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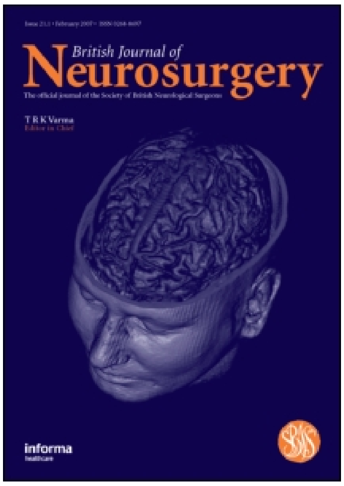

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Intra-operative transit time flowmetry reduces the risk of ischemic neurological deficits in neurosurgery

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ORIGINAL ARTICLE

Intra-operative transit time flowmetry reduces the risk of ischemic neurological deficits in neurosurgery

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Abstract

Intra-operative transit time flowmetry (ITTF) can be used to quantify blood flow in local at risk vessels before and after surgical intervention. As inadvertent vessel compromise represents a major cause of neurological deficit following neurovascular surgery, the purpose of this study was to assess this technology in terms of its indications, ease of implementation and interpretation, safety and reliability. Patients were prospectively invited to participate. ITTF was recorded from at-risk vessels before and after surgical intervention, along with blood pressure and $PaCO_2$. Any episodes of flow compromise or change in surgical procedure were noted and correlated with post-operative neurological deficits and imaging. Twenty-eight patients undergoing 30 craniotomies were enrolled. Operations included $n = 21$ aneurysm clipping or exploration, 2 AVM excision, 2 dural AV fistula disconnections, 2 EC-IC bypass and 3 tumor resections. ITTF led to an alteration in surgery in 8 of the 30 cases (27%). In patients undergoing aneurysmal surgery, inadvertent vessel occlusion was identified in 3 cases, which led to immediate repositioning of the aneurysm clips. In 2 AV fistulae and 2 AVM surgeries, markedly reduced draining vein flow rates were confirmed quantitatively immediately before final surgical disconnection was carried out. In 1 EC-IC bypass patient, the measurement suggested graft vasospasm then treated with papaverine. One aneurysm person awoke with a stroke presumably from an embolic event undetected by ultrasonography. ITTF provides immediate feedback regarding vessel patency. Clip-related arterial compromise and local vasospasm are detected by this technology, but an embolic event may escape detection. This technology was found to have a broad utility in intra-cranial surgery, and was safe, rapidly performed, easy to interpret and generally reliable.

Key words: *Flowmetry, ultrasound, aneurysm, arteriovenous malformation, fistula, bypass.*

Introduction

Post-operative neurological deficits secondary to cerebral infarction can occur as a result of inadvertent vessel compromise during intra-cranial surgery.[1–4] However, intra-operative visual inspection of susceptible vessels, even using the operating microscope, may not detect such compromise.[4–6] Several methods exist to monitor vascular structures and resultant potential ischemia such as intra-operative catheter angiography,[7,8] indocyanine green videoangiography,[9–11] somatosensory evoked potentials,[5,12,13] motor evoked potentials[5,12] and intra-operative Doppler ultrasonography.[2–4,6,14,15] Another technique with recently demonstrated neurosurgical utility is intra-operative transit time flowmetry (ITTF), which can be used to quantify blood flow in local at-risk vessels before and after surgical intervention. Previous studies have used ITTF in aneurysmal surgery, cranial bypass surgery and carotid endarterectomy.[16,17–19] The aim of this study was to assess ITTF technology in terms of its ease of implementation and interpretation, utility, safety and reliability across a wide range of neurosurgical practice. To the knowledge of the authors, this article contains the first reported flowmetry data from intra-cranial arteriovenous malformations and fistulae.

Material and methods

From April 2007 to July 2008, 28 patients undergoing 30 craniotomies involving potential risk to local vascular structures were prospectively invited to participate in this study. All patients gave written informed consent for the use of the flowmetry probe (Transonic Systems Inc., Ithaca, NY). As this technology had not been used in Australian neurosurgery before, approval was sought and obtained by the senior author (V.G.K.) from the Therapeutic Goods Administration (TGA) of the Australian Government (Special Access Scheme No: 459/2007; approved March 13, 2007).

There were 17 females and 11 males; the mean age was 53 years (range, 33–77 years). Operations (*n*)

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included: 21 aneurysm clipping or exploration; 2 arteriovenous malformation (AVM) excision; 2 dural AV fistula (DAVF) disconnection; 2 extra-cranial–intra-cranial (EC-IC) radial artery bypass and 3 tumor resection (Table I). Twenty-two cases were elective and 8 were performed emergently. General anesthesia was obtained by means of monitored ventilation with propofol, remifentanil and muscle relaxant. All patients received cefazolin immediately before skin incision and dexamethasone and mannitol as required.

Intra-operative transit time flow measurements were performed using a 1.5, 2.0 or 4.0 mm tip Charbel Micro-Flow probe® (HQN 1.5MB, HQN 2MB, HQN 4MB, respectively) connected to the Transonic® Flowmeter (HT331-series). The 1.5 and 2.0 mm tip flow probes were typically used for vessels in or near the circle of Willis, whereas the 2.0 and 4.0 mm tip flow probes were typically used for draining veins of certain AVM or DAVF. After simple connection and calibration of the probe as per the manufacturer's instructions, recordings were made from at-risk vessels gently but completely immersed in topically irrigated Ringer's solution, before and after surgical intervention (Fig. 1). Systemic blood pressure and $PaCO_2$ levels were recorded at those times. Any episodes of flow compromise, clip repositioning or change in intra-operative management were noted and correlated with post-operative neurological deficits and relevant imaging.

Results

Alterations in intra-operative management attributable to ITTF

Intra-operative transit time flowmetry led to an alteration in the intra-operative management in 8 of the 30 cases (27%; Table I). In patients undergoing aneurysmal surgery (Fig. 1), inadvertent vessel occlusion was identified quantitatively via ITTF in 3 of 21 (14%) cases, which led to immediate repositioning of the aneurysm clip(s). Before ITTF detection of compromised flow, the surgeon was satisfied with clip positioning. None of these patients experienced infarcts in the territory of the compromised vessels and all awoke without any new neurological deficit. In DAVF (Fig. 2) and AVM (Fig. 3) surgery, markedly reduced draining vein flow rates were confirmed in all 4 (100%) cases, providing the quantitative reassurance required by the surgeon that the operative goal had been achieved. All four lesions were confirmed to be excised or disconnected via post-operative CT angiography or catheter angiography, with no post-operative neurological deficit. ITTF confirmed antegrade radial artery graft flow in both EC-IC bypass surgeries (100%), but also detected compromised graft flow from vasospasm in 1 of the 2 EC-IC bypasses. The compromise was satisfactorily treated with topical papaverine without post-operative neurological deficit or perioperative graft failure.

Implementation and utility of ITTF

ITTF measurements were completed quickly and for the most part easily, adding about 10–15 minutes to the total operative time. Flow measurements themselves took on average 1–2 minutes each, whereas approximately 5–10 minutes of extra microdissection time was required during the case before the first flow measurement to facilitate adequate positioning of the tip of the flow probe around the blood vessel of interest. In 4 of 30 (13%) cases, the flow probe tip was found to be physically too large or too locally invasive to safely record a measurement at the desired time in the particularly narrow (e.g. crani #1 and 19 in Table I) or subarachnoid hematoma-filled (e.g. crani #15 and 16 in Table I) operative corridor. In such instances, the measurement was deferred to later in the case following further microdissection whenever possible. Matching the appropriate flow probe size to the vessel diameter is imperative. For circle of Willis region vessels, a flow probe tip of 1.5 or 2.0 mm was found to be appropriate. For draining veins of DAVF or AVM, a flow probe tip of 2.0 or 4.0 mm was found to be appropriate. Avoidance of constriction of the vessel lumen by the flow probe tip was advised by the manufacturer. During measurements of flow, the flow probe tip was required to be immersed in Ringer's solution while in gentle (non-compressive) contact with the vessel wall at all three probe-contact points (inner part of lateral walls and base) to obtain an accurate reading (Figs. 1–3).

We were able to readily utilise the flow probe across a wide spectrum of intra-cranial cases including aneurysms, AVM and DAVF, EC-IC bypass and in certain brain tumors closely associated with blood vessels.

Complications of ITTF

There was no morbidity or mortality associated with the use of the flow probe. Specifically, there was no vascular avulsion or inadvertent tissue trauma associated with its positioning and use. Careful perivascular microdissection before probe positioning was carried out to avoid such complications.

Reliability of ITTF

ITTF was found to be a reliable predictor of immediate post-operative radiological and clinical outcome in 29 of 30 (97%) cases. The single exception was a 76-year-old woman (crani #2 in Table I) who presented electively for clip reconstruction of an unruptured giant right internal carotid aneurysm. She was noted intra-operatively to have heavily calcified vessels, and despite successful direct

Table I. Clinical and flowmetry data for 28 patients undergoing 30 craniotomies

				Pre-			Post-			After adjustment/treatment		
Crani #	Age/sex	Diagnosis	Vessel	$PaCO_2$	BP (mmHg)	Flow (ml/min)	$PaCO_2$	BP (mmHg)	Flow (ml/min)	$PaCO_2$	BP (mmHg)	Flow (ml/min)
1	61F	Basilar tip unruptured aneurysm	P2	–	–	–	38	136/78	18			
2	76F	R ICA unruptured aneurysm	M1	39	94/48	25	39	96/50	25			
			A1	39	94/48	25	39	96/50	25			
3	59M	L A2/A3 ruptured aneurysm	A3	32	98/44	18	32	78/41	23			
4	45M	R MCA unruptured aneurysm	M2	34	90/53	35	34	91/54	30			
5	45M	L MCA unruptured aneurysm	M2	34	100/57	16	34	102/57	15			
6	42M	L temporoparietal astrocytoma	M3	41	135/72	40	42	130/70	30			
7[a]	38M	R frontal unruptured AVM	DV	29	98/57	35	32	93/55	4			
8	42F	L ICA unruptured aneurysms	ICA	27	88/35	60	27	90/43	57			
9	42F	R ICA unruptured aneurysm	ICA	33	86/50	45	33	105/60	46			
10	58F	R PICA unruptured aneurysm	PICA	33	90/50	22	33	86/47	23			
11[a]	63F	R MCA unruptured aneurysm	M2	35	102/59	27	35	102/56	14	35	102/56	27
12	45F	R MCA unruptured aneurysm	M2	31	83/40	13	31	84/41	14			
13	47F	R MCA unrupured aneurysm	M2	33	95/55	16	33	92/54	24			
14[a]	66F	L MCA unruptured aneurysm	M2	34	83/36	9	33	82/35	0	33	82/35	18
		AcommA ruptured aneurysm	A2	34	83/36	9	34	86/36	15			
15	56F	R PcommA ruptured aneurysm	M1	–	–	–	38	118/58	38			
16	50F	Basilar tip ruptured aneurysm	P1	–	–	–	30	82/42	15			
17[a]	77M	Ethmoidal unruptured DAVF	DV	30	100/52	21	30	100/50	0			
18	44F	Clival meningioma	M1	31	95/55	39	29	126/72	53			
19	48F	Tuberculum sellae meningioma	A1	–	–	–	32	89/59	30			
20	59M	AcommA unruptured aneurysm	A1	30	130/54	16	30	140/67	27			
21	54M	Basilar tip ruptured aneurysm	ICA	30	100/60	29	30	130/70	46			
22[a]	64F	Parafalcine ruptured DAVF	DV	30	120/50	27	30	122/54	2			
23[a]	38F	R ICA occlusion	RA	32	125/65	28	–	–	–	32	118/60	60
24	44F	R MCA unruptured aneurysm	M3	32	120/64	18	32	108/59	15			
25	33F	R ICA unruptured aneurysm	ICA	31	95/53	70	31	95/51	67			
26	44M	R ICA unruptured aneurysm	M1	32	110/60	53	32	106/61	52			
27	77M	R ICA occlusion	RA	–	–	–	39	160/84	86			
28[a]	64F	A2/A3 unrupt. aneurysm	A3	data sheet misplaced; operation report states 30–40% reduction in A3 flow post-clipping, corrected after clip adjustment								
29	48M	R PICA ruptured aneurysm	PICA	32	122/63	6	32	115/60	6			
30[a]	51M	R parietal ruptured AVM	M4 (FA)	33	90/50	115	34	98/55	0			
			DV	34	93/54	54	34	98/55	4			

M = male; F = female; R = right; L = left; A or ACA = anterior cerebral artery; ACommA = anterior communicating artery aneurysm; AVM = arteriovenous malformation; DAVF = dural arteriovenous fistula; DV = draining vein; FA = feeding artery; ICA = internal carotid artery; M or MCA = middle cerebral artery; P = posterior cerebral artery; PcommA = posterior communicating artery; PICA = posterior inferior cerebellar artery; RA = radial artery.

Crani #4 and 5 represent the same patient and crani #8 and 9 represent the same patient.

[a] Flowmetry helpful in altering management during craniotomy.

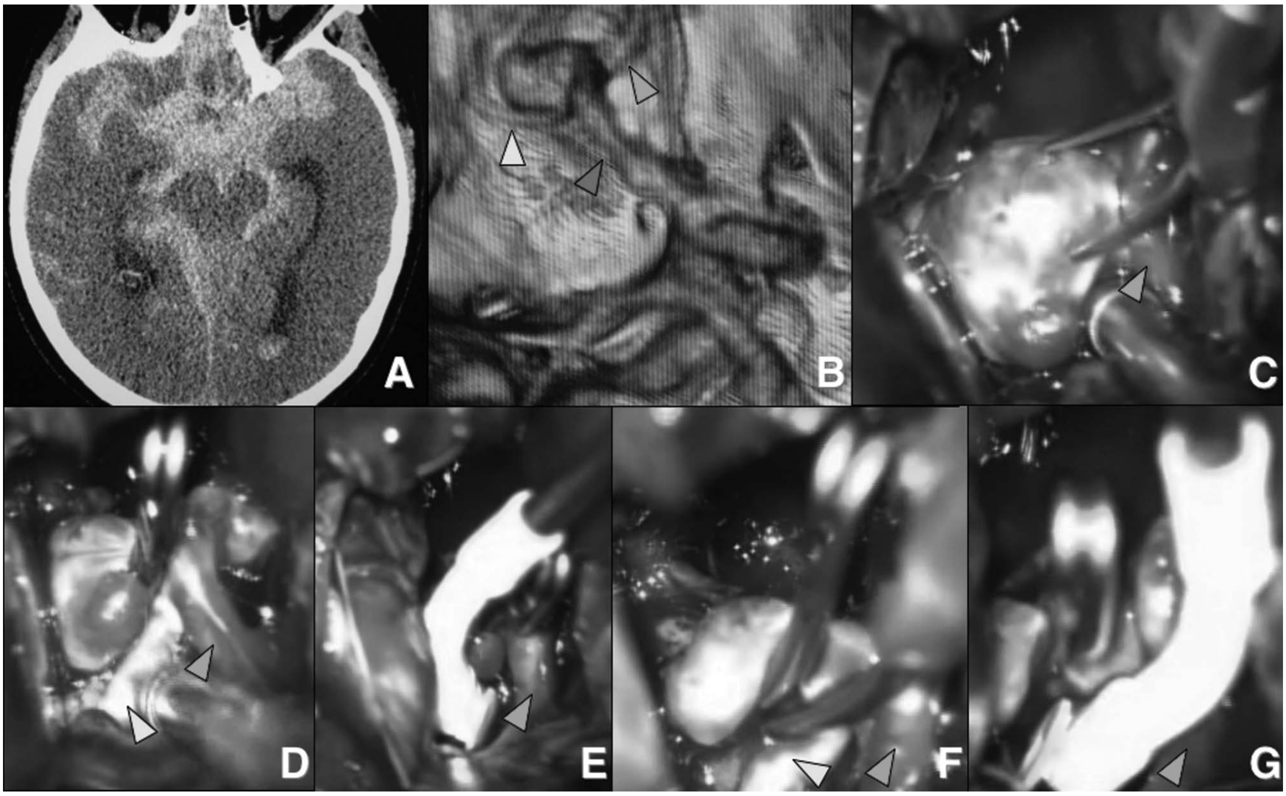

FIG. 1. Flowmetry in aneurysm surgery. (A) Axial noncontrast CT scan (Crani #14 in Table I) of a patient who presented with a massive subarachnoid hemorrhage from a ruptured anterior communicating artery aneurysm with an incidental unruptured large left middle cerebral artery (MCA) aneurysm. (B) Three-dimensional CT angiogram shows M1 (red arrow head), M2 frontal (green arrow head) and M2 temporal (yellow arrow head) branches of the MCA, with aneurysm at the M1/M2 junction. (C) Aneurysm clip about to be placed around neck of MCA aneurysm. M2 frontal branch (green arrow head) can be seen here; M2 temporal branch is under sucker tip. Daughter sac is to the left of the sucker tip. (D) The MCA aneurysm neck appears satisfactorily clipped and the adjacent M2 frontal (green arrow head) and M2 temporal (yellow arrow head) branches appear open. Atheroma noted in M2 temporal branch. (E) A 1.5-mm tip-diameter flow probe has been brought into the field, and placed around M2 temporal branch. Flow in this branch was found to be reduced from 9 ml/min (before clip placement) to 0 ml/min (after clip placement) despite good contact and submersion of the probe tip in Ringer solution (not shown). (F) Original clip being removed, and another clip has been placed further up the aneurysm neck. M2 frontal (green arrow head) and M2 temporal (yellow arrow head) branches seen. (G) Flowmetry probe brought back into field to measure M2 temporal branch flow after clip adjustment. The flow increased from 0 to 18 ml/min indicating good flow restoration in this inadvertently compromised vessel. No further adjustment was made. The small neck remnant between the new clip and the M2 frontal branch (green arrow head) was wrapped in Teflon.

clipping of her aneurysm neck and no quantifiable diminishment of local distal flow (as measured via her M1 branch), the resultant right hemiparesis upon awakening was presumably from an embolic event undetected by ITTF. For the remaining 29 cases, post-operative angiography confirmed good positing of aneurysm or AVM/DAVF clips, patent local vessel or bypass graft flow and AVM/DAVF obliteration as predicted by the intra-operative flowmetry data. With the exception of the aforementioned patient, post-operative CT scanning confirmed no new strokes within 48 hours of surgery.

Post-operative mortality

Two patients died in this series: One patient (crani # 14 in Table I) died on post-subarachnoid hemorrhage day 5 as a consequence of diffuse vasospasm secondary to a ruptured anterior communicating artery aneurysm. The patient also had an incidental ipsilateral unruptured MCA aneurysm. Both of the aneurysms were successfully obliterated by direct neck clipping with good distal parent artery flow based on early post-operative angiography. The MCA aneurysm clip was adjusted based on the flowmetry results (Fig. 1 and Table I). Another patient (crani #1 in Table I) died on post-operative day 9 following presumed perforator and contralateral P1 compromise causing a large brainstem stroke that occurred as a result of intra-operative rupture of the basilar tip aneurysm. In this patient, flow measurement was restricted to the ipsilateral P1 artery following clipping of the basilar artery apex aneurysm. The restriction was due to physical constraints of the flow probe tip diameter in this deep narrow corridor with surrounding perforators and cranial nerves.

Discussion

The need for intra-operative vascular flow assessment

Intra-operative vessel compromise can result in cerebral infarction. In a recent study concerned with patients treated surgically for aneurysmal

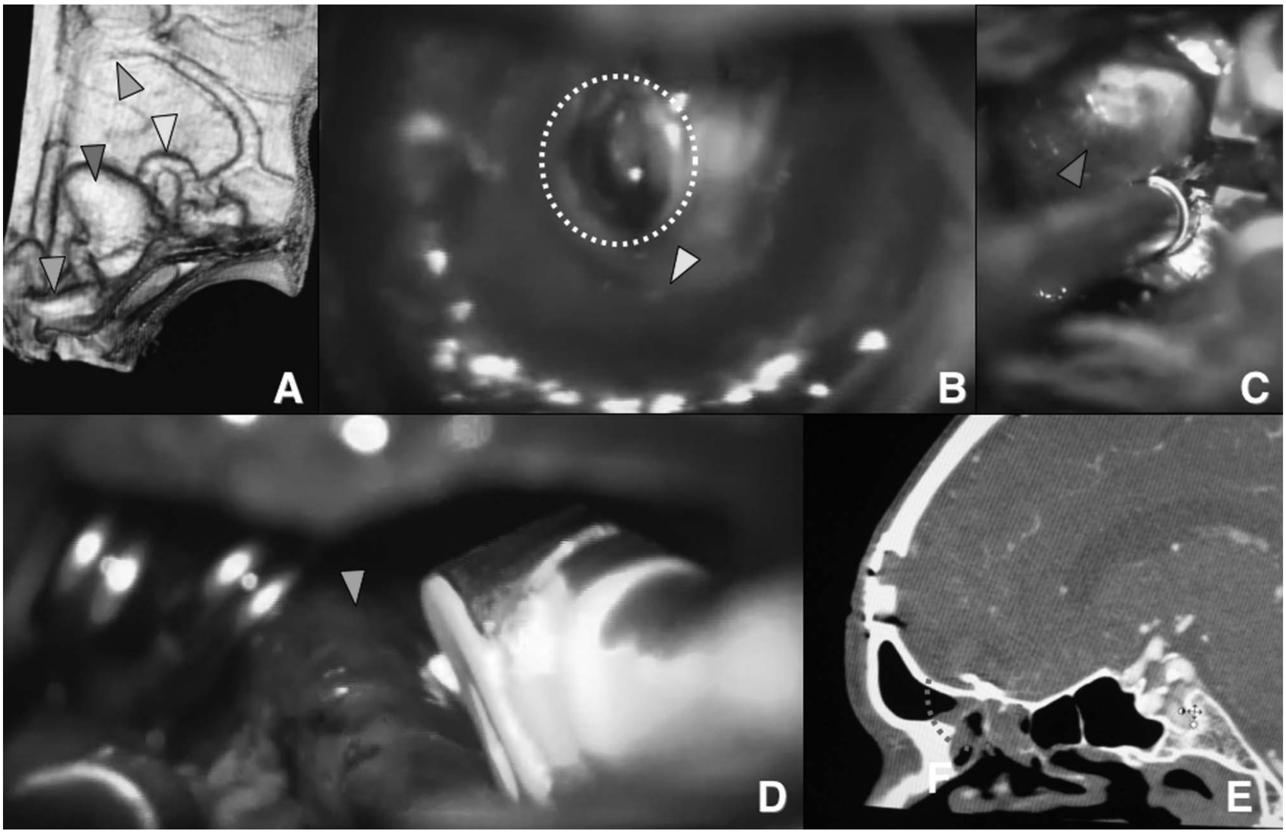

FIG. 2. Flowmetry in dural arteriovenous fistula (DAVF) surgery. (A) Three-dimensional CT angiogram (Crani #17 in Table I) showing a fronto-ethmoidal DAVF fed by bilateral ophthalmic arteries (not shown). The fistula is in the ethmoidal dura to the left of the proximal draining vein (green arrow head). The proximal draining vein expands into a large venous aneurysm (red arrow head). The beginning of the distal draining vein (C-shaped; yellow arrow head) is seen. This terminates (blue arrow head) in the superior sagittal sinus (to the left of the blue arrow head). (B) Intra-operative view of the C-shaped portion of the distal draining vein (yellow arrow head). Note the red hue of this arterialized vein. The local arachnoid has been dissected open (white dashed circle) to allow placement of the flow probe head for imminent local flow measurement. (C) The venous aneurysm (red arrow head) being dissected. (D) The proximal draining vein (green arrow head) has been reached and permanent clips placed across its origin. The 2-mm flow probe head is seen. Flow reduced from 21 ml/min in this arterialized vein (before clip placement) to 0 mL/min (following clip placement), and the blood in the structure changed from red to purple hue. This provided qualitative and quantitative feedback to the surgeon that the fistula was completely disconnected. (E) Post-operative sagittal CT angiogram shows clips on ethmoid bone (red dashed circle). A small supraorbital craniotomy can be seen immediately above the frontal air sinus to the left in this image.

subarachnoid hemorrhage, 29% of new post-operative infarcts were secondary to perforator occlusion.[1] Since intra-operative visual inspection of susceptible vessels even with the operating microscope may not detect compromise, the use of intra-operative flow assessment has been advocated. However, debate exists not only regarding the type of monitoring technique, but whether this should be used routinely or only in selected patients. Even experienced neurosurgeons cannot accurately predict which patients would benefit from intra-operative monitoring. In a recent study[20] investigating the use of intra-operative angiography during aneurysm surgery pre-operatively, it was thought to be necessary in 20% of cases and unnecessary in 80%. However, intra-operative angiography resulted in alteration of surgical procedure in 17% of the former and 4% of the latter. This finding demonstrated that it was difficult to predict who would benefit from intra-operative angiography, which led the authors to comment that selective use was not recommended. Significantly, in these cases, 36% of changes to surgical procedure were made because of vessel occlusion.[20] Therefore, as monitoring is advocated, the chosen technique should be easy to use, minimally invasive, reliable, repeatable and have a broad utility.

Ultrasonography

Because of the invasiveness and time-consumption of intra-operative catheter angiography, we chose to investigate quantitative intra-operative ultrasonographic transit time flowmetry (ITTF) in this study. For clarification, ITTF is not the same as Doppler ultrasonography. Intra-operative microvascular Doppler ultrasonography (MDU) provides qualitative information on blood velocity in at-risk vessels rather than quantitative volume flow, and has been extensively studied.[2–4,6,14,15] Stendel *et al.*[3] reported MDU use in cerebral aneurysm surgery. Vessel compromise, which was not noticed on visual inspection, was identified by MDU in 17 out of 90 cases (18.9%).[3] Marchese *et al.*[14] demonstrated persistent flow in the aneurysm requiring clip repositioning in 3.7% cases

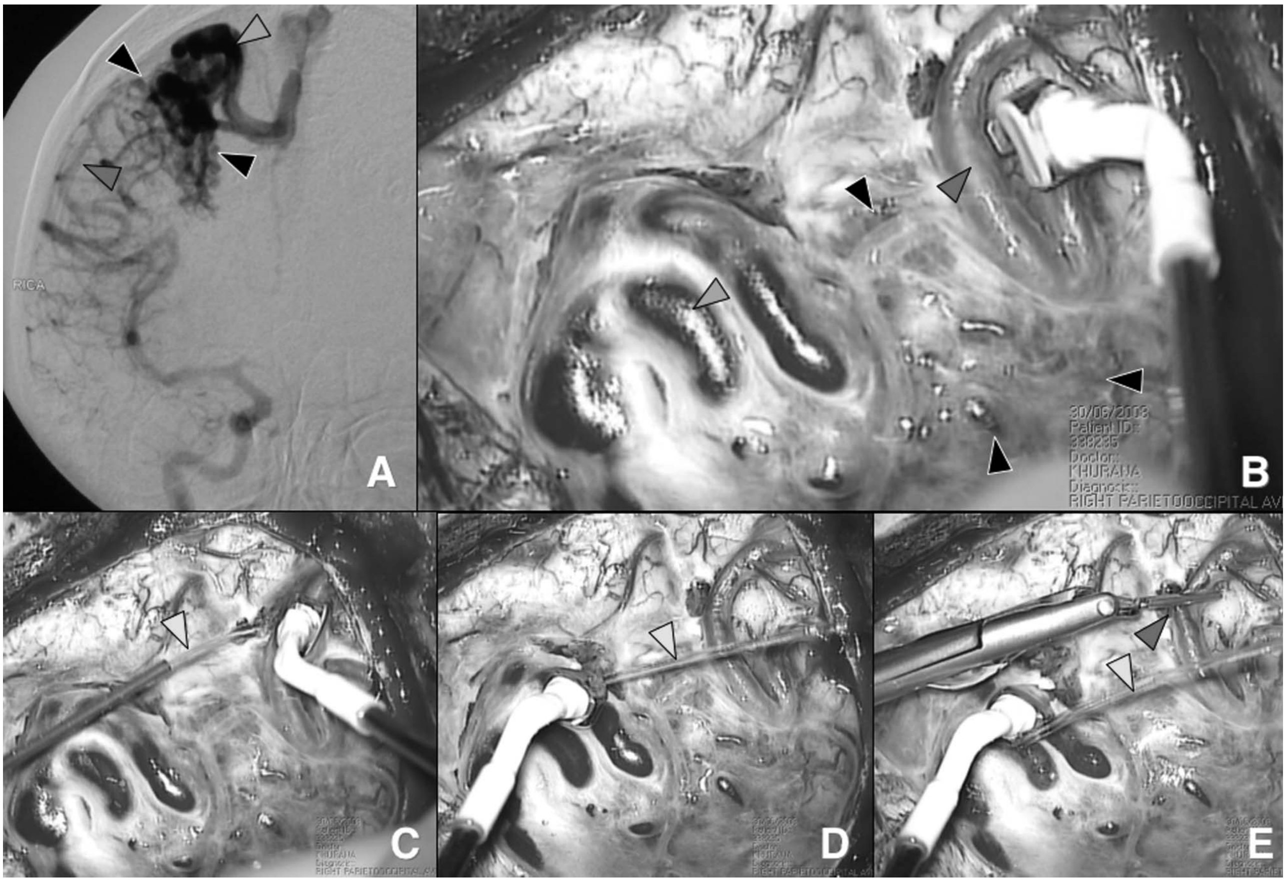

FIG. 3. Flowmetry in arteriovenous malformation (AVM) surgery. (A) The catheter cerebral angiogram's right internal carotid artery (ICA) injection antero-posterior view is shown here (Crani #30 in Table I). The main feeding artery of this AVM is a M4 middle cerebral artery (MCA) branch (red arrow head). Another posterior cerebral artery feeder is not seen in this injection. The nidus of the AVM (between the black arrow heads) and the main draining vein (blue arrow head) are shown. (B) The right parietal dura has been opened exposing the cortical surface of the AVM. The 2-mm flow probe is seen about to be placed around the M4 feeding artery (red arrow head). The superficial portion of the nidus can be seen (between the black arrow heads) as can the origin of the main draining vein (blue arrow head). (C) Flow being recorded from the M4 feeder. It was measured at 115 ml/min (relatively very high volume flow for a cortical artery). The Ringer irrigation jet (yellow arrow head) from the blunt tip needle is seen here. (D) Flow is now recorded from the proximal portion of the main draining vein before arterial clipping. Flow in this vein was 54 ml/min (relatively very high volume flow for a cortical vein). Irrigation jet is also shown (yellow arrow head). (E) A clip has been placed on the M4 feeding artery (red arrow head), with simultaneous flow recording from the main draining vein. Flow in this vein dropped to 4 ml/min indicating satisfactory shut down of this main portion of the AVM before its removal.

and vessel compromise in 18.3%. However, distal branch flow diminutions may not be detected by the Doppler sound probe. Furthermore, in the presence of stenosis, a strong signal may be heard even though the overall volume of flow is decreased. Therefore, vessel compromise may still go undetected.[18] Doppler ultrasound flow meters are also impractical as measurements are heavily influenced by the diameter and thickness of the target vessel wall, accurate probe contact and isonation angle.[16]

Transit time flowmetry works on the principle that the time taken for an ultrasound wave to move a defined distance upstream (against blood flow) will take longer than an ultrasound wave moving the same distance downstream (with blood flow). Two transducers are placed at right angles to one another on the same side of the flowmetry probe and a reflector plate placed in the middle of the two transducers, but on the opposite side of the probe (Fig. 4). An ultrasound wave is alternately emitted from each transducer,

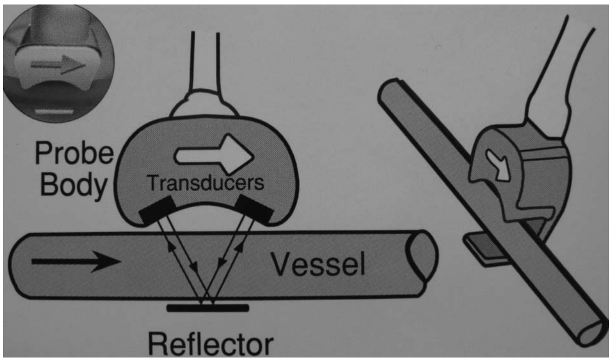

FIG. 4. Basic physics of the flow probe during flow recording. Direction of blood flow indicated by the large black and white arrows. Small black arrow heads between the transducers and the reflector indicate the path of 'downstream' and 'upstream' sound waves during recording. Note that the vessel fits comfortably in the flow probe head (i.e. there is no physical distortion of the vessel, and no large separation between the vessel wall and surrounding flow probe's transduction and reflection surfaces). See text for details. Artwork courtesy Transonic Systems Inc.

bounced off the reflector plate and reaches the other transducer after passing through the blood vessel. The time taken to pass between the two transducers is called the transit time, and the difference between the upstream and downstream transit times is proportional to blood flow.[16] This technique does not rely on direct probe contact and the isonation angle is fixed within the probe. Furthermore, vessel wall thickness, hematocrit and heart rate do not influence readings as these factors cancel each other out in the upstream and downstream cycles. ITTF has been validated in laboratory and surgical practice.[21,22]

ITTF in Neurosurgery

ITTF has been used frequently in cardiothoracic and vascular surgery.[23–25] More recently, as the probe size has become smaller, ITTF has been used in various intra-cranial surgical procedures. Charbel *et al.*[18] reported the use of ITTF during clipping of a superior cerebellar artery (SCA) aneurysm. Baseline flow in the SCA was 18 ml/min; however, post-clipping flow in this artery dropped to 4 ml/min. After clip repositioning, flow returned to baseline. In this case, the authors noted that before measuring flow, on visual observation, the surgeon was happy with clip placement. The time taken from initial measurement to repositioning clip was less than 5 minutes, and the patient awoke with no clinical consequence.[18] Nakayama *et al.*[16] described flowmetry measurements in 25 patients undergoing intracranial surgery. In 50% of aneurysm cases, ITTF detected decreased flow post-clipping, which was resolved on repositioning of the aneurysm clip. Amin-Hanjani *et al.*[19] also investigated the use of ITTF in 103 patients undergoing aneurysmal surgery. They demonstrated significant reduction in flow in 31.1% of cases. They also found that ITTF identified vessel spasm in 5.8% of cases, which responded to papaverine or retractor repositioning. No ischemic infarcts were noted post-operatively. They concluded that ITTF was easier to interpret than Doppler ultrasonography and easier and faster than intra-operative DSA. Other authors have confirmed that ITTF is extremely helpful in surgical repair of complex aneurysms as it is fast, easy to perform and can be repeated multiple times.[17]

To our knowledge, this is the first study to document use of ITTF in DAVF and AVM surgery and additionally examines a wide variety of neurosurgical applications. Demonstrating dramatically reduced flow in the draining veins aided confidence in surgical disconnection of the AVM or DAVF. This occurred quickly and easily and has become routine practice in our institution. During excision of complex tumors surrounding vascular structures, ITTF was invaluable in confirming that vessel compromise was not occurring secondary to brain retraction.

However, ITTF does have limitations. The probe head has been manufactured to be small, but in some instances may still be difficult to maneuver in narrow and deep or clot-filled operative corridors as we found in 13% of our cases. In addition, since the vessel of interest has to sit in the probe, at least 180° of the circumference of the vessel requires to be free. This may result in more dissection than would normally be required. Currently, probe size dictates that very small perforator vessels cannot be measured, but this may change with newer probe sizes in the future. Finally, as expected, ITTF does not appear to be able to detect embolic events (although it would be expected to detect significant local thrombosis). Hoh *et al.*[1] reported an incidence of thromboembolic stroke of 0.4% in patients undergoing surgery for ruptured cerebral aneurysms. Therefore, although the use of this technology can improve outcome due to the prevention of vessel compromise, unexpected neurological deficit can still occur after distal embolism.

Conclusion

Intra-operative transit time flowmetry is an easy-to-use, safe and readily interpretable tool, which provides real-time feedback regarding the flow in the vessels of the circle of Willis and major perforating vessels. Although this technique can safeguard against ischemic deficits, it cannot protect against embolic events. However, its use does contribute significantly to the safety of patients undergoing a wide spectrum of neurosurgical procedures.

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