Intraoperative evaluation of cerebral hemodynamics using directional Doppler technique

Part 2: Saccular aneurysms

Helge Nornes, M.D., Arne Grip, M. Sc., and Per Wikeby, M.D.

Department of Neurosurgery, National Hospital of Norway, Rikshospitalet, Oslo, Norway

The use of a pulsed echo Doppler technique during procedures for occlusion of intracranial aneurysms is described. Saccular aneurysms can be located with reference to probe position and depth setting. Tracings of intra-aneurysmal flow are presented, and the characteristic flow pattern is discussed. Special emphasis has been placed on the parent artery flow, particularly the effect of lumen reduction on flow velocity. Results of flow velocity studies on the cognate (direct) and collateral flow in the middle cerebral artery and the proximal anterior cerebral artery are presented and discussed.

Key Words: intracranial aneurysm, ultrasonic Doppler flowmeter, arterial flow velocity, intra-aneurysmal flow, cognate flow, collateral flow

The occlusion of an intracranial aneurysm by clip or ligature should be considered a reconstructive procedure. The surgeon must be able to predict the consequences of a proposed procedure and to evaluate the result by determining the sufficiency of the vascular blood flow to the area. Operative hemodynamics are no longer regarded as irrelevant to patient management. The need for determination of blood flow is perhaps even more important in microvascular procedures than in surgery on large vessels. Since only limited information can be obtained from angiograms, other means must be used to determine flow in a particular microvascular system. In contrast to the electromagnetic flowmeter, which requires exposure of the vessel for application of a cuff probe, ultrasonic Doppler techniques determine blood-flow velocity noninvasively through the intact skin, through intact, exposed cerebrum, or through saline when the vessel is exposed.

We have previously reported the use of both methods during intracranial procedures. This paper presents our experience with a pulsed echo Doppler technique in aneurysm surgery, with a short discussion of the critical role of circulatory dynamics in aneurysm patients.

Clinical Material and Methods

This study included 31 patients who underwent intracranial operation for a saccular aneurysm. Fourteen aneurysms were located on the anterior communicating artery (ACoA) or the anterior cerebral artery (ACA), eight were middle cerebral artery (MCA) aneurysms, and nine were internal carotid artery (ICA) aneurysms. The average time between last subarachnoid hemorrhage (SAH) and operation was nearly 10 days. One patient had not had an SAH.

Anesthesia was induced with thiopentone and diallyl-nor-toxiferon, and maintained with nitrous oxide and fentanyl citrate. Hypotension was induced in all cases by trimethaphan camsylate (Arfonad), as described elsewhere. The PaCO<sub>2</sub> was maintained between 28 and 37 mm Hg during monitoring of blood flow.

We used a pulsed echo Doppler flowmeter* operating at 6 mHz, with gas-sterilized miniature ultrasound probes. A detailed description of the flowmeter

*Doppler flowmeter manufactured by A/S Vingmed, Oslo, Norway.
and its basic principles is given in Part 1 of this study.\textsuperscript{18} This Doppler flowmeter can sense the direction of flow and determine maximum flow velocity as well as the mean of velocities across a vessel lumen.\textsuperscript{18} Arterial blood pressure (ABP) was recorded from the femoral artery; all measurements were tape recorded and later transferred to an ink-jet paper recorder.\textsuperscript{t}

Summary of Cases

Targeted Approach

Our usual procedure for intracranial aneurysms is the traditional approach along the feeding artery, in order to control it before dissection of the aneurysm. The Doppler flowmeter technique was used in 12 patients for localization and targeted approach as shown in Fig. 1. Aneurysms with diameter as small as 3 mm could be identified and localized with reference to direction and depth from the probe. The operative depth range for this equipment is from 0.4 to 4 cm. By changing the position of the probe and the depth setting for ultrasound interrogation for each position of the probe, it is possible to detect the aneurysm by the characteristic intra-aneurysmal flow pattern. The net

\textsuperscript{t}Ink-jet paper recorder manufactured by Elema-Schönander 81, Stockholm, Sweden.

Fig. 1. Schematic drawing showing a surgeon homing in on a middle cerebral artery trifurcation aneurysm. Two Doppler probe positions are shown. The dotted lines indicate the ultrasound beam.

Fig. 2. Intra-aneurysmal flow velocity tracings of a middle cerebral artery aneurysm in a 31-year-old woman. $V_{\text{max}}$ = maximum velocity; $V_{\text{mean}}$ = mean of flow velocities in the sampling area. Note the difference between nearly zero $V_{\text{mean}}$ and very high and irregular $V_{\text{max}}$ values. The section between arrows 1 and 2 is a recording from a trifurcation branch obtained by a slight change in probe position. See Fig. 1.
flow-through time is practically zero across the aneurysm and a highly irregular and partly turbulent flow could be detected in the non-directional mode for maximum velocity ($V_{\text{max}}$). An example is shown in Fig. 2. The tracing between arrows 1 and 2 shows the effect of a slight change in the angle of the probe and the recording of flow velocity from a trifurcation branch of the MCA. In all 12 patients, dissection of the aneurysm could be achieved more boldly and precisely by using repeat ultrasound interrogation during the course of approach.

Detailed studies on flow velocity in 21 exposed aneurysms up to 20 mm in diameter showed that in some cases, particularly the larger ones, there were more or less regular streamlines with flow separation in the aneurysm neck. This flow pattern was most marked for the inflow during systole and in large aneurysms (Fig. 3). However, the intra-aneurysmal flow velocity was always quite distinct from the adjacent arterial and venous pattern.

This targeted approach, or "homing in" on the aneurysm, was of great help, particularly when approaching MCA trifurcation aneurysms. This method was also useful in five patients with ACoA aneurysm, and in two cases of distal ACA (pericallosal) aneurysm.

**Parent Artery Flow**

Electromagnetic blood-flow measurements must be made either proximal or distal to the aneurysm, because of the necessity of mounting the cuff probe. With the Doppler flowmeter technique, one can measure the flow velocity in the parent artery at the clip site itself. Figure 4 shows why this ability might be important. Even a slight reduction in vessel lumen in a "tight clip" situation will instantly increase the blood-flow velocity ($V_s$) at that point ($A_2$). The important thing is that this will occur well before reaching the rather marked lumen narrowing below which an abrupt decrease in bulk flow occurs. An example of change in flow velocity due to such vessel narrowing from clip application on an atheromatous MCA aneurysm neck is seen in Fig. 5. After temporary occlusion of the MCA and an endoaneurysmectomy in that patient, a proper clip application was achieved which did not impair flow in the parent artery.

**Arterial Spasm**

In studies with electromagnetic flowmeters, recording was always omitted when signs of arterial spasm were seen. Because of its noninvasive principle, the Doppler flowmeter method could be used to study flow velocity in cases of arterial spasm. Figure 6 shows an example of a mean velocity of about 110 cm/sec and a maximum velocity of 160 cm/sec in a spastic branch at the MCA trifurcation. Velocities of about 200 cm/sec were observed in another patient.

The effect of topical application of papaverine 3% was tested in two patients with ICA aneurysm and spasm. There was no change in blood velocity in one patient, while the second showed a definite reduction in flow velocity at the site of application. However, velocities in the MCA and ACA were unchanged, and the reduction in ICA velocity was simply a consequence of the local dilatation of the ICA that was seen. When volume flow is constant, velocity is inversely related to the cross-sectional area of the vessel.

**Collateral Flow**

The principles and indications for measurement of collateral flow have been discussed elsewhere. In spite of improved microsurgical technique during the last decade, trap ligation is still the method of choice in some patients. Figure 7 shows the reversal of flow through the aneurysm due to the arterial collateral.
in an ACA at test occlusion of the distal segment of the ICA: reverse flow from the contralateral carotid system through the ACoA is now the sole supply to the MCA (collateral flow). It is important to observe that "flow demand" from the MCA in this situation is definitely higher than the normal or steady state of forward flow in this ACA (cognate ACA flow). The anterior section of the circle of Willis in this patient obviously has a good capacity.

A similar ICA test occlusion was carried out in another patient with the probe recording from the MCA (Fig. 8). Instant flow reduction is nearly 40% and the throttling effect on pulsatile MCA flow (collateral) is clearly seen. We studied 13 patients with regard to reverse ACA flow, and this flow ranged from 25% to 240% (mean 106%) of steady state forward flow in the ACA. In the eight patients in whom direct measurements were made on the MCA, collateral flow ranged from 20% to 85% (mean 62%) of direct MCA flow.

Discussion

Mann, et al., first pointed out that a substantial decrease in lumen of a vessel must occur before a drop in pressure and flow can be detected distal to the point of constriction. However, it is well known that beyond a certain degree of narrowing, small reductions in the lumen area result in marked changes in flow. The cross-sectional area below which this phenomenon occurs has been termed "critical stenosis." This critical figure also depends on the length of constriction or stenosis, which therefore becomes an important factor in extensive arterial spasm. The problem of critical stenosis, the prediction of its occurrence, and the understanding of its physical mechanisms are not theoretical problems but matters that have direct significance in the planning of routine vascular surgery. From a neurosurgical point of view, a stenosis is critical to the patient at a much smaller lumen reduction than the "critical stenosis" as defined.
FIG. 6. Flow velocities in middle cerebral artery (MCA) trifurcation branch with spasm in a 29-year-old woman. This marked increase in flow velocity compensates, within certain limits, for the effect of lumen reduction on bulk flow in the artery. Note the high end-diastolic flow velocity. $V_{\text{max}}$ = maximum velocity; $V_{\text{mean}}$ = mean of flow velocities at the sampling area; ABP = arterial blood pressure.

FIG. 7. Reversal of flow in proximal anterior cerebral artery (ACA) during a short test occlusion of the distal internal carotid artery (ICA) in a 68-year-old woman. $V_{\text{max}}$ = maximum velocity; $V_{\text{mean}}$ = mean of flow velocities at the sampling area; ABP = arterial blood pressure.
Cerebral hemodynamics and Doppler technique

**MCA flow velocity**

\[ V_{\text{max}} \]

\[ V_{\text{mean}} \]

\[ \text{ABP} \]

**FIG. 8.** Test occlusion of the internal carotid artery (ICA) while recording from the middle cerebral artery (MCA) in a 57-year-old man. Compare the cognate and collateral flow velocities. \( V_{\text{max}} \) = maximum velocity; \( V_{\text{mean}} \) = mean of flow velocities at the sampling area; \( \text{ABP} \) = arterial blood pressure.

The immediate increase in flow velocity shown in Figs. 4 and 5 is simply a way of compensating for the reduction in vessel lumen, and tends to keep the flow volume practically unchanged. It is of considerable importance to be able to recognize this increase in flow velocity because it heralds a critical condition. This hemodynamic early warning cannot be picked up by electromagnetic flowmeters or the other techniques available today.

**Arterial Spasm**

The normal contribution of myogenic tone to the determination of caliber in cerebral conduit arteries remains obscure, as does the mechanism of so-called arterial spasm. What can be said in general is that the vasomotor change in arteries will have two hemodynamic consequences, one caused by the change in cross-sectional area, and the other arising from changes in elastic moduli of the vessel wall. Localized spasms and their effect on blood flow can be understood more readily because the condition is comparable to a short stenosis or constriction of any kind. What is still unknown is the real nature and extent of vascular alteration in extensive, widespread spasms. The possible change in dimensions and particularly the vasomotor function of the angiographically non-visible part of the system is less well understood and is probably a very important part of the problem.

**Collateral Flow**

The word “cognate” was introduced by Green, et al., who borrowed it from genealogy. It is used in a similar sense to refer to a direct linear path in contrast to a collateral path. The effective collateral circulation is that rate of blood flow which actually passes from the collateral bed, across the anastomotic channel, and through the cognate bed when the cognate artery is occluded. The magnitude of this flow is determined by several factors. The most important are the anatomy and the dimensions of the collateral channel, and thereby the resistance of this segment. Evidently the anastomotic channels as well as the conduit arteries, and particularly the arterioles in the cognate bed possess vasomotor function. Furthermore, systemic \( \text{ABP} \), the intracranial pressure, and the intracranial outflow conditions must be constant during such comparisons. Previous studies with electromagnetic flowmeters have shown that vasomotor changes are involved, and that continuous flow monitoring is necessary to obtain correct information because such responses occur instantly in some patients.

The need to evaluate collateral flow is not very common. In our series of 468 consecutive patients operated on for saccular aneurysms only 23 (4.6%) were treated with a trapping procedure. However, for such patients these questions are of considerable importance.
Collateral flow into the MCA from the ACA during ICA occlusion can be determined either by recording the reverse flow in the ACA or by direct measurement of MCA velocity. This direct MCA recording gives an instant and exact figure in percentage change of MCA flow (Fig. 8), because true flow is directly proportional to velocity in such situations, assuming no change in probe position and vessel diameter. A reasonably good estimate of the internal arterial diameter can be obtained through the microscope, and enables a calculation of flow in ml/min simply by multiplying mean blood velocity with lumen area. This method is feasible for intraoperative determination of collateral potentials, and the tracings that result are fully comparable with previously presented electromagnetic flowmeter tracings.

Targeted Approach and Aneurysm Flow

The basic physical principle that makes it possible to locate a saccular aneurysm with the Doppler flowmeter technique is comparable to that described for arteriovenous malformations in Part 1 of this study. Flow in the parent artery and its branches is practically laminar in a parabolic fashion. This means that maximum flow velocity \(V_{\text{max}}\) should be double the mean velocity across the lumen \(V_{\text{mean}}\). On the other hand, flow in an aneurysm has two characteristics: the net flow-through time is very low or practically zero, and the flow is highly irregular and turbulent at very low flow rates. The pulsatile flow in a berry aneurysm does not have completely random flow motions, however. Some of our recordings show the whirlpool-like motion sometimes seen through thin-walled sacs. As demonstrated by Ferguson, these main streamlines show turbulence at their constantly changing border areas.

The ability to determine maximum flow components is of particular importance in the identification of a non-thrombosed berry aneurysm, and the Doppler signal, made audible by means of a loudspeaker, was helpful to the surgeon while homing in on the aneurysm. Furthermore we were surprised by the clear signals obtained and the existence of very high intra-aneurysmal velocity components as shown in Fig. 2.

Most surgeons are relieved when they are able to see the aneurysm and control the parent artery. A rupture at this stage is very seldom a serious event. Targeted approach guided by the Doppler flowmeter technique was helpful in avoiding the aneurysm dome during exposure. There were no ruptures in this series.

Stereotaxic methods for aneurysm treatment have been reported. The stereotaxic thrombosis procedure described by Alksne and Smith, in particular, might benefit from the Doppler flowmeter technique, which would reduce the number of x-ray exposures required.

The major disadvantages of the method is that the Doppler shift frequency is dependent upon the angle at which the emitted energy impinges upon the blood stream. Furthermore, the inner diameter of the vessel should be known to determine true flow, and it should be stressed that velocity must not be misinterpreted for flow. However, the concept of pulsatile flow velocities and their distribution in space and time is of clinical interest, and the method described here might be a useful alternative to instrumentation for blood flow studies in cerebral vascular surgery.

References

1. Alksne JF: Personal communication, 1978
Cerebral hemodynamics and Doppler technique


Address reprint requests to: Helge Nornes, M.D., Department of Neurosurgery, National Hospital of Norway, Rikshospitalet, Oslo, Norway.