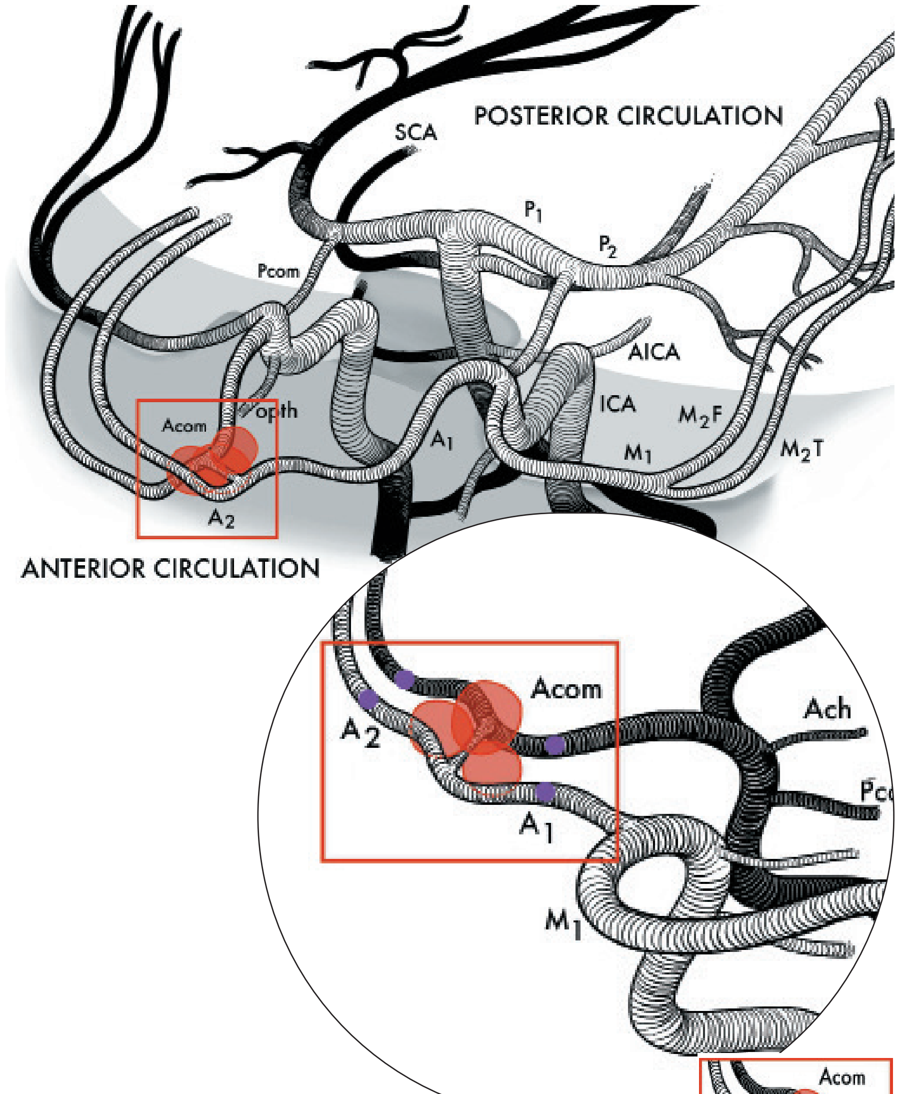
Flow Measurement Sites (Fig. D29)

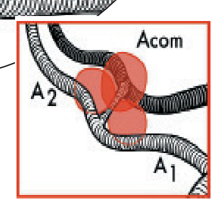
Aneurysm Site	Probe Placement	Size (mm)	Expected Flows (ml/min)
Anterior Communicating A (ACom)	A1 (ipsilateral)	2.0	40-60
	A1 (contralateral)	2.0	40-60
	A2 (ACA)	1.5	40-50

Flow Measurement

Surgery is high risk. The technical challenge is to preserve flow in both A2 outlet vessels as well as the ipsilateral and/or contralateral A1 segments.

Flow is measured in the both left and right A2 and A1 segments and compared to baseline flows.





AComA Aneurysms

Fig. D29: Location of AComA aneurysms and sites • for flow measurements during aneurysm clipping surgery.

D3e2. Anterior Communicating Artery (AComA) Aneurysm

Case Examples: AComA Aneurysms

Case # 1

Introduction

A 73-year-old patient presented with SAH. An anterior communicating artery (AComA) aneurysm was diagnosed.

Baseline Flows

Baseline flows were measured in the A2 segments of the left ACA and right ACAs. Flow in the left A2 segment measured 22 ml/min. Flow in the right A2 segment measured 26 ml/min.

Aneurysm Clipped Flows Remeasured

M1 and A1 segment flows were rechecked after aneurysm clipping. Post-clip right A2 segment flow measured 23 ml/min, close to baseline. However, post-clip left A2 segment flow measured only 4 ml/min. This prompted the surgeon to immediately reposition the clip.

Clip Repositioned and Flows Remeasured

The clip was repositioned and flows in both ACA segments were remeasured. Right and left A2 segment flows measured 24 ml/min and 23 ml/min, respectively, each comparable to their respective baseline flows.

AComA Aneurysm Flow Summary (ml/min)				
Vessel	Probe Size (mm)	Baseline Flow	Post-Clip Flow	Clip Repositioned
Left A2	1.5	22	4	23
Right A2	1.5	26	23	24

Flow-QC® Benefits

- Compromised left A2 flow (4 ml/min) after the first positioning of the clip prompted the surgeon to react quickly to reposition the clip.
- After repositioning the clip, flow measurements were restored to baseline assuring the surgeon that flow was preserved in distal arterial conduits.
- Flow-QC® measurements assisted in decision making during this high risk AComA aneurysm clipping case.

Pre-op Angiogram

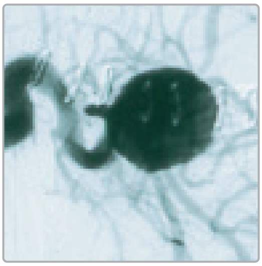


Fig. D30: Pre-operative angiogram showing giant anterior communicating aneurysm.

Post-clip left A2 flow

Fig. D31: Post-clip flow in left A2 checked with Flowprobe.

Post-clip right A2 flow

Fig. D32: Post-clip flow in right A2 checked with Flowprobe.

Case # 2

Introduction

A patient with a giant AComA aneurysm was referred for treatment (Fig. D30). The patient had been operated on at another hospital, but after exposure of the aneurysm, clipping was not attempted due to the high risk of compromising the left A2 segment.

Baseline Flows Measured

The aneurysm was exposed and baseline flows were measured in the left A1, left A2, right A2 and right A1.

Temporary Clip Placed

The surgeon sized a fenestrated clip against the neck of the aneurysm and positioned a temporary clip. The aneurysm was punctured and decompressed.

Aneurysm Clipped

The aneurysm was clipped and the temporary clips were removed.

Post-clip Flows Measured

Post-clip flows were measured in the right A2 and left A2. Flow in the left A2 had decreased from a baseline of 29 ml/min to only 2-3 ml/min (Fig. D31). The clip is adjusted and left A2 flow was rechecked. After the first clip adjustment left A2 flow was 7-8 ml/min.

Flow-QC® Benefits

This case demonstrates how Transonic intraoperative flow measurements assist a surgeon in determining operative strategy.

- Multiple clip re-applications coupled with flow measurements were required to obtain full preservation of distal flow in the left A2, which was key to operative success.
- The immediacy of Transonic® measurements enabled the surgeon to react quickly to suboptimal clip placement and reposition the clip.
- No other flow technology gives the surgeon the ability to react this quickly to flow compromise during surgery.

Case Examples: AComA Aneurysms cont.

Clip Removed and Flow Rechecked

The clip is taken off. Left A2 flow was rechecked and was again 29 ml/min confirming that the fenestrated clip was compromising the left A2.

Clip Reapplied and Readjusted

The clip is reapplied and left A2 flow was rechecked. After the second clip adjustment left A2 flow was 12 ml/min, less than 50% of baseline. The clip was adjusted and left A2 flow was rechecked. After the third clip adjustment left A2 was 34 ml/min, fully restored to baseline. Flow in the right A2 is also checked and was 15 ml/min, the same as baseline (Fig. D32).

AComA Aneurysm Flow Summary ml/min							
Vessel	Probe Size (mm)	Baseline Flow	Post-Clip Flow	Clip Repositioned	Clip Off	Clip Reapplied	Clip Readjusted
Left A1	2	36					
Left A2	1.5	29	2	8	29	12	34
Right A2	1.5	15	15			15	
Right A1	2	6					

Sequential Left A2 Flow Measurements

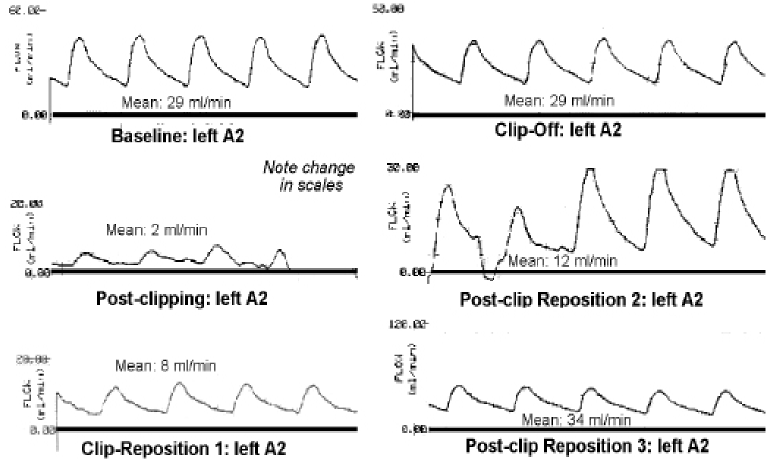


Fig. D33: A2 Flows during the course of the surgery.

Case Example: Multiple Aneurysms: ICA & AComA

Pre-op Angiogram

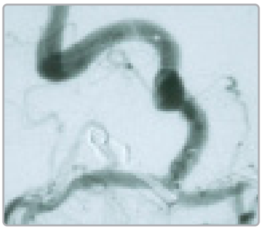


Fig. D34: Pre-operative angiogram.

ICA Baseline Flow

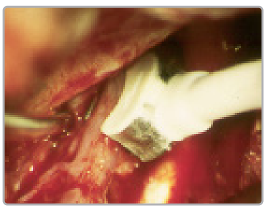


Fig. D35: ICA baseline flow measured 163 ml/min.

ACA Baseline Flow

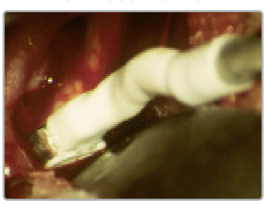


Fig. D36: Baseline ACA flow measured 40 ml/min.

MCA Baseline Flow

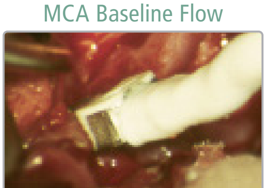


Fig. D37: Baseline MCA flow measured 80 ml/min.

Introduction

A woman presented with SAH (Grade 4-5) after an aneurysm reruptured after coiling. She underwent surgery for clipping of two aneurysms, a left ICA bifurcation aneurysm and an AComA aneurysm (Fig. D34).

Carotid Bifurcation Aneurysm

Baseline flows were measured in ICA, ACA & MCA (Figs. D35-37). A temporary clip was placed on the ICA and the carotid bifurcation aneurysm was clipped. Post-clip flows were rechecked in the ICA, ACA and MCA arteries.

ICA Aneurysm Flow Summary ml/min			
Vessel	Probe Size (mm)	Baseline Flow	Post-Clip Flow
ICA	2	163	163
ACA	2	40	40
MCA	2	80	80

AComA Aneurysm

Baseline flows were measured in the left A1 and A2 segments of AComA. Flows were rechecked in the A1 and A2 segments after clipping. Left A1 flow was unchanged. A2 flow was severely compromised, 0 ml/min, down from 40 ml/min. The clip was readjusted. A2 branch flow was rechecked and had returned to slightly above baseline, about 53 ml/min indicating slight reperfusion hyperemia.

AComA Aneurysm Flow Summary ml/min				
Vessel	Probe Size (mm)	Baseline Flow	Post-Clip Flow	Clip Repositioned
Left A1	2	40	40	
Left A2	1.5	40	2	53

Case Example: Multiple Aneurysms: ICA & AComA cont.

AComA Aneurysm Comparison of Flows

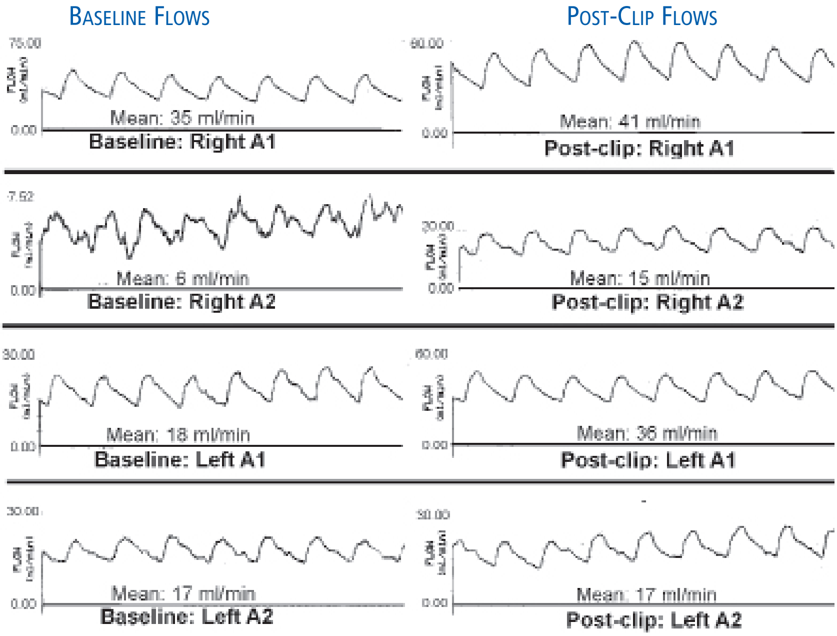


Fig. D38: Baseline flow measurements of this anterior communicating aneurysm indicated that flow in the right A2 segment was severely compromised at 6 ml/min. Flow in the left A1 segment was also lower than expected at 18 ml/min when compared to flow in its ipsilateral counterpart, the right A1 segment, at 35 ml/min. Following aneurysm clipping, post-clip flows were rechecked and compared to baseline flows. Flow in the right A2 segment increased from 6 ml/min to 15 ml/min. Flow in the left A1 segment also improved to 36 ml/min. Flows in the right A1 segment and A2 segments compared to baseline flows.

Flow-QC® Benefits

- Flow measurements confirmed that flow was fully preserved after clipping of the internal carotid artery bifurcation aneurysm.
- Flow measurements alerted the surgeon to a compromise in flow in the left A2 segment after clipping the AComA aneurysm.
- Flow-QC® measurements confirmed that A2 segment flow was fully restored to baseline after readjustment of the clip.

Morphology

The MCA arises at the termination of the ICA trunk at its bifurcation. It is twice as large as the other fork originating at the bifurcation, the ACA. The diameter of the MCA averages 3.9 mm (range 2.4 - 4.6 mm). From its origin, the MCA's M1 trunk extends about 15 mm and then divides into segments. In most cases (64-78%), the M1 trunk bifurcates into two M2 segments: a superior M2 frontal artery that supplies the parietal lobe and an inferior M2 temporal segment which supplies the temporal lobe. In twelve to twenty-five percent of cases, the M1 trunk trifurcates into three segments. In rare instances (~ 6%), the M1 trunk will divide into more than three branches.

Presentation

MCA aneurysms generally present upon rupture. Due to a higher propensity for intracranial hemorrhage, they often exhibit more devastating clinical effects than other aneurysms. Seizures may also result.

Occurrence

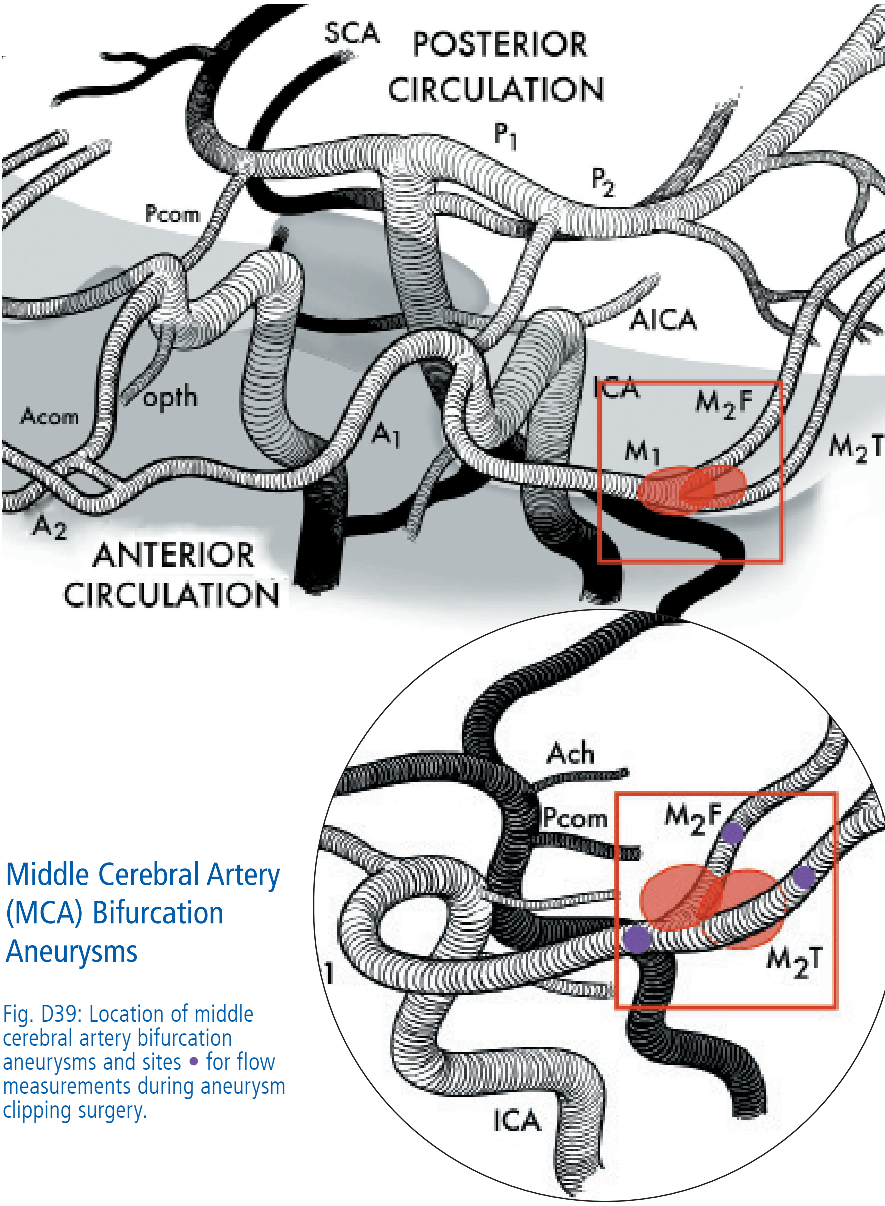
Most MCA aneurysms (89%) occur at the bifurcation of the MCA into its branches.

Flow Measurement Sites (Fig. D39)

Aneurysm Site	Probe Placement	Size (mm)	Expected Flows (ml/min)
MCA Circulation Bifurcation Aneurysm	M1 (outlet)	2.0	80-120
	M2T (temporal	2.0	50-80
	M2F (frontal)	2.0	50-80

Flow Measurement

The goal of middle cerebral artery aneurysm clipping surgery is to exclude the aneurysm from the circulation while preserving flow in distal M2 (MCA) outlet vessels. Extreme care must be taken to also ensure preservation of all nearby perforators. Baseline flows are first measured in the M1 trunk, and M2 segments. Following clipping of the aneurysm, post-clip flows are measured again in the proximal M1 trunk and distal M2 segments and are then compared to baseline flows to ensure that flow is preserved.



Middle Cerebral Artery (MCA) Bifurcation Aneurysms

Fig. D39: Location of middle cerebral artery bifurcation aneurysms and sites • for flow measurements during aneurysm clipping surgery.

Morphology

The MCA is divided into four segments as it traverses the cranium to supply most of its lateral surface. The first M1 segment lies deep in the sylvian fissure, beginning at the bifurcation of the internal carotid artery and then running parallel and posterior to the sphenoid ridge for about 15 mm before dividing into various branches. An average number of ten perforating branches arise along this M1 trunk.

Presentation

MCA aneurysms generally present with rupture. Once the aneurysm has ruptured, patients will lose consciousness or experience unilateral headache on the side of the aneurysm. Focal neurologic defects due to intracerebral hematomas can also present.

Occurrence

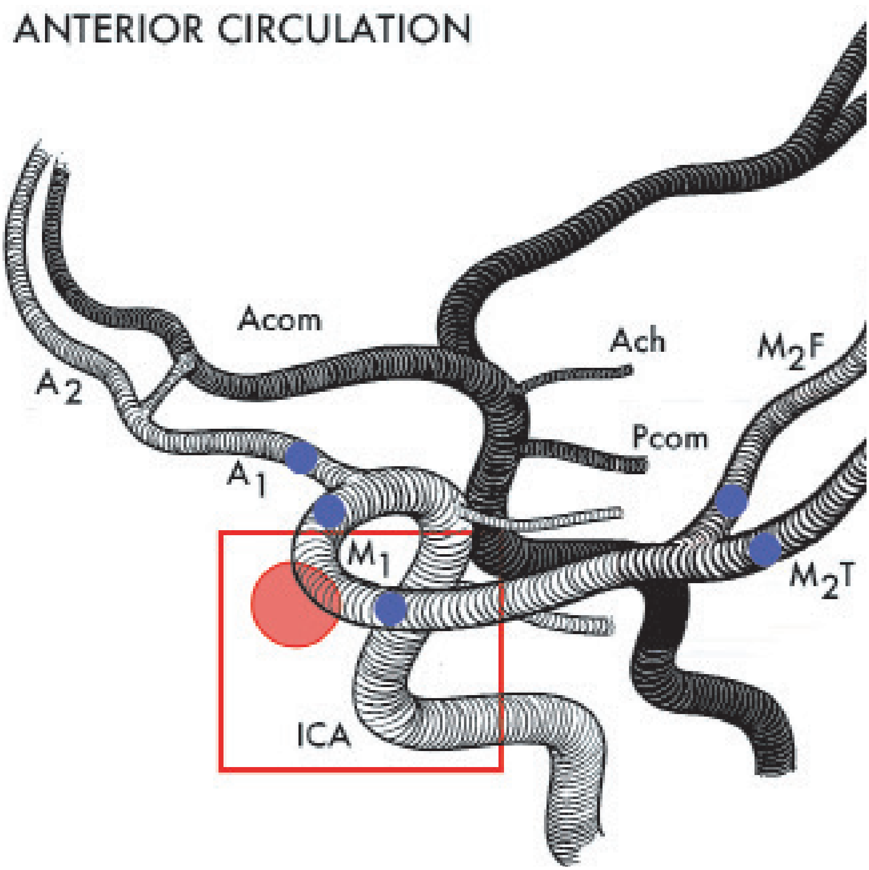
The MCA is the third most common site for aneurysms. Approximately twenty to twenty-five percent of all intracranial aneurysms occur along the middle cerebral artery. Twelve percent of these MCA aneurysms occur along the main M1 trunk at the origins of early branches. Saccular M1 aneurysms are often associated with multiple aneurysms at other sites or with a familial history of aneurysms. Giant aneurysms of more than twenty-five millimeters in diameter also occur in the MCA.

Flow Measurement

Flow must be preserved in distal M2 MCA outlet vessels and care must also be taken to ensure preservation of all neighboring perforators. Post-clip flows are measured in the proximal M1, the distal M2 temporal segment, distal M2 frontal segment and, when possible, the anterior cerebral artery and are then compared to baseline flows.

Flow Measurement Sites (Fig. D40)

Aneurysm Site	Probe Placement	Size (mm)	Expected Flows (ml/min)
MCA Circulation M1 Segment Aneurysm	M1 (outlet)	2.0	80-120
	M2T (temporal	2.0	50-80
	M2F (frontal)	2.0	50-80
	ACA (when possible))	2.0	40-60



M1 Segment MCA Aneurysm

Fig. D40: Location of middle cerebral artery M1 trunk aneurysm and sites
• for flow measurements during aneurysm clipping surgery.

Case Examples: MCA Aneurysms

Pre-op Angiogram

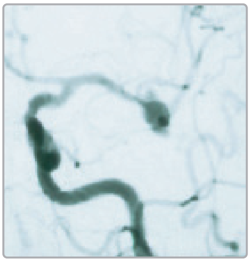


Fig. D41: Pre-operative angiogram.

Surgical Exposure

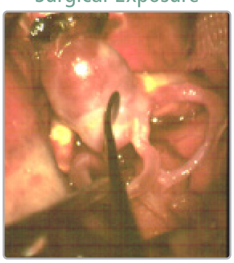


Fig. D42: Inspection shows two frontal branches coming off the aneurysm.

Baseline measurement

Fig. D43: Baseline measurement of the M2F2 branch.

Case # 1

Introduction

A 74-year-old woman presented with a grade 3 subarachnoid hemorrhage. Pre-operative angiogram showed a left multi-lobulated MCA aneurysm (Fig. D41) at the MCA trifurcation. Surgical exposure of the aneurysm revealed two MCA frontal branches (M2F1, M2F2) which came directly off the aneurysm (Fig. D42). The challenge was to preserve the flow entering these branches after clipping the aneurysm. A middle cerebral artery temporal branch (M2T) completed the MCA trifurcation.

Baseline Flows Measured

Baseline flows were measured in the vessels at risk: both MCA frontal branches and the temporal branch (Fig. D43). Baseline flows were M2F1, 2.5 ml/min; M2F2, 14 ml.min; M2T, 14 ml/min respectively (Fig. D43).

Aneurysm Clipped & Post-clip Flows Measured

Flows were rechecked in the M2F1, M2F2, and M2T branches. After clipping, M2F1 and M2T branch flows were compared to baseline. M2F2 flow had dropped from 14 ml/min to 7 ml/min. This prompted the surgeon to inspect the take-off site and find that this branch was caught by one of the clips.

Clip Readjusted and M2F2 Flow Remeasured

The clip was readjusted and M2F2 branch flow was rechecked. It had returned to baseline. Post-operative angiography confirmed obliteration of the aneurysm with full preservation of flow in all distal branches.

MCA Aneurysm Flow Summary ml/min				
Vessel	Probe Size (mm)	Baseline Flow	Post-Clip Flow	Clip Repositioned
M2T branch	1.5	14	14	
M2F1 branch	1.5	2.5	2.5	
M2F2 branch	1.5	14	7	14

MCA Aneurysm Case # 2

Introduction
A 44-year-old female patient was diagnosed with a right MCA aneurysm.

Baseline Flows Measured
MCA, right frontal (M2F) branch baseline flow was 40 ml/min; right temporal (M2T) branch baseline flow was 16 ml/min.

Aneurysm Clipped with Two Clips
The first clip was applied to the aneurysm. Flows in both branches were remeasured and compared favorably to baseline. A second clip was applied to the aneurysm. Flows were remeasured. Post-clip M2T branch flow dropped to 1 ml/min indicating that the clip was compromising flow.

Second Clip Repositioned
The clip was repositioned and flow was remeasured in both branches. M2F branch flow was 36 ml/min and M2T branch flow returned to baseline at 22 ml/min.

MCA Aneurysm Flow Summary (ml/min)					
Vessel	Probe Size (mm)	Baseline Flow	Post First Clip Flow	Post 2nd Clip Flow	2nd Clip Readjusted
M2F	1.5	40	40	38	36
M2T	1.5	16	15	1	22

MCA Aneurysm Case # 2

Introduction
A 53-year-old woman was diagnosed with a large left MCA aneurysm.

Baseline Flows
MCA left frontal branch (M2F) baseline flow was 40 ml/min.

MCA Aneurysm Flow Summary (ml/min)				
Vessel	Probe Size (mm)	Baseline Flow	Post-Clip Flow	Clip Repositioned
M2F2 branch	1.5	40	10	40

Aneurysm Clipped
The aneurysm was clipped. Post-clip M2F branch flow was 10 ml/min.

Clip Repositioned
The clip was repositioned and flow was remeasured. M2F branch flow confirmed that flow had returned to baseline.

MCA Aneurysm Case # 4:

Baseline & Post-Clip Flows

The flow composite of pre- and post-clipping flow measurements chronicles a MCA bifurcation aneurysm clipping case. The sequence of baseline flow measurements are on the left-hand column with their respective post-clip flow measurements on the right.

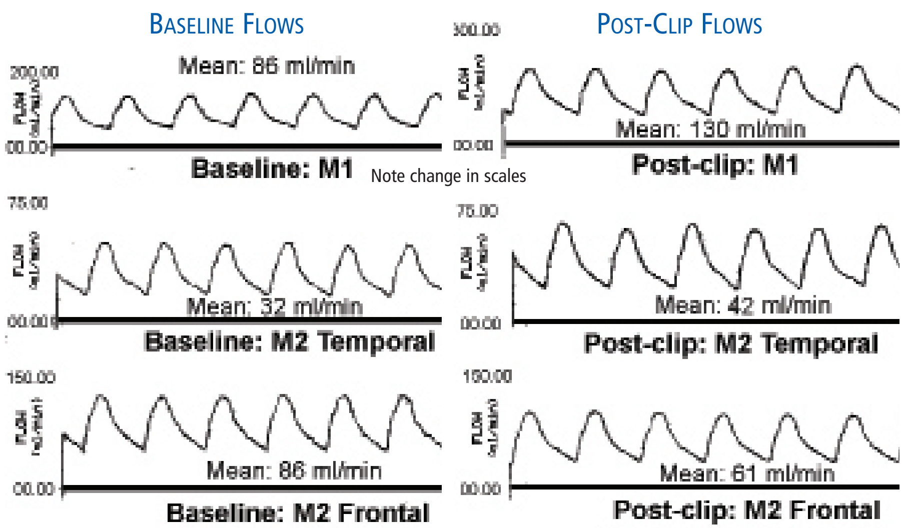


Fig. D43: Baseline flow measurements of this MCA aneurysm were M1, 86 ml/min; M2 Temporal, 32 ml/min; and M2 Frontal, 86 ml/min respectively. M2 Temporal flow was below the expected value for this vessel indicating that the aneurysm might be compromising flow in this MCA branch. After aneurysm clipping, Post-clip M2T flow increased by 25% to 42 ml/min. Flow in the M2F branch decreased 25% from 85 ml/min to 61 ml/min. M1 flow increased post-clip to 130 ml/min from baseline 86 ml/min.

MCA Aneurysm Flow Summary (ml/min)			
Vessel	Probe Size (mm)	Baseline Flow	Post-Clip Flow
M1	2	86	130
M2T (temporal)	1.5	32	42
M2F (frontal)	1.5	86	61

Flow-QC® Benefits

In each of these MCA aneurysm cases, the surgeon formulated an operative strategy assisted by timely intraoperative flow measurements.

D4. Posterior Circulation Aneurysms

Posterior Cerebral Circulation (Fig. D45)

Vertebral Artery (VA) and Branches
Basilar Artery (BA) and Branches
Posterior Cerebral Artery (PCA)

The posterior circulation consists of the bilateral Vertebral Arteries (VA) and their branches, notably the left and right Posterior Inferior Cerebellar Arteries (PICAs); the Basilar Artery (BA) with its branches including the left and right Anterior Inferior Cerebellar Arteries (AICAs) and the left and right Superior Cerebellar Arteries (SCAs) and the Posterior Cerebral Arteries (PCAs).

Less than 15% of all intracranial aneurysms occur in the posterior cerebral circulation. As in the anterior circulation, aneurysms often arise at the origin of a branch of the parent artery and project in the direction that blood would have flowed if the vessel had not branched. Most posterior circulation aneurysms occur at the apex of the basilar artery where it divides into the two posterior cerebral arteries. The next most common sites are at the junctions of the superior cerebellar artery with the basilar artery and the junctions of the posterior inferior cerebellar artery with the vertebral arteries.

Less common posterior circulation aneurysms include those of the right and left posterior cerebral arteries, those at the junction of the vertebral arteries with the basilar artery and those at the junctions of the anterior inferior cerebellar artery with the basilar artery. These aneurysms will not be presented in this handbook.

Vessel	Expected Flows (ml/min)
BA	60-75
VA	100-200
SCA	18-20
PCA	10-15

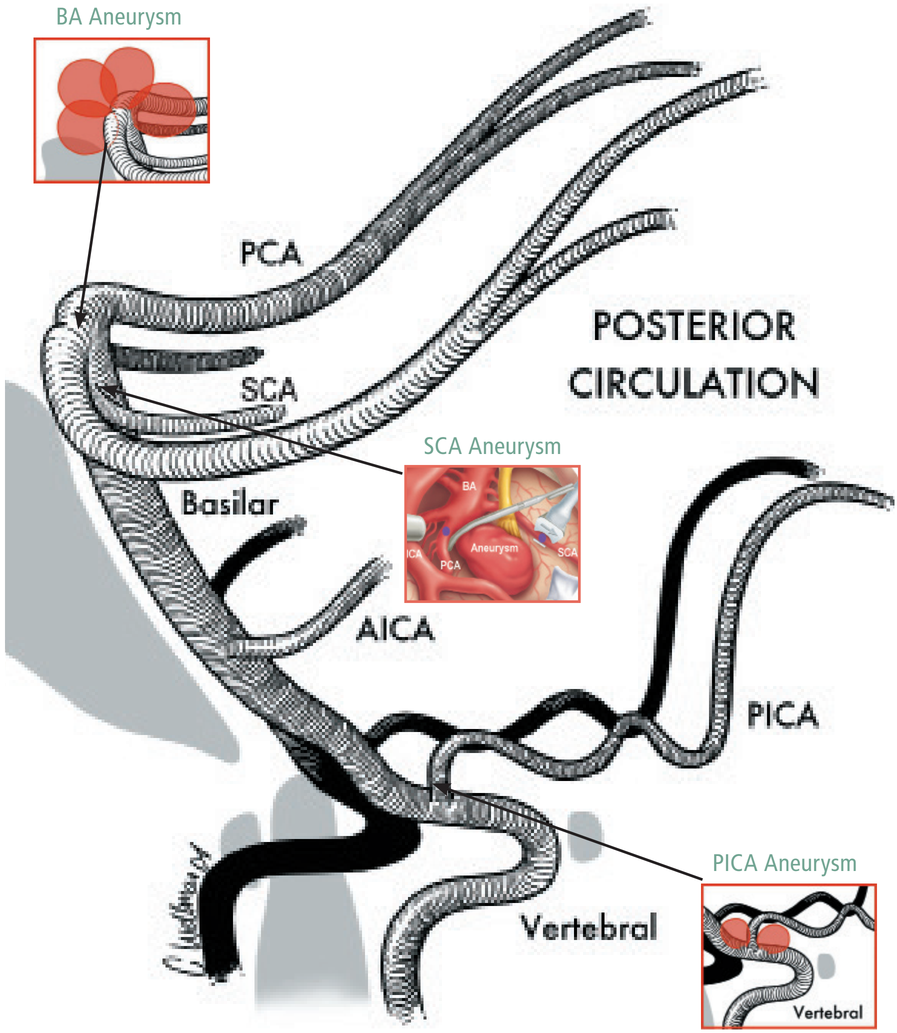


Fig. D45: Most common sites of aneurysm in the posterior cerebral circulation.

D4a. Posterior Inferior Cerebellar Artery (PICA) Aneurysms

Morphology

The PICA originates from the vertebral artery before the bilateral vertebrals join to form the basilar trunk of the posterior circulation. The PICA is one of three vessels that supply the cerebellum. The other two, the Anterior Inferior Cerebellar Artery (AICA) and the Superior Cerebellar Artery (SCA) both originate from the basilar trunk.

Presentation

Patients with PICA aneurysms present with subarachnoid hemorrhage (SAH). Sometimes they experience sudden loss of consciousness or respiratory or cardiac arrest because the aneurysm is often located close to the medulla. If the aneurysm compresses the sixth cranial nerve, palsy can occur.

Occurrence

PICA aneurysms at the junction with the vertebral artery account for about 3% of all intracranial aneurysms and are reported to occur more frequently in females.

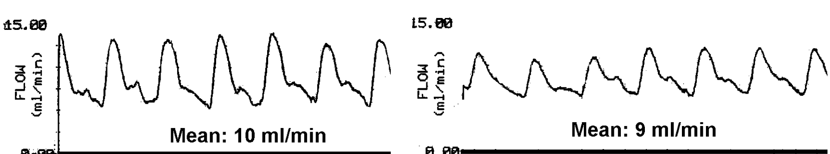
Flow Measurement Sites (Fig. D47)

Aneurysm Site	Probe Placement	Size (mm)	Expected Flows (ml/min)
Post. Inferior Cerebellar A (PICA)	VA	3.0	100-200
	PICA	2.0	10-15

Flow Measurement

Flow must be preserved in the parent vertebral artery and in the PICA artery. Flow is therefore checked in the vertebral and ipsilateral PICA arteries.

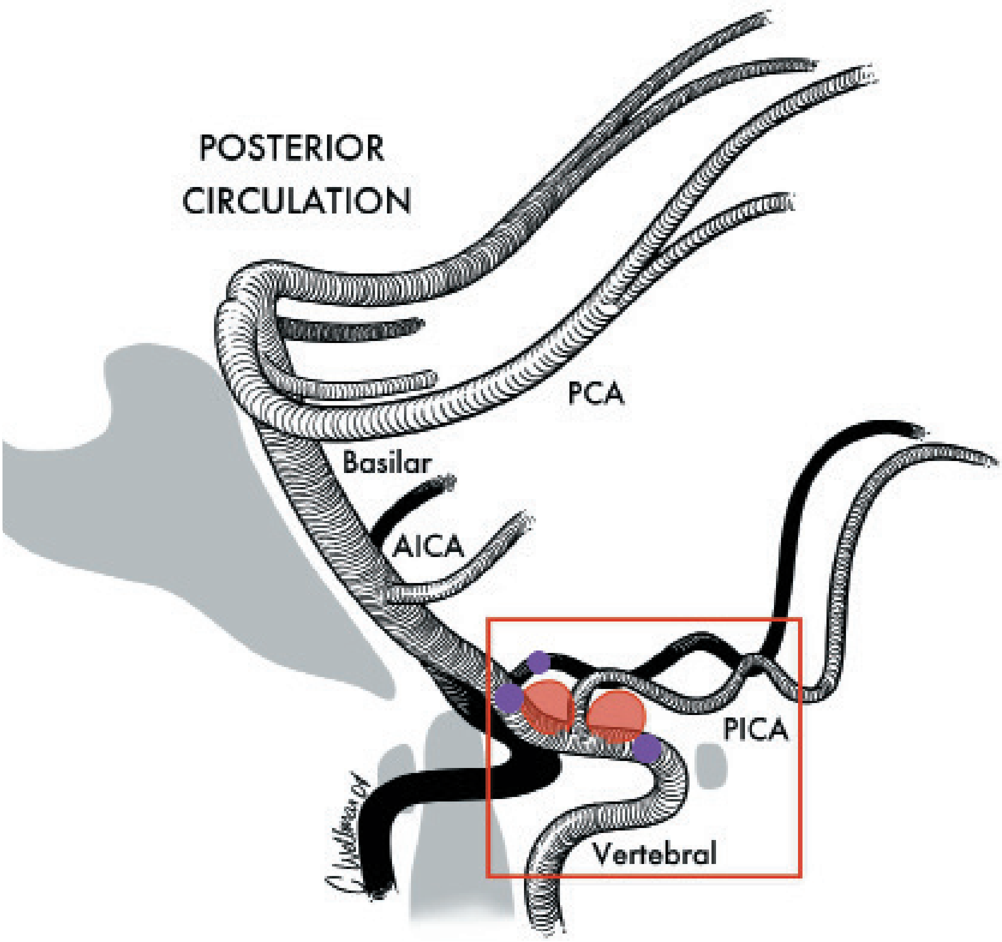
Flow Example: VA/PICA Aneurysm Trapping & Clipping



Baseline PICA Flow

PICA Flow: Post Aneurysm Clipping

Fig. D46: Before trapping the aneurysm, baseline PICA flow measured 10 ml/min. After first trapping and then surgically clipping the aneurysm at the vertebral-PICA junction, PICA post-clip flow remained steady at 9 ml/min.



Posterior Inferior Cerebellar Artery (PICA) Aneurysm

Fig. D47: Location of PICA aneurysms and sites • for flow measurements during aneurysm clipping surgery.

D4b. Basilar Apex Artery (BAA) Aneurysms

Morphology

The basilar artery is formed by a merge of the two vertebral arteries at the level of junction of the pons and medulla. It spawns a number of perforators and in older persons, in particular, can exhibit a circuitous, serpentine S-shaped course. The limitation for surgical access and the complex vasculature near the basilar artery apex make surgical clipping of basilar artery aneurysms among the most challenging for the neurosurgeon.

Presentation

Eighty percent of patients with basilar apex aneurysms present with subarachnoid hemorrhage (SAH) or neurologic symptoms.

Occurrence

Basilar apex aneurysms are the most common posterior circulation aneurysms and comprise five to eight percent of all aneurysms. They occur most frequently in women in their sixties.

Flow Measurement Sites (Fig. D49)

Aneurysm Site	Probe Placement	Size (mm)	Expected Flows (ml/min)
Basilar Tip A (BA)	P2 (ipsilateral)	2.0	26-30 and
	SCA	1.5	18-20
	PCom (prelude to sacrifice)		

Flow Measurement

Flow must be preserved in the superior cerebellar artery (SCA) and in the basilar artery. Flow is also measured in the ipsilateral posterior cerebral artery. Care must be taken not to inadvertently clip perforators (PCA).

Flow Example: Basilar Apex Aneurysm

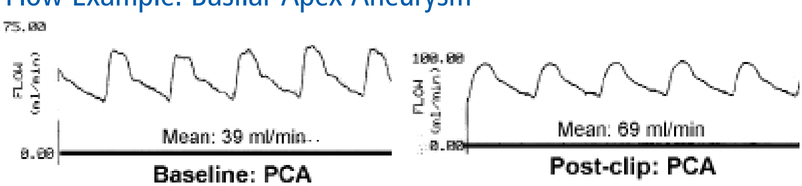
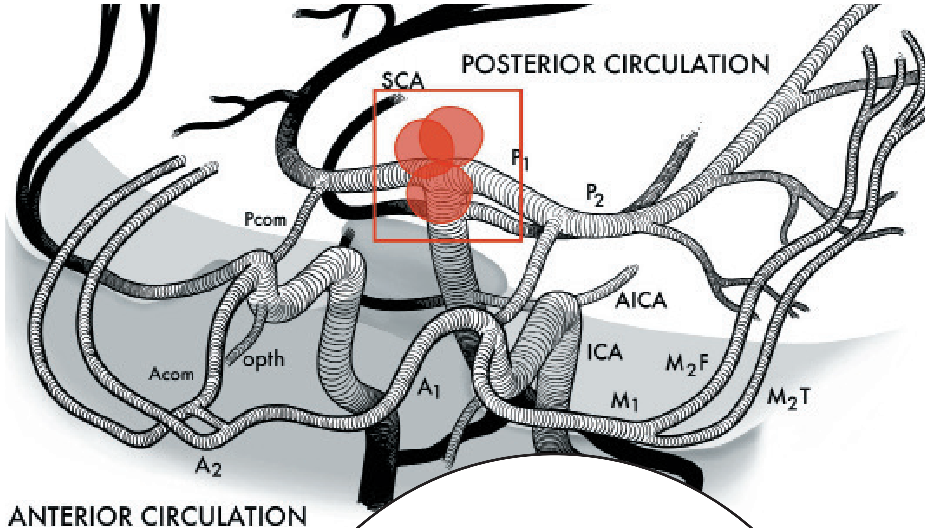
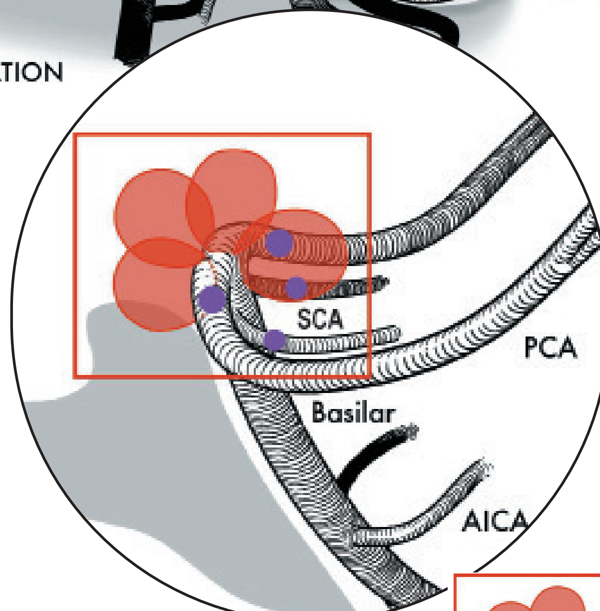
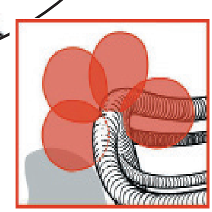


Fig. D48: PCA baseline flow before a basilar aneurysm was clipped measured 39 ml/min. After clipping the aneurysm flow improved to 69 ml/min.







Basilar Artery Apex (BAA) Aneurysms

Fig. D49: Location of basilar apex aneurysm and sites • for flow measurements during aneurysm clipping surgery.

D4c. Superior Cerebellar Artery (SCA) Aneurysms

Morphology

The SCA arises bilaterally from the basilar trunk close to the basilar bifurcation into the two posterior cerebral arteries. SCA aneurysms close to the basilar trunk often incorporate the origin of branch vessels in their necks and have close proximity to the oculomotor nerve.

Presentation

Patients present with subarachnoid hemorrhage (SAH). Occasionally, oculomotor dysfunction may be associated with rupture of aneurysms of the basilar tip and SCA.

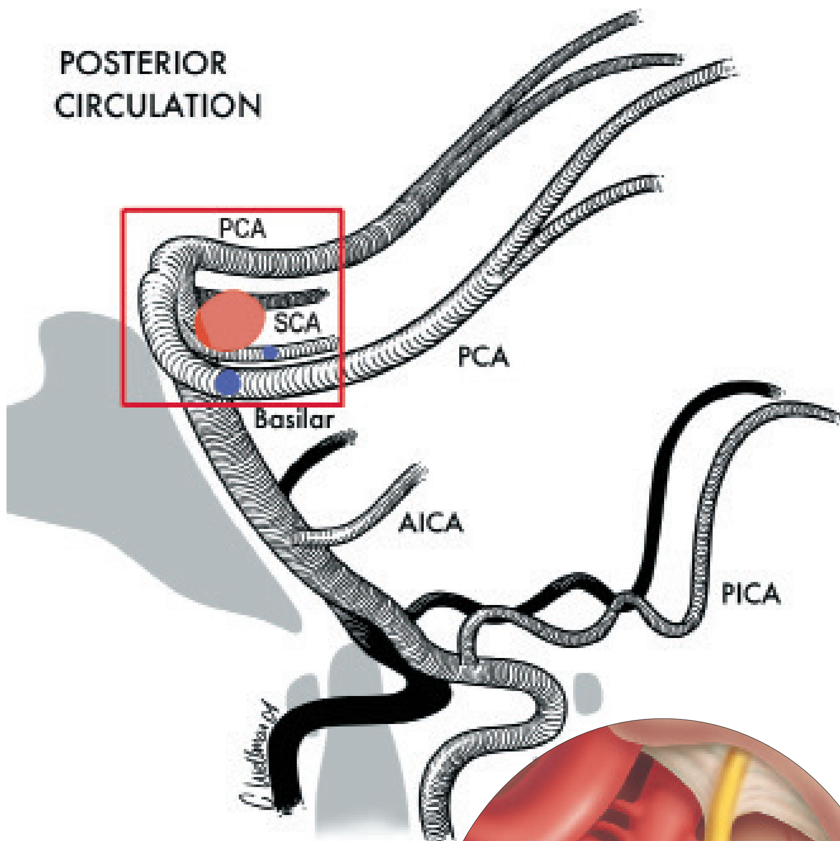
Occurrence

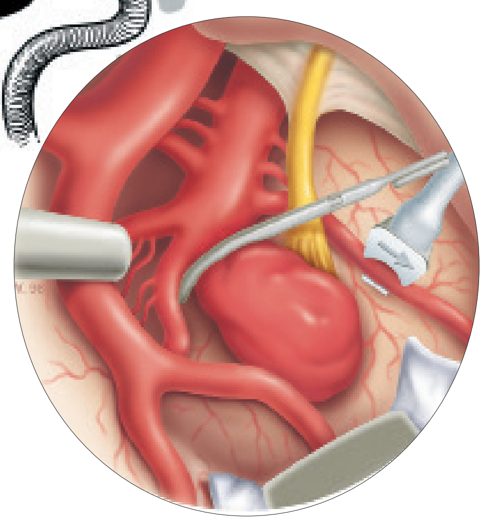
After basilar tip aneurysms, SCA aneurysms are the most common type of posterior circulation aneurysm.

Flow Measurement Sites (Fig. D51)

Aneurysm Site	Probe Placement	Size (mm)	Expected Flow (ml/min)
Superior Cerebellar A (SCA)	SCA (ipsilateral)	1.5	18-20
	PCA	2.0	26-30

Fig. D50: Site of superior cerebellar artery aneurysm in relationship to ICA trunk.





Superior Cerebellar Artery (SCA) Aneurysms

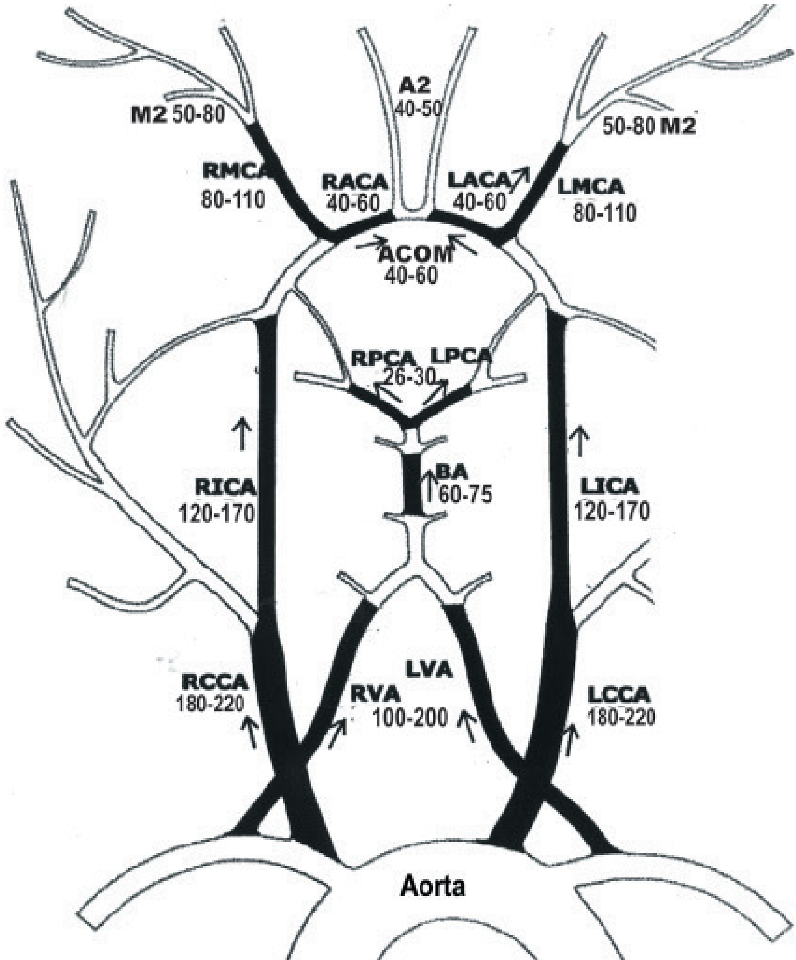
Fig. D51: Location of superior cerebellar artery aneurysms and sites • for flow measurements during aneurysm clipping surgery.

D5. Cerebral Flow Measurement Summary

Flow Summary after Aneurysm Clipping Surgery (ml/min)

Flow Measurement Summary			
Aneurysm Site	Probe Placement	Size (mm)	Expected Flows* (ml/min)
Carotid Ophthamic A (Opth)	M1	2.0	80-110 and/or
	A1	2.0	40-60
	ICA	3.0	120-170
Posterior Communicating A (PCom)	M1	2.0	80-110 and/or
	A1	2.0	40-60
	ICA	3.0	120-170
Anterior Choroidal A (ACh)	M1	2.0	80-110 and/or
	A1	2.0	40-60
	ICA	3.0	120-170
	AChA	1.5	20-60
Carotid Bifurcation (ICA)	M1	2.0	80-110 and/or
	A1	2.0	40-60
Anterior Communicating A (ACom)	A1 (ipsilateral)	2.0	40-60
	A1 (contralateral)	2.0	40-60
	A2 (both)	1.5	40-50
Middle Cerebral A (MCA)	M2 (outlet)	2.0	50-80
Post. Inferior Cerebellar A (PICA)	VA	3.0	100-200 and
	PICA	2.0	10-15
Superior Cerebellar A (SCA)	SCA (ipsilateral)	1.5	18-20 and
	PCA	2.0	26-30
Basilar Tip A (BA)	P2 (ipsilateral)	2.0	26-30 and
	SCA	1.5	18-20
	PCom (prelude to sacrifice)		
* Expected Flow rates courtesy of F.T. Charbel M.D., F.A.C.S			

Expected Volume Flow Rates after Aneurysm Clipping Surgery (ml/min)



Key:

RCCA, LCCA: right and left Common Carotid Artery;
RICA, LICA: right and left Internal Carotid Artery;
RMCA, LMCA: right and left Middle Cerebral Artery;
ACOM: Anterior Communicating Artery;
RACA, LACA: right and left Anterior Cerebral Artery;
RPCA, LPCA: right and left Posterior Cerebral Artery;
BA: Basilar Artery;
RVA, LVA: right and left Vertebral Artery

Intraoperative Measurement of Arterial Blood Flow Using a Transit Time Flowmeter: Monitoring of Hemodynamic Changes during Cerebrovascular Surgery

Nakyama N et al, Department of Neurosurgery, Hokkaido University, School of Medicine, Sapporo, Japan

Study Objective

The usefulness and reliability of transit-time ultrasound blood flow measurements during intracranial and carotid surgeries was examined in 25 patients.

- Aneurysm Clipping Surgery (n=4): M2 MCA blood flow was measured before and after clipping with 2 mm Flowprobe.
- EC-IC Bypass: superficial temporal artery (STA) - middle cerebral artery (MCA) (n=11); 4 IC occlusions; 7 moyamoya: Blood flow was measured in the STA before and after the STA-MCA anastomosis.
- Carotid Endarterectomy (n=8): Blood flow was measured in the cervical internal carotid artery (ICA) before and after endarterectomy with a 4 mm or 6 mm Flowprobe.
- Aneurysm Trapping Surgery (n=2) external carotid artery (ECA) - radial artery - (MCA) bypass for aneurysm trapping, where blood flow was monitored in the MCA and STA during radial artery grafting.

Results

- Aneurysm Clipping Surgery (n=4): In 2 cases a decrease in M2 flow after clipping triggered reclipping and a return of flow to baseline.
- STA-MCA Bypass (n=11): STA blood flow increased after anastomosis to the MCA. In 2 cases, post-bypass STA flow increased to > 50 ml/min and hyperfusion syndrome or intra-cerebral hemorrhage occurred after surgery.
- Carotid Endarterectomy: Blood flow increased considerably in one case (90-400ml/min) and hyperfusion developed after surgery. In one case in which ICA flow decreased (170-150 ml/min) ICA occlusion developed after surgery.

Conclusions

- Transit-time flow measurements are useful for surgical management during cerebrovascular surgery. The technique was simple to use and provided sensitive, stable, reliable results. The method revealed distal branch flow drop after aneurysm clipping, or residual flow during temporary clipping, and has the potential to predict post-operative complications in bypass or carotid endarterectomy surgeries.

Reference

Nakayama N, Kuroda S, Houkin K, Takikawa S, Abe H, “Intraoperative Measurement of Arterial Blood Flow Using a Transit Time Flowmeter: Monitoring of Hemodynamic Changes during Cerebrovascular Surgery,” Acta Neurochiurgica 2001; 143:17-24. (Transonic Reference # 1831AH)

Aneurysm Trapping

Temporary Trapping

Temporary occlusion or trapping of an aneurysm with temporary clips is a useful adjunct employed during aneurysm surgery.

Why Temporary Occlusion

- To soften the aneurysm, making the final micro-surgical dissection safer.
- Reduce the chance of intraoperative rupture of the aneurysm.

How Long Can One Safely Temporarily Occlude the Parent Vessel?

The usual interval is 2-15 minutes.

At Mass General Hospital Aneurysm/AVM Center, they extend the time of temporary occlusion up to 30 to 60 minutes by:

- Introducing mild hypothermia (32 - 34°C) to lower tissue metabolism;
- Introducing mannitol intravenously to improve cerebral blood flow;
- Induce hypertension using an intravenous pressor agent to improve collateral blood flow into the area of hypoperfused tissue.

Permanent Trapping

Proximal occlusion of the vessel after an extracranial - intracranial bypass (EC-IC) has been performed.

Introduction

An extracranial to intracranial (EC-IC) bypass is an operative strategy used to:

1) Preserve or replace flow in cerebral territories for treatment of complex aneurysms or tumors that require aneurysm trapping and sacrifice of a parent vessel (Flow Preservation/Replacement);
2) Augment cerebral flow in patients for treatment of cerebral ischemia in those patients with occlusive disease including moyamoya disease (Flow Augmentation).

A variety of extracranial vessels are used to construct an EC-IC bypass.

- Low Flow Bypass: This “workhorse” bypass uses a pedicle superficial temporal artery (STA) or occipital artery (OA) as a bypass to the middle cerebral artery (MCA).
- Medium Flow Bypass: the radial artery from the lower arm can be harvested to be a medium flow bypass. It connects proximally (in most cases) to the internal carotid artery (ICA) and distally to a cerebral vessel.
- High Flow Bypass: may use a harvested saphenous vein as a bypass around an internal carotid artery aneurysm.

1. Flow Measurement in Replacement EC-IC Bypass

When the location or complexity of an aneurysm necessitates its trapping prior to clipping to be followed by parent vessel sacrifice, Extracranial to Intracranial (EC-IC) Bypass provides a possible flow preservation/ replacement strategy.

Whether the conduit used for a bypass is the STA, OA, radial artery or saphenous vein, Transonic® F•A•S•T® measurements with the Charbel Flowprobe® can be valuable in assessing the patency of the bypass and the adequacy of flow during and after its construction.

1) Measurements confirm that the bypass is working before the surgeons leave the operating room.
2) If the bypass is not working, measurements prompt a timely revision of a non-functional bypass.
3) Measurements taken periodically during closure of the skin incision ensure that the graft has not kinked or twisted (see report on page 86).

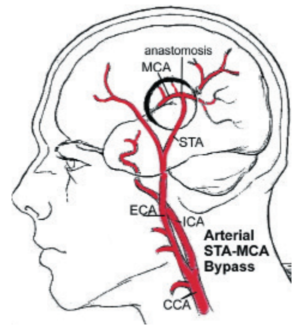


Fig.E1: Lateral view of a arterial EC-IC Bypass. Eight to ten centimeters of the superficial temporal artery (STA) is dissected and isolated from its surrounding tissue. A craniotomy is performed and a suitable recipient cortical MCA branch is identified preferably with a diameter of 1.5 mm or greater. The donor STA is then prepared and free flow through the cut end is measured by removing the temporary clip and measuring and document-ting flow with a Transonic® Charbel Micro-Flow Probe®. The anastomosis is completed and flow through the STA bypass is again measured and documented. Cut Flow Index (ratio of bypass flow to initial cut flow) is calculated to predict bypass function.

Arterial Bypass (STA, OA, Radial)

For an arterial bypass, baseline flows are first measured in the extracranial and intracranial vessels. After the extracranial donor artery is dissected free of its surrounding cuff of tissue and cut, free flow of the artery is measured as the cut distal end bleeds for 15-20 seconds (Fig. E2). This “free” flow or the amount of flow at zero resistance is the “carrying” capacity of the bypass, the maximum flow the artery can deliver.

Bypass Adequacy Strategy for Flow Replacement during Aneurysm Clipping

At a 2006 international conference in Taipai, Taiwan, Dr. Sepideh Amin-Hanjani introduced a new strategy to assess the adequacy of a superficial temporal artery (STA) or occipital artery (OA) bypass to replace flow when an aneurysm has to be trapped and a parent vessel sacrificed. The strategy first calls for flow in the artery or territory distal to the aneurysm to be measured and recorded. The vessel to be sacrificed is then temporarily occluded and flow is again measured in the distal artery or territory. The difference between the two flows represents the amount of flow deficit that can be expected if the parent vessel is sacrificed. This is the flow that the bypass will have to replace.

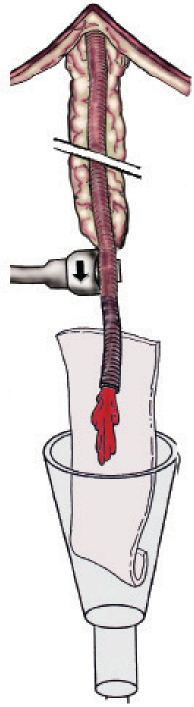


Fig. E2: Measurement of free “cut” flow of extracranial arterial bypass before anastomosis.

Fig. E3: Flow measurement of bypass after anastomosis to recipient artery.

The “free” or “Cut Flow” of the intended bypass is then measured. This Cut Flow value is compared to deficit flow. If the Cut Flow value equals or exceeds the potential flow deficit, the EC-IC bypass can be completed and the vessel sacrificed with reasonable assurance that the bypass flow will compensate for the flow deficit from the sacrificed parent vessel (see below).

Dr. Amin-Hanjani reports that this selective strategy allows the surgical team to:

- Access the adequacy of a bypass before completing its construction;
- Select the best match for a bypass;
- Evaluate the bypass immediately.

EC-IC Bypass ICA Aneurysm: Clipped, Trapped and ICA Sacrificed

Example: STA to M3 Bypass

- M1 baseline flow measured: 70 ml/min
- M1 flow measured with ICA temporarily occluded: 50 ml/min
- Anticipated Flow Deficit Calculated: 20 ml/min (if aneurysm trapped & parent vessel sacrificed)
- STA Cut Flow measured: 44 ml/min (Conclusion: STA bypass should be able to supply the flow deficit)
- STA Bypass to (MCA) M3 completed; aneurysm clipped and trapped
- STA Bypass Graft Flow measured: 24 ml/min (bypass good - bypass flow compensates for anticipated flow deficit)

Flow Measurement Steps: Arterial EC - IC Bypass

Extracranial Donor Artery

1) Choose the appropriate size Flowprobe and measure baseline flow in the extracranial donor artery. Record flow on the EC-IC Bypass Record (Fig. E8).

Probe Size	Nonrestrictive Vessel Range
3 mm	2.7 - 4.0 mm
4 mm	3.0 - 5.0 mm
6 mm	4.0 - 7.3 mm

2) After cutting the extracranial artery in preparation for the bypass, measure the free flow in the donor (Fig. E1) to determine the flow or "carrying" capacity of the bypass. Record flow on the EC-IC Bypass Record (Fig. E7).
3) After the bypass has been anastomosed to the recipient vessel, measure post-bypass flow in the donor (Fig. E3) and compare with free flow. Record flow on the EC-IC Bypass Record (Fig. E7).
4) If post-bypass flow in the donor artery is substantially less (CFI < 0.5) than free flow, reexamine the anastomosis and redo, if necessary.

Intracranial Recipient Artery

1) Choose an appropriate size Flowprobe for the intracranial recipient vessel (diameter $\geq$1.5 mm) and measure baseline flow. Record flow on the EC-IC Bypass Record (Fig. E7).
2) After the bypass has been anastomosed to the recipient vessel, measure flow in the recipient vessel and compare to pre-bypass (bypass) flow. Record flow on the EC-IC Bypass Record.
3) If post-bypass flow in the recipient artery is substantially less pre-bypass flow, reexamine the bypass and redo, if necessary.

References:

Amin-Hanjani, et al, "The Cut Flow Index: An Intraoperative Predictor of the Success of EC-IC Bypass for Occlusive Cerebrovascular Disease," Neurosurgery, January 2005.

Amin-Hanjani, S, "EC-IC Bypass for Aneurysm: Decision Making Using Intraoperative Flow Measurements," 8th International Conference on Cerebrovascular Surgery, Taipei, 2006.

Algorithm: Evaluating Adequacy of EC-IC Bypass for Aneurysm Clipping and Trapping Surgery

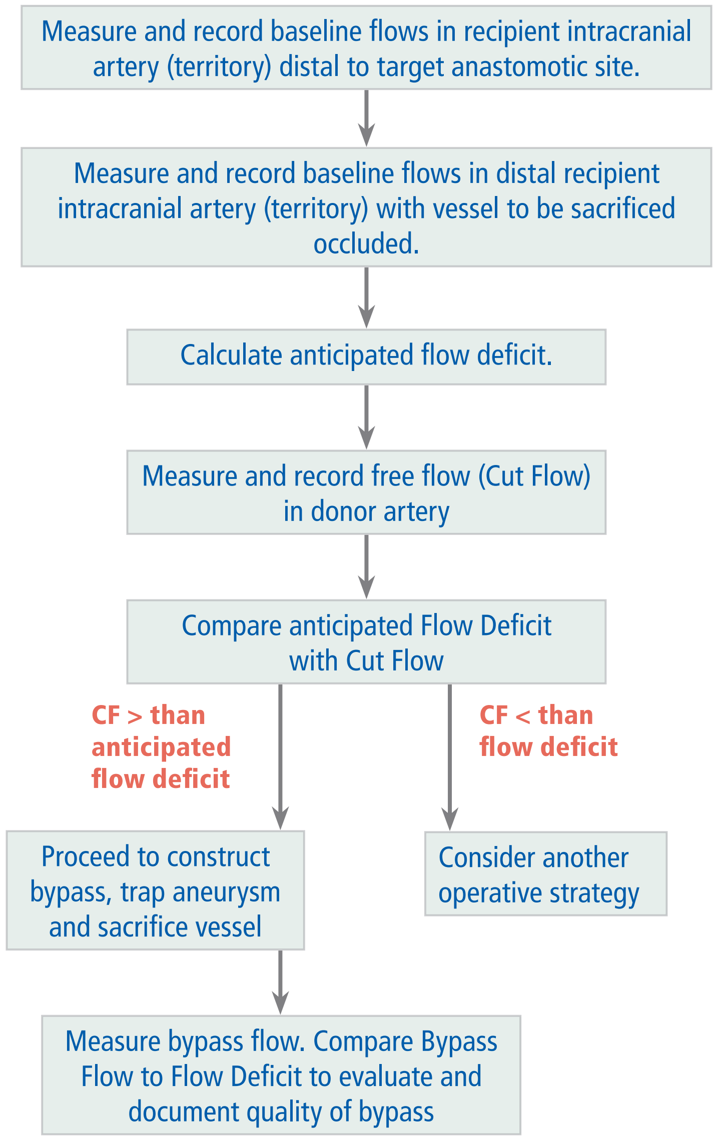


Fig. E4: Flow chart of EC-IC bypass evaluation algorithm.

E1b. EC-IC Bypass: Flow Replacement Surgery (Venous Bypass)

Venous EC - IC Bypass

When construction of an arterial graft is not possible due to atherosclerosis, twisting or a bad section of the artery, the surgeon may choose to harvest a vein graft to create an EC-IC Bypass (Fig. E5, E6).

After the vein is harvested, the proximal end of the vein graft is anastomosed to a carotid artery. One concern with this type of graft is that it will produce too much flow for the recipient vasculature. Free flow is therefore measured in the graft once it has been anastomosed to the carotid to determine the maximum flow capacity for the graft and to match the graft hemodynamically to its recipient arterial vasculature. Baseline flows are also measured in the intracranial recipient vessel before anastomosis.

After the bypass graft has been constructed, post-anastomotic flows are measured in the graft and recipient intracranial artery and compared with baseline flows.

As the surgery progresses, flow measurements provide quick and immediate feedback that aids the surgeon in defining specific hemodynamic parameters and formulating the surgical strategy for each case.

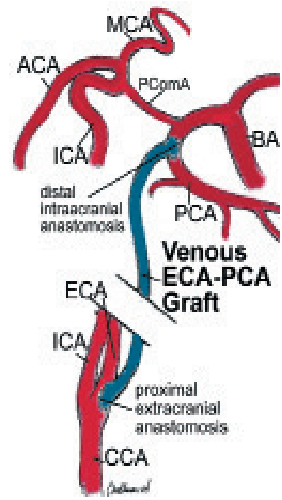


Fig. E5: Venous bypass from the external carotid artery (ECA) to the posterior cerebral artery (PCA).

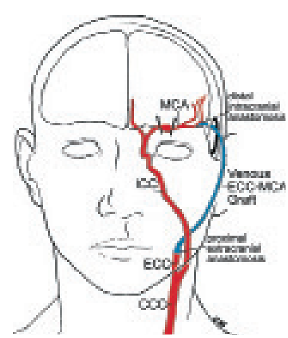


Fig. E6: Frontal view of a venous EC-IC Bypass. A venous graft is harvested and then anastomosed proximally to the External Carotid Artery (ECA) and distally to the Middle Cerebral Artery (MCA).

Flow Record
EC-IC Bypass

Patient Label (optional) or Name/Age/Sex

Date	Type of Bypass		Reason for Bypass		Surgeon
Extracranial Donor	**Probe Size**	**BP Mean**	**Pre-Bypass Flow** ml/min	**Post-Bypass Flow1** ml/min	**Post-Bypass Flow2** ml/min
Intracranial Recipient Artery	**Probe Size**	**BP Mean**	**Pre-Bypass Flow** ml/min	**Post-Bypass Flow1** ml/min	**Post-Bypass Flow2** ml/min

Fig. E7: Sample record for documenting flows during EC-IC bypass.

E1b. EC-IC Bypass: Flow Replacement Surgery (Venous Bypass) cont.

Excimer Laser Assisted Non-occlusive Anastomosis (ELANA) Technique

ELANA gives a cerebrovascular neurosurgeon the opportunity to create a high flow bypass without conventional anastomosis risks or time constraints. On vessels greater than 2.5 mm, it is used to make an end-to-side (T-shaped) anastomosis without temporary occlusion of the recipient artery.

Cerebral bypass surgery sometimes requires clipping an artery and temporarily stopping blood flow. However, for about 1,000 patients annually in the US, even a temporary cessation of blood flow would place them at high risk for stroke so the procedure is not considered safe.

To create a bypass with ELANA, the surgeon sutures a ring and a section of the replacement blood vessel onto the surface of the affected artery. Once attached, the surgeon tunnels the tip of a laser handpiece down the open end of the replacement blood vessel until the laser tip touches the ring.

The laser then cuts a circular hole in the artery. Suction removes the cut tissue. The process is repeated with a second replacement blood vessel. Once both replacement blood vessels are in place, the open ends of the two replacement vessels are sutured together to complete the bypass around the aneurysm or tumor.

For more information, see www.elana.com

Algorithm: Venous EC-IC Bypass Flow Measurement

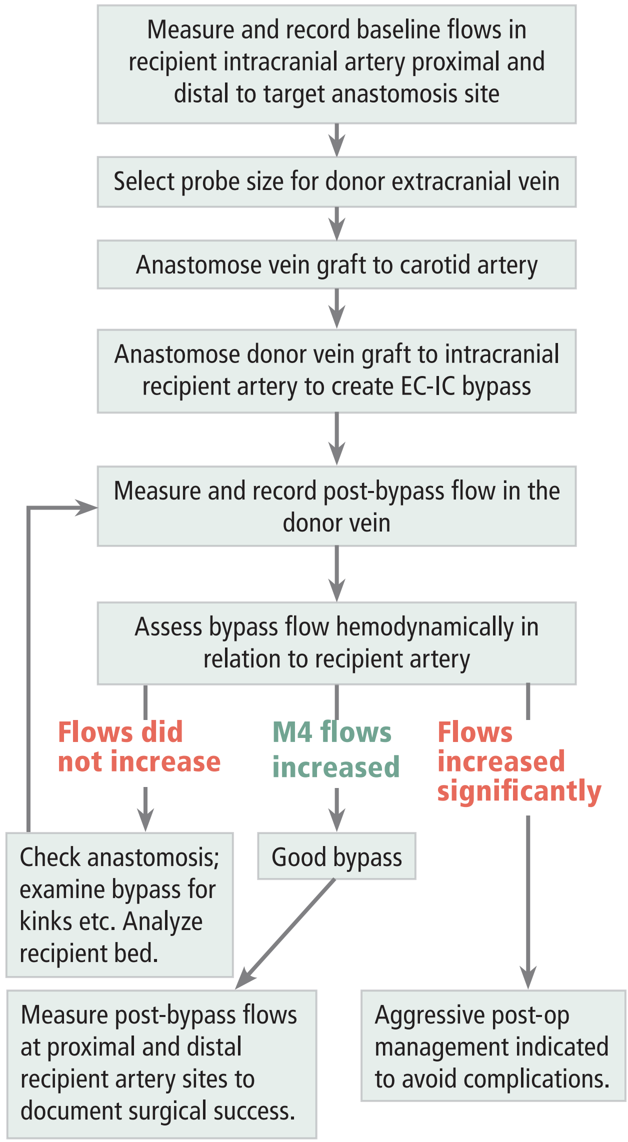


Fig. E8: Flow measurement algorithm for measuring flow during a venous EC-IC bypass.

Changes in Bypass Flow during Temporary Occlusion of Unused Branch of Superficial Temporal Artery

Dept. of Neurosurgery, Bucheon St. Mary's Hospital, The Catholic University of Korea College of Medicine, Bucheon, Korea

Study Objective

To investigate changes in bypass flow during temporary occlusion of superficial temporal artery (STA) branches that are sometimes ligated so are not used in standard STA-to-middle cerebral artery (MCA) bypass.

Method

Bypass blood flow was measured by a Charbel Flowprobe® before and after temporary occlusion of STA branches not used for a STA-MCA bypass.

- Measurements performed on 12 patients: 7 cases of atheroscherotic steno-occlusive disease; 5, Moyamoya
- Digital subtraction angiography used to observe post-operative changes in STA diameters;
- Distal MCA (to the anastomosis) and proximal (to the anastomosis) flows were measured and statistically analyzed (Fig. A).

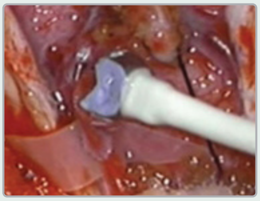


Fig. A: STA bypass flow measured following anastomosis to the MCA.

Results

- Initial STA flow ranged from 15 mL/min to 85 mL/min.
- Flow did not change significantly during occlusion as compared with pre-occlusion flow.
- Occlusion time was extended by 30 minutes in all cases, but this did not contribute to any significant flow change.

Conclusions

- STA bypass flow seems to be influenced, not by donor vessel status, but by recipient vessel demand.
- Ligation of the unused STA branch after completion of anastomosis does not contribute to improvement in bypass flow immediately after surgery, and carries some risk of skin necrosis.
- The authors suggest that unused branches of the STA be left intact for potential use in secondary operation and to prevent donor vessel occlusion.

Reference

Kim JY, Jo, KY, Kim YW, Kim SR, Park, IS, Baik, MW, "Changes in Bypass Flow during Temporary Occlusion of Unused Branch of Superficial Temporal Artery," J Korean Neurosurg Soc 48: 105-108, 2010. (Transonic Reference: # 8006AH)

Flow Measurement in EC-IC Bypass

When cerebrovascular occlusive disease limits blood flow to cerebral vessels, EC-IC Bypass can be selected as a flow augmentation strategy to treat anterior or posterior circulation ischemia. Transonic® F•A•S•T® measurements help predict postoperative bypass patency. Measurements taken periodically during closure of the skin incision also ensure that the graft has not kinked or twisted.

Cut Flow Index (CFI)

Drs. Amin-Hanjani and Charbel from the University of Illinois at Chicago, reported the results of 51 surgical EC-IC revascularization cases over a five-year period in which a Cut Flow Index (CFI) was calculated. The CFI either predicted high rates of postoperative bypass patency or alerted surgeons to potential difficulty with the donor vessel, the anastomosis or the recipient vessel.

Calculating CFI

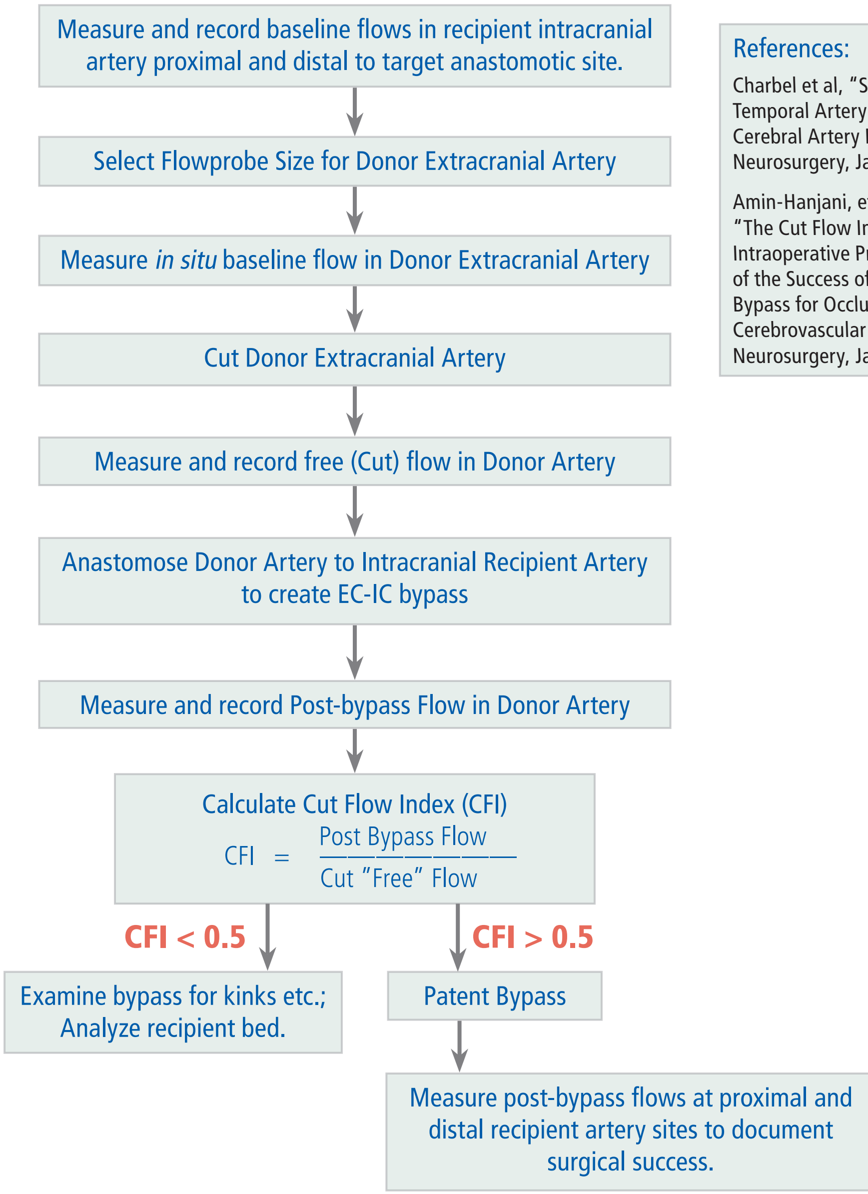
With a superficial temporal artery or occipital artery bypass, baseline flows are first measured in the extracranial donor artery. Flow is then measured on the intracranial recipient artery. When the extracranial donor artery is dissected free of its surrounding cuff of tissue and cut, free flow of the artery is measured as the cut distal end freely bleeds for 15-20 seconds (Fig. E1). This free flow is the amount of flow at zero resistance or the "carrying" capacity of the bypass, the maximum flow the artery can deliver. After performing the bypass, post-anastomotic flows are measured (Fig. E2) and Cut Flow Index (CFI) is calculated.

$$\text{Cut Flow Index (CFI)} = \frac{\text{Bypass Flow}}{\text{Cut ``Free'' Flow}}$$

CFI of > 0.5 was shown to be a sensitive predictor of postoperative bypass patency. If the CFI is < 0.5 with no clinical justification such as a poor quality recipient vessel, the surgeon should reexamine the bypass for technical problems, and revise if necessary. Moreover, a CFI close to 1.0 is physiologic confirmation of impaired cerebrovascular reserve in the recipient bed confirming the need for flow augmentation through EC-IC bypass revascualarization.

E2a. EC-IC Bypass: Flow Augmentation Surgery (Cut Flow Index) cont.

Algorithm: Flow Measurement during Arterial EC-IC Bypass



References:

Charbel et al, "Superficial Temporal Artery - Middle Cerebral Artery Bypass," Neurosurgery, January 2005.

Amin-Hanjani, et al, "The Cut Flow Index: An Intraoperative Predictor of the Success of EC-IC Bypass for Occlusive Cerebrovascular Disease," Neurosurgery, January 2005.

Fig. E9: Algorithm for Flow Augmentation EC-IC bypass using the Cut Flow Index.

E2a. EC-IC Bypass: Flow Augmentation Surgery (Cut Flow Index) cont.

Case Summary: Superficial Temporal Artery (STA) — Middle Cerebral Artery (MCA) Bypass

In-Situ STA Flow

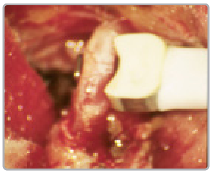


Fig. E10: In-situ STA flow measured.

STA Free Flow

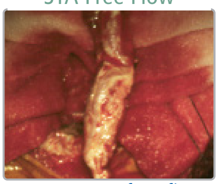


Fig. E11: STA free flow measured.

Recipient Baseline Flow

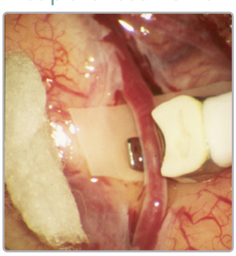


Fig. E12: Baseline flow is checked in the recipient cortical branch vessel.

STA Post-Bypass Flow

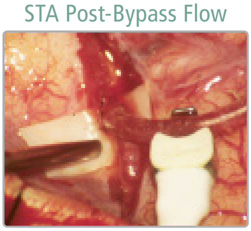
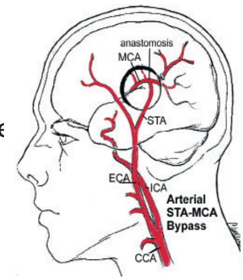


Fig. E13: STA bypass flow is checked after completion of bypass and Cut Flow Index is calculated.

Introduction



A patient with cerebrovascular occlusive disease underwent surgery to construct an EC-IC bypass from the superficial temporal artery (STA) to a cortical branch of the middle cerebral artery (MCA).

Transonic® intraoperative flow measurements were used to assess the patency and adequacy of the bypass. Key measurements were the free flow in the STA to assess the maximum capacity of the bypass and the post-anastomotic flow in the bypass. When the Cut Flow Index is greater than 0.5 there is high predictability of postoperative bypass patency.

In Situ STA Flow measured 5 ml/min (Fig. E10)

STA Free Flow measured 68 ml/min (Fig. E11)

Recipient Baseline Flow:

Flow was measured in the MCA recipient vessel before doing the bypass (Fig. E12).

STA Post-Bypass Flow

- STA post-bypass flow was 75 ml/min, slightly higher than the free flow due to reperfusion hyperemia.
- Cut Flow Index was 1.1 indicating a well functional bypass.

STA Flow Summary (ml/min)				
Vessel	In-Situ Flow	Free "Cut" Flow	Post Bypass Flow	Cut Flow Index
STA	15	68	75	1.1

F•A•S•T® Detects Anastomotic Embolus that Jeopardizes Successful EC-IC Bypass Surgery

Case study courtesy of: F.T. Charbel, M.D., F.A.C.S.

Introduction: EC-IC Bypass Surgery

A surgical team headed by Dr. Sepideh Hanjani undertook extracranial to intracranial (EC-IC) bypass surgery to construct a bypass from the superficial temporal artery (STA) to the middle cerebral artery (MCA).

Cut Flow Measured

Per their standard algorithm, they measured the Cut Flow of the intended bypass conduit, the STA, with a Charbel Flowprobe®. STA Cut Flow measured 82 ml/min indicating that the STA had good carrying capacity for a bypass.

Bypass Flow Measured

After the bypass was completed, STA bypass flow was measured. It measured 80 ml/min and the surgeons were pleased with an excellent Cut Flow Index of 0.98. After repeated measurements and stable flows, wound closure commenced.

Last Flow Check before Wound Closure

Just before placing the last few skin stitches, the surgeon again rechecked bypass flow. To the surgical team's surprise, bypass flow had dropped to less than 20 ml/min.

Embolus Removed/Flow Measured/Flow Restored

The wound was reopened and the surgeon discovered an embolus at the site of the anastomosis. The embolus had presumably formed in the STA during the surgery and had dislodged after removal of the muscle retractors and had traveled to the anastomotic site. The microscope was quickly returned into the field and Dr. Hanjani made a small cut in the recipient artery at a branching site distal to the anastomosis. The incision allowed the thrombus to escape. Subsequent intraoperative flow measurements corroborated restoration of flow in the bypass to the pre-embolus level.

STA Bypass Flow Summary (ml/min)		
STA	In-Situ Flow	Cut Flow Index
Free Flow	82	
Bypass	80	0.98
Bypass at wound closure	20	
Bypass after embolus release	80	

Introduction

Surgical creation of an arterial extracranial to intracranial (EC-IC) bypass is used to augment cerebral blood flow and mitigate symptoms of moyamoya disease.

During EC-IC bypass surgery, the Charbel Micro-Flow Probe® is used to measure direct volume blood flow in the STA bypass and target M4/MCA vessels. Intraoperative blood flow measurements confirm the quality of the anastomosis and assure that the target area is receiving blood from the bypass. Measurements also prompt revision if a technical error is suspected.

Flow Measurement Steps

Measure mean arterial pressure (MAP), end-tidal CO_2 and temperature and record values on the EC-IC Bypass Flow Record (E16, page 90).

Pre-anastomosis: Intracranial Recipient Artery

1) Measure the diameter of the intracranial recipient arteries and choose appropriately-sized Charbel Micro-Flowprobes to measure recipient

Probe Size	Vessel Range, Outer Diameter
1.5 mm	1.1 - 1.6 mm
2 mm	1.6 - 2.4 mm
3 mm	2.6 - 3.8 mm

2) Measure recipient vessels (M4 branches/MCA) flow.
3) Record flow rates and flow direction on the EC-IC Bypass Record (E16, page 90).

Extracranial Donor Artery

4) Dissect the extracranial STA artery free and clear a site of any fat for application of the Flowprobe.
5) Measure the diameter of the extracranial donor artery (STA) and choose the appropriate-sized Flowprobe to measure STA baseline flow.

Flow Revascularization for Moyamoya Angiopathy cont.

Probe Size	Vessel Range, Outer Diameter
1.5 mm	1.1 - 1.6 mm
2 mm	1.6 - 2.4 mm
3 mm	2.6 - 3.8 mm
4 mm	3.0 - 5.0 mm
6 mm	4.0 - 7.3 mm

Post-anastomosis Flow Measurements

6) After construction of a one donor artery (STA) to two recipient arteries (M4 branches/ MCA) with a side-to-side and an end-to-side anastomoses (1D2R) bypass[1,2], measure post-anastomotic flows in the intracranial and extracranial arteries sequentially in the following order:
    1) distal M4 branch/MCA;
    2) proximal M4 branch/MCA;
    3) distal STA;
    4) proximal STA.

7. If post-bypass flow in the recipient arteries (sum of absolute values of distal and proximal M4/MCA recipient flows) is not significantly above the pre-bypass flow, re-examine the anastomoses and the bypass for kinks or twists and redo, if necessary. Apply a vasodilator (papaverine) when there is vasospasm due to manipulation of the vessel and/or if flow measurements seem to be low or absent.

8. Record flow rates and flow directions, MAP, end-tidal CO_2, and occlusion time on the EC-IC Bypass

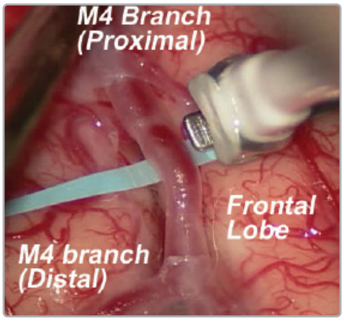


Fig. E14: This photo shows the M4/MCA site just before the Flowprobe is slipped around the vessel to measure baseline M4 flow before anastomosing the bypass to the vessel. The high- visibility background (blue) is placed to help the anastomosis and guide the Probe around the vessel.

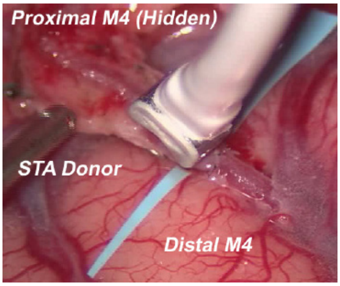


Fig. E14: Measuring blood flow in recipient M4/MCA artery after anastomosis to STA bypass.

E2b. EC-IC Bypass: Flow Augmentation Surgery (Moyamoya Revascularization) cont.

References:

Khan NR, Morcos JJ *et al*, One-donor, two-recipient extracranial-intracranial bypass series for moyamoya and cerebral occlusive disease: rationale, clinical and angiographic outcomes, and intraoperative blood flow analysis. J Neurosurg. 2021 Aug 20:1-10. (Transonic Reference # NS2021-30AH)

Arnone GD, Hage ZA, Charbel FT. Single Vessel Double Anastomosis for Flow Augmentation - A Novel Technique for Direct Extracranial to Intracranial Bypass Surgery. Oper Neurosurg (Hagerstown). 2019 Oct 1;17(4):365-375. (Transonic Reference # NS2019-30AH)

Lee M, Steinberg GK *et al*, "Intraoperative blood flow analysis of direct revascular-ization procedures in patients with moyamoya disease. J Cereb Blood Flow Metab. 2011; 31(1): 262-74.

Lee M *et al*, "Quantitative hemodynamic studies in moyamoya disease: a review." Neurosurg Focus; 26(4): E5

Guzman R et al, "Clinical outcome after 450 revascular-ization procedures for moyamoya disease." J Neurosurg. 2009; 111(5): 927-3.

Golby, AJ et al, "Direct and Combined Revascularization in Pediatric Moyamoya Disease," 1999; 45: 50-60.

Zipfel, GJ, et al, "Moyamoya Disease in Adults: The Role of Cerebral Revascularization." Skull Base, 2005, 1:27-41.

http://www.webmd.com/hw/health guide atoz/nord617.asp

http://www.childrenshospital.org/clinicalservices/Site2156/mainpageS2156P0.html,

Algorithm: Flow Measurement: EC-IC Bypass Revascularization for Moyamoya Disease

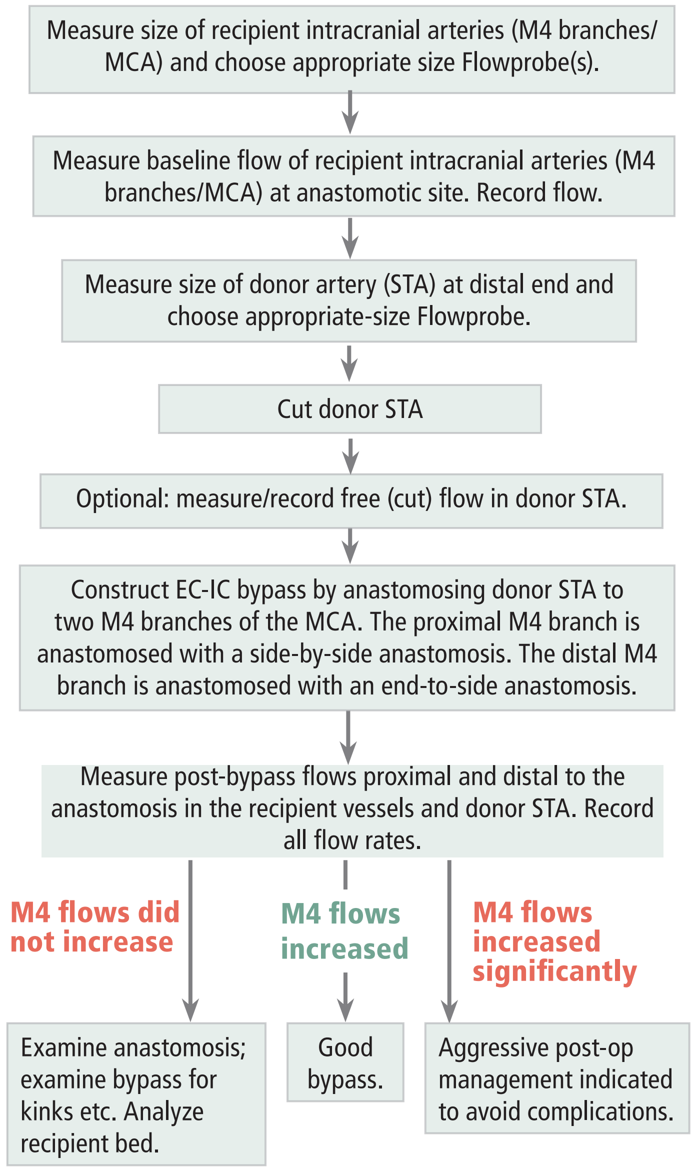


Fig. E16: Moyamoya EC-IC bypass algorithm.

Patient ID

STA-MCA Bypass Flow Record for Moyamoya Disease

Date: _______ Right ____ Left ____ Direct ____ Indirect ____

STA (mm) _____ M4 branch1 ____ M4 branch 2 ____ Temp: (°C) _____

Pre-anastomosis:

Vessel	Volume Flow (mm)		MAP	End Tidal CO2
M4/MCA branch 1, 2				
Cut STA				
Other				

Post-anastomosis:

Vessel	Volume Flow (mm)		MAP	End Tidal CO2
Distal M4/MCA				
Proximal M4/MCA				
Distal STA				
Proximal STA				

Total Occlusion Time: _______

Comments

Samples Collected:
Serum _______
CSF _______
STA _______
MCA _______

Database entered: _______

F. F•A•S•T during Arteriovenous Malformation (AVM) Resection

Transit-time ultrasound flow measurements guide cerebrovascular surgical strategies including AVM microsurgical resection/obliteration.

Measurements Steps:

Pre-resection:

1. Identify Vessels to be Measured
   Expose and identify the AVM's afferent and venous outflow vessels.
2. Select Flowprobe Size
   Measure the vessel's diameter with a gauge before opening the Flowprobe package. Select a Flowprobe size so that the vessel will fill between 75% - 100% of the ultrasonic sensing window of the Flowprobe.
3. Apply Flowprobe
   Determine the optimal position for applying the Probe on the vessel by selecting a site wide enough to accommodate the Flowprobe's acoustic reflector without compromising perforating arteries. Apply the Flowprobe so that the entire vessel lies within the ultrasonic sensing window of the Flowprobe and aligns with the Probe body (Fig. 1).

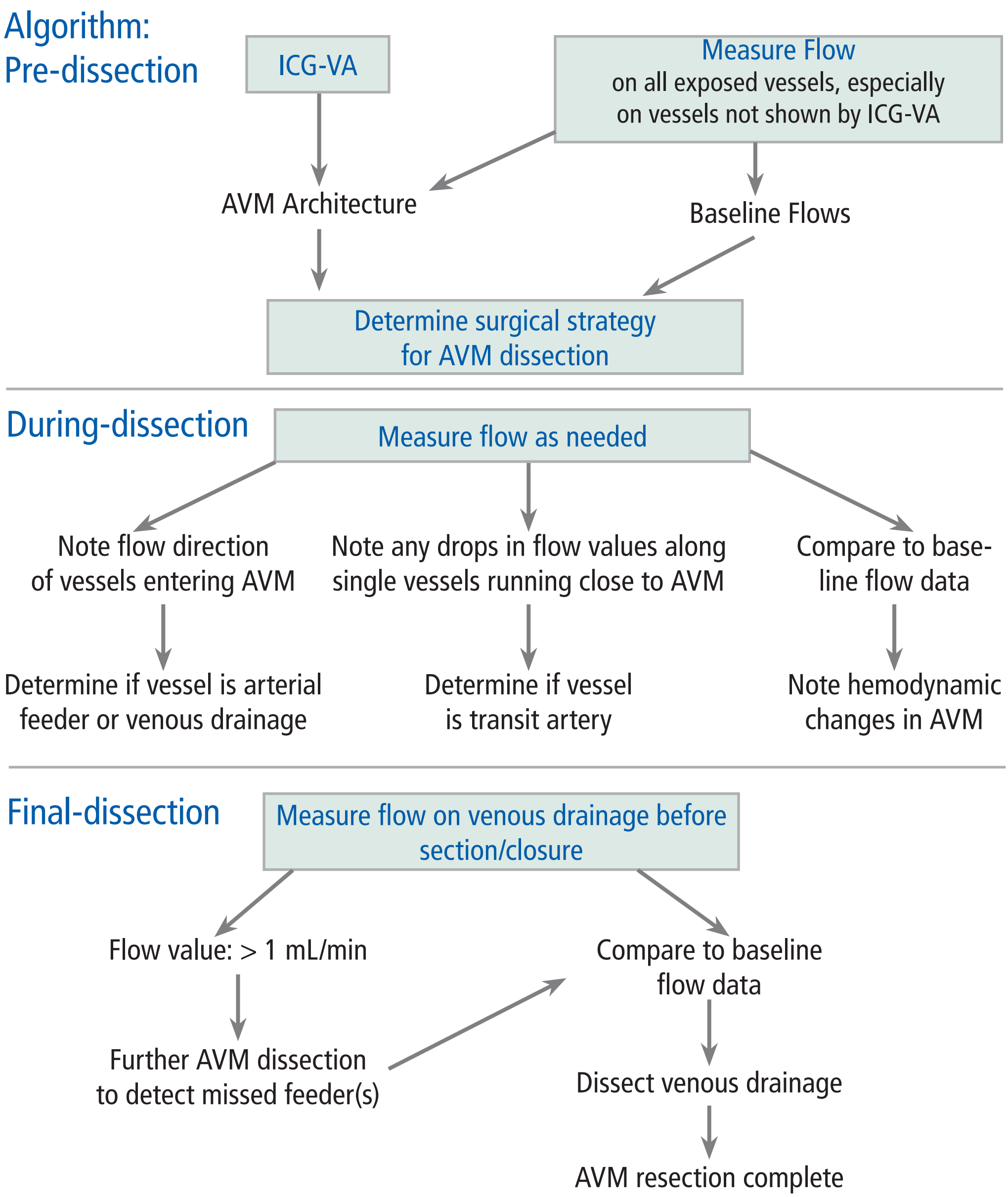
   

   Fig. 1:

   Bend the Probe's flexible neck segment as needed to apply the Flowprobe. Listen to FlowSound®. The higher the pitch, the greater the flow.

   Sterile saline or cerebrospinal fluid may be used to flood the Flowprobe's lumen and provide ultrasound coupling. Do not irrigate continuously because the Flowprobe will also measure saline flow. The Signal Quality Indicator on the Flowmeter or Monitor indicates acoustic contact. If acoustic contact falls below an acceptable value, an acoustic error message will be displayed.
4. Measure Baseline Flows before Resection
   Before AVM resection, and following burst suppression, measure baseline flows in all afferent, transient and venous vessels. Record the baseline flow measurements and the patient's blood pressure on a Flow Record.
5. Measure Flows during and Post Resection
   During resection, measure flows as needed in each of the vessels. In possible transient arteries measure at different sites along the vessel. A drop in flow between two points on the vessel might identify an additional feeder into the AVM. Compare flows with baseline flows to guide the surgical procedure. Measure flows post resection to ensure total obliteration of the AVM.
6. Document Flows
   To document flow values, wait 10-15 seconds after applying the Flowprobe for mean readings to stabilize. If the Flowmeter displays a negative flow, press the INVERT button to change the polarity before printing the waveform.

F. F•A•S•T AVM Resection cont.



1 Modified from Fig. 3, page 273 of Della Puppa A, Rustemi O, Scienza R, "Intraoperative Flow Measurement by Microflow Probe During Surgery for Brain Arteriovenous Malformations," Neurosurg 2015; Jun;11 Suppl 2:268-73. (Transonic Reference # 10288AH) (Transonic Reference # 10288AH)

Why shouldn't I just continue using my pen-tip Doppler to assess flow preservation during aneurysm clipping surgery?

The Doppler Probe measures velocity, not flow. When a pen-tip Doppler is placed against the wall of a vessel exposed during surgery, it registers how fast blood is moving, not how much blood is moving. Doppler readings are unreliable because high velocities can occur despite low flows. A Doppler measurement cannot distinguish between normal diameter flows and a Grade IV stenosis (Fig. F1). Doppler will identify Grade V (occlusive or near-occlusive) stenoses, and residual flow within an aneurysm if clip placement is incomplete. However, Doppler does not quantify flow so it is impossible to compare pre- and post-clip flow values to determine if flow has been compromised.

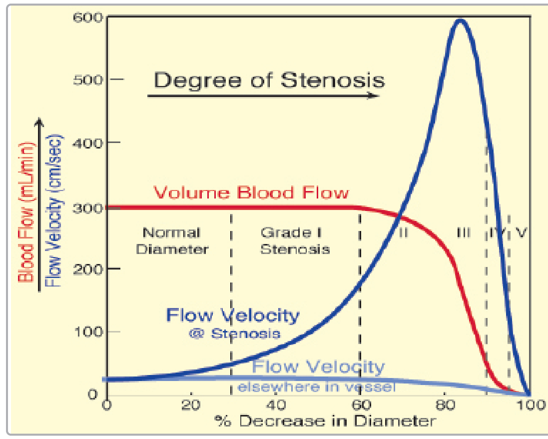


Fig. F1: Graph that demonstrates that volume flow will decrease during a Grade II & III stenosis (75% occlusion), as flow velocity first spikes before dropping during a Graft IV stenosis (90% occlusion). (Adapted from Spencer P, Reid, J.M., "Quantification of Carotid Stenosis with Continuous-Wave (C-W) Doppler Ultrasound," Stroke 1979; 10(3) 326-330.)

When do I take flow measurements?

Baseline flows are measured in the parent vessel and distal branches after surgical exposure, but before clipping the aneurysm. In this way, the patient serves as his or her own control. Flows are measured again after aneurysm clipping. The surgeon compares pre- and post-clip values to confirm that flow has not been compromised. Post-clip flows in the parent vessel and distal branches should be comparable to or greater than baseline flows. If there has been temporary occlusion of the vessel, there can be higher flows after clipping due to hyperemia. A reduction in flow >50% prompts the surgeon to reposition the clip. Flows should be measured after burst suppression is administered for brain protection, since these protective agents will decrease flow.

G. Frequently Asked Questions (FAQs) cont.

Time is of the essence. How long do Transonic® flow measurements take?

No other flow technology provides intraoperative measurements as quickly. Measurements are instantaneous once the Flowprobe is applied to the vessel. With FlowSound®, an audible indication of volume flow, the surgeon never has to take his or her eyes away from the operating field. After a couple of seconds for flows to stabilize, flow can then be documented. The strength of transit time technology is its accuracy and this immediacy of measurement. Surgeons can know flow instantaneously without disrupting the course of the surgery and can then incorporate flow data into their surgical strategy.

Do I have to put the Probe behind the vessel? What about perforators?

Yes, it is necessary to position the Flowprobe around the vessel so that the vessel lies fully in the lumen of the Probe and is aligned as shown in Fig. F2. Measurement accuracy depends on accurate alignment of the reflector to the Probe body. To free up room to position the Flowprobe, the surgeon must meticulously dissect around the Probe's target area and feel for perforators in order to select a location where the Probe reflector will fit between the perforators. It is useful to first practice using the Flowprobe on the larger more accessible vessels where it is easier to apply the Flowprobe. Then, as one becomes more familiar and comfortable with the Flowprobe, start applying the Probe to smaller vessels. ICG angiography is helpful in visualizing perforators.

Fig. F2. Alignment of vessel within flowprobe lumen.

Does the Flowprobe measure direction of flow?

Yes, the Flowprobes measure the amount and the direction of flow. An arrow on the side of the Probe, easily seen under the microscope, indicates positive direction of flow (Fig. F2). The Flowmeter displays flow running in the opposite direction through the Probe with a minus sign (if the Meter's "Invert" button is not engaged.)

What exactly does transit-time ultrasound flowmetry measure?

Using wide-beam ultrasonic illumination, transit-time ultrasound measures pulsatile and average flow directly. One ultrasonic beam undergoes a phase shift in transit time proportional to the average velocity of the liquid times the path length over which this velocity is encountered. With wide-beam ultrasonic illumination (Fig. F3), the receiving transducer sums (integrates) these velocity - chord products over the vessel's full width and yields volume flow: average velocity times the vessel's cross sectional area. Since the transit time is sampled at all points across the vessel diameter, volume flow measurement is independent of the flow velocity profile. Ultrasonic beams which cross the acoustic window without intersecting the vessel do not contribute to the volume flow integral. Volume flow is therefore sensed by perivascular Probes even when the vessel is smaller than the acoustic window.

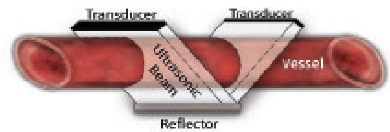


Fig. F3. The vessel is placed within a beam that fully and evenly illuminates the entire blood vessel. The transit time of the wide beam then becomes a function of the volume flow intersecting the beam, independent of vessel dimensions.[1]

Why do I sometimes see a reading on the Flowmeter when the Flowprobe is not on a vessel?

Charbel Micro-Flow Probes® operate at a relatively high frequency and the distances between the transducers and the reflector are very short. As a result, these Probes (particularly the 1.5 mm) are susceptible to acoustical reverberations. This means that if the Probe has been immersed in saline and then pulled out into the air, a minute drop of saline might still be clinging to the Probe and it may pick up enough signal to show up as a reading when the Probe is not on the vessel. This is simply an artifact and should be ignored. Acoustical reverberations do not occur when the Probe is on the vessel, because the lumen of the Probe is filled and there are no large air pockets.

Don't some surgeons still rely on palpation to indicate flow?

Each surgeon has a choice of technologies for intraoperative assessment of blood flow and vascular stenosis. Every technology can be useful for optimizing surgical outcomes in certain circumstances, and each has distinct advantages as well as disadvantages. "Pulse," while the least expensive, is the most suspect. When there is a partial occlusion, the proximal pulse will increase and the distal pulse will decrease.

Do I have to use ultrasound gel to get a signal?

Neurosurgeons generally do not use ultrasound gel inside the brain cavity. There is usually enough cerebrospinal fluid or saline already in the operative field to obtain good acoustic contact between the vessel and Probe. The lighted bucket display on the Flowmeter's front panel indicates the quality of the ultrasound signal. If necessary, the surgeon may add a little more saline to get good

[1] Drost, C.J., "Vessel Diameter-Independent Volume Flow Measurements Using Ultrasound," Proceedings San Diego Biomedical Symposium, 1978; 17: 299-302. U.S. PATENT 4,227,407, 1980.

contact. If the surgeon is measuring flow in an EC-IC bypass, gel can be used on the extracranial segment.

I'm concerned about vasospasm. Will using the Flowprobe cause vasospasm?

The Charbel Micro-Flow Probe® is designed with an open lumen so that the Flowprobe will not constrict the vessel during measurement and contribute to vasospasm. Administration of papaverin is also advised to avoid vasospasm.

EC-IC Bypass has been controversial. Why should I be performing EC-IC Bypass and using flow measurements during aneurysm surgery?

Indications for EC-IC bypass fall into two major categories based on the purpose for the bypass. They are:

- Flow Replacement for treatment of complex aneurysms or tumors which require vessel sacrifice.
- Flow Augmentation for treatment of cerebral ischemia in those patients demonstrating misery perfusion.

The first flow-based category of EC-IC bypass is Flow Replacement EC-IC Bypass. This bypass strategy is used to preserve flow in a vessel that is at risk of being compromised, typically during complex aneurysm or tumor surgery. No controversy exists here. Expertise with performing EC-IC Bypass with FAST (Flow-assisted Surgical Technique) is essential now that aneurysms that are referred to surgery are ever more complex and challenging and are more likely to need some sort of flow preservation procedure. Charbel et al[2] have delineated the technical nuances important during surgical creation of a Superficial Temporary Artery - Middle Cerebral Artery Bypass (STA-MCA) bypass.

The second, Flow Augmentation Bypass, is used to correct ischemia caused by cerebrovascular occlusive disease. The popularity of this type of EC-IC bypass declined after a 1985 randomized study failed to demonstrate concrete benefits resulting from EC-IC bypass. Subsequent studies indicated significant shortcomings in the methodology of the study and suggested that EC-IC bypass still had flow augmentation value. Recently, Amin-Hanjani et al[1] has authored a retrospective study evaluating the use of intraoperative blood flow measurements in predicting graft success in 51 patients after EC-IC bypass for cerebrovascular occlusive disease. In all cases, "Cut Flow" (free flow from the cut end of the donor vessel) was measured intraoperatively with the Transonic® Flowprobe. A "Cut Flow Index" (cut flow divided by bypass flow) was derived, and correlated with bypass patency, postoperative bypass flow, and cerebrovascular reserve to test the clinical outcome. The study's conclusion was that a poor Cut Flow Index (CFI) can alert surgeons intraoperatively to potential difficulties with the donor vessel, the anastomosis, or the recipient vessel. Also, a CFI near 1.0 provides physiologic confirmation of impaired cerebrovascular reserve in the recipient bed.

Isn't intraoperative angiography still considered the Gold Standard for intraoperative assessment of blood flow during cerebral aneurysm surgery?

Yes, intraoperative angiography is the gold standard. However, it not universally available, is cumbersome, time consuming and disrupts the flow of surgery. If the angiogram shows little or no flow in the vessel, the surgeon has to make a correction and then wait another 30 minutes or so to see the results. The brain can only survive without blood flow for approximately 11-15 minutes before an irreversible ischemic deficit occurs. In the absence of sufficient collateral flow, patients with compromised cerebral vessels will suffer an intraoperative stroke. Angiography does, however, present a visual image of a region of the circulatory system and is invaluable during pre-operative diagnosis and post-operative confirmation of aneurysm obliteration and flow preservation.

Can I use ICG (indocyanine green) angiography to measure flow?

Yes, ICG angiography is complementary to the transit-time ultrasound volume flow measurement. Along with the Flowprobe which measures single vessel volume flow, ICG is excellent for visualizing small vessels and perforators, particularly for complex aneurysms that require multiple clips.

What percentage of aneurysms are coiled versus surgically clipped?

Nationwide, approximately 70% endovascularly coiled and 30% surgically clipped. Coiling is minimally invasive to the patient, but more invasive to the cerebral vessels.

How much does the equipment cost to measure flow?

This question can best be answered by its counter opposite, "How much does it cost not to measure flow?" This "cost" must consider: a patient's hardship if a preventable intraoperative stroke occurs; the cost of longer hospital stays, more post-surgical tests and possibly reoperation; and the cost of a long and slow recovery after a stroke. While it is impossible to place a cost figure on all these savings, and of the peace of mind that a surgeon receives by using the flow-assisted aneurysm surgery approach, the cost of a single preventable intraoperative stroke far exceeds the cost of Transonic® system for flow assisted aneurysm surgery.

H. Cerebrovascular Surgery References

Publications

Amin-Hanjani S, "Cerebral revascularization: extracranial-intracranial bypass," J Neurosurg Sci. 2011; 55(2): 107-16. (Transonic Reference # 9554)

Lee M, Guzman R, Bell-Stephens T, Steinberg GK, "Intraoperative blood flow analysis of direct revascularization procedures in patients with moyamoya disease," J Cereb Blood Flow Metab 2011; 31(1): 262-74. Epub 2010 Jun 30. (Transonic Reference # 7969AH)

Amin-Hanjani S, Alaraj A, Charbel FT, "Flow replacement bypass for aneurysms: decision-making using intraoperative blood flow measurements," Acta Neurochir (Wien). 2010; 152(6): 1021-32; discussion 1032. (Transonic Reference # 7940AH)

Kim JY, Jo, KY, Kim YW, Kim SR, Park, IS, Baik, MW, "Changes in Bypass Flow during Temporary Occlusion of Unused Branch of Superficial Temporal Artery," J Korean Neurosurg Soc 2010; 48: 105-108. (Transonic Reference # 8006AH)

Scienza R, Pavesti G, Pasqualin A, Benericetti E, Boccaletti R, Pinn GP, Profeta G, Sanatoro A, "Flow-assisted Aneurysm Clipping. A Cooperative Study," The Proceedings of the 12th European Congress of Neurosurgery (EANS) 2003; 309-314. (Transonic Reference # 2909AH)

Della Puppa A, Volpin F, Gioffre G, Rustemi O, Troncon I, Scienza R, "Microsurgical clipping of intracranial aneurysms assisted by green indocyanine videoangiography (ICGV) and ultrasonic perivascular microflow probe measurement," Clin Neurol Neurosurg. 2014 Jan;116:35-40. (Transonic Reference # 10080AH)

Della Puppa A, Rustemi O, Scienza R, "Intraoperative Flow Measurement by Microflow Probe During Surgery for Brain Arteriovenous Malformations," Neurosurg 2015; Jun;11 Suppl 2:268-73. (Transonic Reference # 10288AH)

Kirk HJ, Rao PJ, Seow J, Fuller N, Chandran N, Khurana VG, "Intra-operative transit time flowmetry reduces the risk of ischemic neurological deficits in neurosurgery?" British J Neurosurg 2009; 23(1): 40-47. (Transonic Reference # 7744AH)

Durand A, Penchet G, Thines L,"Intraoperative monitoring by imaging and electrophysiological techniques during giant intracranial aneurysm surgery," Neurochirurgie. 2016; 62(1): 14-9. (Transonic Reference # 11175AH)

Rustemi O, Amin-Hanjani S, Shakur SF, Du X, Charbel, FT,"Donor Selection in Flow Replacement Bypass Surgery for Cerebral Aneurysms: Quantitative Analysis of Long-term Native Donor Flow Sufficiency," Neurosurgery 2016; 78 (3): 332-342. (Transonic Reference # 11178AH)

Thines L, Durand A, Penchet G, Proust F, Lenci H, Debailleul A, Lejeune JP, Pelissou-Guyotat I,"Microsurgical neurovascular anastomosis: the example of superficial temporal artery to middle cerebral artery bypass. Technical principles," Neurochirurgie. 2014; 60(4): 158-64. (Transonic Reference # 11176AH)

Hage ZA, Charbel FT "Clipping of a ruptured anterior communicating artery aneurysm with right A1-A2 sectioning and reanastomosis," Neurosurg Focus. 2015 Jul;39 Video Suppl 1:V10. (Transonic Reference # 11095AH)

Della Puppa A, Rustemi O, Scienza R, "Intraoperative Flow Measurement by Microflow Probe During Spinal Dural Arteriovenous Fistula Surgery.," World Neurosurg. 2016; 89: 413-9. (Transonic Reference # 10793AH)

Hage ZA, Behbahani M, Amin-Hanjani S, Charbel FT, "Carotid bypass for carotid occlusion," UCurr Atheroscler Rep. 2015 Jul;17(7):517. (Transonic Reference # 10328AH)

Hage ZA, Charbel FT, "Clipping of bilateral MCA aneurysms and a coiled ACOM aneurysm through a modified lateral supraorbital craniotomy," Neurosurg Focus. 2015 Jan;38(VideoSuppl1):Video19. (Transonic Reference # 10329AH)

Rayan TS, Amin-Hanjani, "Suture retraction technique to prevent parent vessel obstruction following aneurysm tandem clipping," J Neurosurg. 2015 Feb 27:1-3. (Transonic Reference # 10244AH)

Amin-Hanjani S, Goodin S, Charbel FT, Alaraj A, "Resolution of bilateral moyamoya associated collateral vessel aneurysms: Rationale for endovascular versus surgical intervention," Surg Neurol Int. 2014 19;5(Suppl 4):S155-60.

Lehecka M, Dashti R, Laakso A, van Popta JS, Romani R, Navratil O, Kivipelto L, Kivisaari R, Foroughi M, Kokuzawa J, Lehto H, Niemelä M, Rinne J, Ronkainen A, Koivisto T, Jääskelainen JE, Hernesniemi J, "Microneurosurgical management of anterior choroid artery aneurysms," World Neurosurg 2010; 73(5): 486-99. (Transonic Reference # 8013AH)

Carter BS, Farrell C, Owen C, "Microsurgical clip obliteration of middle cerebral aneurysm using intraoperative flow assessment," J Vis Exp. 2009 Sep

25;(31). pii: 1294. (Transonic Reference # 7850AH)

Amin-Hanjani S, "Diagnosis and neurosurgical treatment of intracranial vascular occlusive syndromes." Curr Treat Options Cardiovasc Med 2009; 11(3): 212-20. (Transonic Reference # 7821AH)

Charbel FT, Alaraj A, Amin-Hanjani S, "Advanced Strategies and Techniques for Surgical Aneurysm Treatment," 8th International Conference on Cerebrovascular Surgery, Taipai, Taiwan 2006. Medimond S.r.l. GY30R9093.

Guzman R, Steinberg GK, "Direct bypass techniques for the treatment of pediatric moyamoya disease," Neurosurg Clin N Am. 2010; 21(3): 565-73. (Transonic Reference # 8010AH)

Lee M, Zaharchuk G, Guzman R, Achrol A, Bell-Stephens T, Steinberg GK, "Quantitative hemodynamic studies in moyamoya disease: a review," Neurosurg Focus. 2009 Apr; 26(4): E5. (Transonic Reference # 7762AH)

Hayden MG, Lee M, Guzman R, Steinberg GK, "The evolution of cerebral revascularization surgery." Neurosurg Focus. 2009; 26(5): E17.(Transonic Reference # 7780AHR)

Amin-Hanjani S, Charbel FT, "Is extracranial-intracranial bypass surgery effective in certain patients?" Neurosurg Clin N Am. 2008; 19(3): 477-87. (Transonic Reference # 7703AH)

Ashley WW, Amin-Hanjani S, Alaraj A, Shin JH, Charbel FT, "Flow-assisted surgical cerebral revascularization." Neurosurg Focus 2008; 24(2): E20. (Transonic Reference # 7587AH)

Alaraj A, Ashley WW Jr, Charbel FT, Amin-Hanjani S, "The superficial temporal artery trunk as a donor vessel in cerebral revascularization: benefits and pitfalls," Neurosurg Focus 2008; 24(2):E7. (Transonic Reference # 7587AH)

Amin-Hanjani S, Charbel FT, "Flow-assisted surgical technique in cerebrovascular surgery," Surg Neurol 2007; 68: Suppl 1:S4-11. (Transonic Reference # 7560AHR)

Charbel FT, Alaraj A, Amin-Hanjani S, "Surgical Treatment of Intracranial Atherosclerosis: Update on the State of the Art," 8th International Conference on Cerebrovascular Surgery, Taipai, Taiwan 2006. Medimond S.r.l. GY30R9093.

Amin-Hanjani S, , Charbel FT, "Is extracranial-intracranial bypass surgery effective in certain patients?" Neurol Clin 2006; 24(4): 729-43. (Transonic Reference # 9555AH)

Charbel FT, Meglio G, Amin-Hanjani S, "Superficial Temporal Artery - Middle Cerebral Artery Bypass," Neurosurgery 2005; 56:186-90. (Transonic Reference # 2921AH)

Charbel FT, Hoffman WE, Misra M, Ostergren L, "Ultrasonic Perivascular Flow Probe: Technique and Application in Neurosurgery." Neurosurg Res 1998; 20: 439-442. (Transonic Reference # 1151AH)

Amin-Hanjani S, Du X, Milnarevich N, Meglio G, Zhao M, Charbel FT, "The Cut Flow Index: An Intraoperative Predictor of the Success of EC-IC Bypass for Occlusive Cerebrovascular Disease," Neurosurgery 2005; 56: 75-85. (Transonic Reference # 2922AH)

Amin-Hanjani S, Meglio G, Gatto R, Bauer BS, Charbel FT, "The Utility of Intraoperative Blood Flow Measurements in Aneurysm Surgery Using an Ultrasonic Perivascular Flow Probe," Neurosurgery 2006; 58: 305-12; republished in Neurosurgery 2008; 62(6 Suppl 3): 1346-53. (Transonic Reference # 7226AH)

Calderon-Arnulphi M, Amin-Hanjani S, Alaraj A, Zhao M, Du X, Ruland S, Zhou XJ, Thulborn KR, Charbel FT, "In vivo evaluation of quantitative MR angiography in a canine carotid artery stenosis model,"AJNR Am J Neuroradiol. 2011, Sep;32(8):1552-9. (Transonic Reference # 9591A

Fagundes-Pereyra WJ, Hoffman WE, Misra M., Charbel FT, "Clip readjustment in aneurysm surgery after flow evaluation using the ultrasonic perivascular Probe: case report," Arq Neuropsiquiatr. 2005; 63(2A): 339-44. (Transonic Reference # 7010AH)

Wanebo JE, Amin-Hanjani S, Boyd C, Peery T, "Assessing Success after Cerebral Revascularization for Ischemia," Skull Base 15(3): 215-27, 2005. (Transonic Reference # 7225AH)

Nakayama N, Kuroda S, Houkin K, Takikawa S. Abe H, "Intraop-erative Measurement of Arterial Blood Flow Using a Transit Time Flowmeter: Monitoring of Hemodynamic Changes during Cerebrovascular Surgery." Acta Neurochir 2001; 143(1): 7-24. (Transonic Reference # 1831AH)

Charbel FT, Guppy KH, Zhao M, Clark ME, "Computerized Hemodynamic Evaluation of the Cerebral Circulation for Bypass." Neurosurgical Clinical N Am 2001;12(3): 499-508, viii. (Transonic Reference # 2819AH)

Charbel FT, Hoffman WE, Misra M, Hannigan K, Ausman JI, "Role of Perivascular Ultrasonic Micro-flow Probe in Aneurysm Surgery," Neurol Med Chir (Tokyo) 1998; 38: Suppl35-38. (Transonic Reference # 1674AH)

Charbel FT, Gonzales-Portillo G, Hoffman WE, Cochran E, "Distal Internal Carotid Artery Pseudo-aneurysms: Technique and Pitfalls of Surgical Management: Two Technical Case Reports," Neurosurg 1998; 45(3): 643-648. (Transonic Reference # 1274AH)

Della Puppa A, Rustemi O, Scienza R, "Intraoperative Flow Measurement by Microflow Probe During Spinal Dural Arteriovenous Fistula (SDAVF) Surgery," World Neurosurgery. (Transonic Reference # 10795AH)

Langer DJ, Vajkoczy P, "ELANA: Excimer Laser-Assisted Nonocclusive Anastomosis for Extracranial-to-Intracranial and Intracranial-to-Intracranial Bypass: A Review," Skull Base 2005; 15(3): 191-205. (Transonic Reference # 7241AH)

Streefkerk HJ, Wolfs JF, Sorteberg W, Sorteberg AG, Tulleken CA, "The ELANA technique: constructing a high flow bypass using a non-occlusive anastomosis on the ICA and a conventional anastomosis on the SCA in the treatment of a fusiform giant basilar trunk aneurysm," Acta Neurochir (Wien). 2004; 146(9): 1009-19. (Transonic Reference # 3024AH)

Tulleken CA, Streefkerk HJ, van der Zwan A, "Construction of a new posterior communicating artery in a patient with poor posterior fossa circulation: technical case report," Neurosurgery. 2002; 50(2): 415-9; discussion 419-20. (Transonic Reference # 3026AH)

Streefkerk HJ, Van der Zwan A, Verdaasdonk RM, Beck HJ, Tulleken CA,"Cerebral revascularization," Adv Tech Stand Neurosurg. 2003; 28: 145-225. (Transonic Reference # 3027AH)

Tulleken CA, van der Zwan A, Kappelle LJ. "High-flow transcranial bypass for prevention of brain ischemia." Ned Tijdschr Geneeskd. 1999 Nov 6;143(45):2281-5. (Transonic Reference # 3028AH)

Streefkerk HJ, Kleinveld S, Koedam EL, Bulder MM, Meelduk HD, Verdaasdonk RM, Beck RJ, van der Zwan B, Tulleken CA, "Long-term reendothelialization of excimer laser-assisted nonocclu-sive anastomoses compared with conventionally sutured anastomoses in pigs." J Neurosurg 2005; 103(2): 328-36. (Transonic Reference # 7051A)

van Doormaal TP, van der Zwan A, Verweij BH, Han KS, Langer DJ, Tulleken CA, "Treatment of giant middle cerebral artery aneurysms with a flow replacement bypass using the excimer laser-assisted nonocclusive anastomosis technique." Neurosurgery 2008; 63(1):12-20. (Transonic Reference # 7787AH)

van Doormaal TP, van der Zwan A, Verweij BH, Langer DJ, Tulleken CA, "Treatment of giant and large internal carotid artery aneurysms with a high-flow replacement bypass using the excimer laser- assisted nonocclusive anastomosis technique." Neurosurgery 2006; 59(4 Suppl 2):ONS328-34; 2008;62(6 Suppl 3):1411-8. (Transonic Reference # 7786AH)

Friedman JA, Anderson RE, Meyer FB, "Techniques of Intraoperative Cerebral Blood Flow Measurement," Neurosurg Focus 2000; 9(5). (Transonic Reference # 2684AH)

Hoffman WE, Charbel FT., Ausman JI, "Cerebral Blood Flow and Metabolic Response to Etomidate and Ischemia," Neurosurg Res 1997; 19: 41-44.(Transonic Reference # 1673AH)

Hoffman WE, Charbel FT, Abood C, Ausman JI, "Regional Ischemia during Cerebral Bypass Surgery," Surg Neurol 1997; 47(5): 455-459.

Leobowitz R, So HM, Marcellus ML, Chang SD, Marks MP, "Parent Vessel Occlusion for Vertebrobasilar Fusiform and Dissecting Aneurysms." Am J Neuroradi 2003; 24(5): 902-907.

Tulleken, CA, van der Zan A, Van Rooij WJ. Ramos LM, "High-flow Bypass Using Nonocclusive Excimer Laser-assisted End-to-side Anastomosis of the External Carotid Artery to the P1 Segment of the Posterior Cerebral Artery Via the Sylvian Route. Technical Note." J Neurosurg 1998; 88(5): 925-927. (Transonic Reference # 1025AH)

Tulleken CA, van der Zwan A, Kappelle LJ, "High-flow Transcranial Bypass for Prevention of Brain Ischemia," Ned Tijdschr Geneeskd. 1999; 143(45): 2281-5.

van der Zwan A, Tulleken CA, Hillen B, "Flow Quantification of the Non-occlusive Excimer Laser-assisted EC-IC Bypass." Acta Neurochir (Wein) 2001; 43(7): 647-54. (Transonic Reference # 2042AH)

Charbel FT, Maksoud YA, Corsten L, Du X, Zhao M, Guppy K, Ausman J, "Breakthrough Hemorrhage after EC-IC Bypass Surgery: Risk Factors and Avoidance Strategy," AANS/CNS 2001, Oral Scientific Presentation #69. (1775AH) during Cerebrovascular Surgery," Acta Neurochir 2001; 143(1): 7-24. (Transonic Reference # 1831AH)

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