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Intravascular microcatheter pressure monitoring: experimental results and early clinical evaluation.

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With the use of Tracker and Balt microcatheter systems, intravascular pressure measurements were obtained in an experimental animal model, establishing the reliability of mean blood pressure measurements from these microcatheter systems. In the experimental model, selective occlusion of branches of the external carotid artery with simultaneous pressure measurements showed significant and reproducible changes in intravascular pressures. Also, pharmacologic manipulation of the blood pressure with simultaneous microcatheter and 6-French catheter recordings demonstrated an accurate and linear response of the microcatheter systems to mean blood pressure as it varied from 30 to 130 mm Hg. Preliminary results in humans with vascular malformations yielded similar results. We studied two cases of brain arteriovenous malformations (AVMs), one sigmoid-transverse sinus dural AVM, and one brain arteriovenous fistula (AVF). In these four cases the pressure dropped substantially, approaching the level of the shunt. In the case of the brain AVF, pressures rose in the same vessel after embolization. In the case of the dural AVM, correlation of the venous pouch pressures and the angiographic appearance indicated that shunting was no longer present when the venous and arterial pressures equalized.

This system can be of substantial benefit in the evaluation and therapy of these lesions, and may increase our understanding of the physiology of vascular malformations.

It is theorized that during endovascular therapy of arteriovenous malformations (AVMs) and arteriovenous fistulas (AVFs), the cerebral hemodynamics may change and result in hemorrhage and/or edema. This is thought to be due to changes in the uninvolved or "normal" vessels secondary to steal from the AVM or AVF [1–3]. It is postulated that these normal vessels lose their autoregulatory capability when exposed to chronically reduced perfusion pressure. When these vessels are acutely exposed to elevated (normal) pressure after occlusion of the vascular malformation, the vessels cannot respond appropriately, with resultant hemorrhage and/or edema. This has been referred to as the normal perfusion pressure breakthrough (NPPB) phenomenon [4].

Currently, during endovascular procedures, the end point of therapy is indicated primarily by angiographic means and clinical experience. Embolization of feeding vessels to AVMs is performed in a stepwise fashion. The lesion may not be embolized maximally during the first procedure owing to the fear of causing NPPB [3, 5, 6]. Therefore, treatment may require up to three or four separate procedures [7], with the hope that the risk of NPPB and intracerebral hemorrhage is thereby reduced.

Monitoring of intravascular pressure is a well-established technique used extensively in body angiography [8–11]. Measurements of intracerebral vascular pressure previously have been obtained by direct intraoperative puncture of vessels. Two studies have shown that the arteries supplying AVMs had significantly reduced

pressures that were elevated markedly after obliteration of the feeding vessels to the AVM [12, 13]. Recently, Jungreis et al. [14] reported similar changes in arterial pressures via the endovascular route during embolization therapy. They used Tracker-18 microcatheters to monitor the pressure changes. However, the accuracy and reliability of pressure measurements obtained with these microcatheters were not addressed in their article, nor were regional pressures obtained. Our study was undertaken to assess the feasibility and reliability of monitoring endovascular pressure and to assess the altered hemodynamic states of vascular lesions in the CNS before therapy and the changes that follow endovascular therapy.

Materials, Subjects, and Methods

All pressure measurements were obtained on Hewlett-Packard 78205D pressure monitors (amplifiers) (Hewlett-Packard, Co., Waltham, MA) with Spectramed TNF-R pressure transducers (Spectramed, Inc., Oxnard, CA). Pressure measurements were obtained through varying microcatheter systems including Tracker-18 and Tracker-18 Hi-Flow (Target Therapeutics, Inc., Los Angeles, CA) and Balt 1.8-French Magic Progressive Suppleness Pursil catheter (Balt, Montmorency, France) systems. Additionally, Tracker-25 (0–0.025 in. [0.06 cm] inner diameter) catheters (Target Therapeutics) were also used for venous measurements. Simultaneous coaxial pressures were obtained with catheters no smaller than 5-French.

Eight Red Duroc and Poland-China pigs were used in the experimental phase of the study. The animals were anesthetized with halothane anesthesia. The common carotid arteries of three animals were catheterized with 6-French thin-walled, nontapered catheters (Balt) with coaxially placed microcatheters (Tracker-18, Tracker-18 Hi-Flow, or Balt 1.8-French Magic). Blood pressure measurements were obtained from the 6-French catheters before and after placement of the microcatheter systems to confirm that there was no significant damping of the pressure recording. The microcatheters were then placed into the internal maxillary arteries of the animals. Dopamine and nitroprusside were then infused alternately into a superficial vein, and simultaneous pressure measurements were obtained from both the 6-French and microcatheters.

Five experiments were performed with 6- or 8-French guiding catheters in the common carotid arteries with placement of balloon occlusion catheters coaxially into the internal maxillary arteries. Pressures were obtained from the guiding catheter during inflation and/or deflation of the occluding balloon system. The balloon systems used were latex Debrun balloons (Ingenor, Paris, France) mounted on either 4/2-French Ingenor (Ingenor) or Tracker-18 microcatheters.

Patients involved in the study included two with brain AVMs, one with a brain AVF, and one with a dural AVM. The patients were monitored in the same way as the experimental animals with the same microcatheter systems, pressure monitors, and transducers. Angiograms were obtained on either a GE DF 5000 digital fluoroscopy unit (General Electric Medical Systems, Milwaukee, WI) or an OEC Angio Plus portable digital radiography unit (OEC-Diasonics, Salt Lake City, UT). Guiding catheters were 5–7-French, thin-walled, and nontapered (Balt).

Results

Animal Studies

During the intravascular pressure correlation phase of this study, three microcatheter systems were used, including the
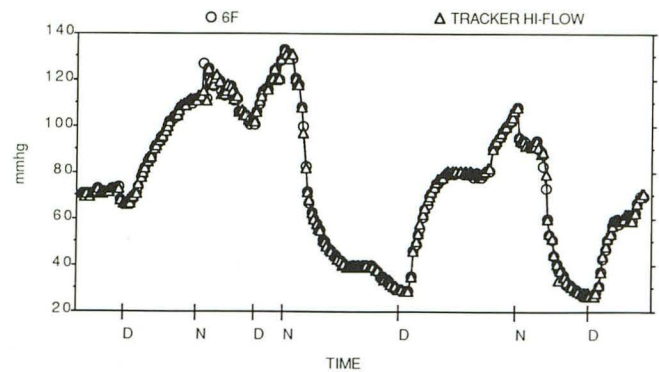

Fig. 1.—Graphic display of mean pressures obtained from Tracker Hi-Flow catheter and 6-French guiding catheter during manipulation of blood pressure in the experimental animal, using dopamine (D) and nitroprusside (N). The Tracker Hi-Flow catheter was in the internal maxillary artery and the 6-French catheter was in the external carotid artery.
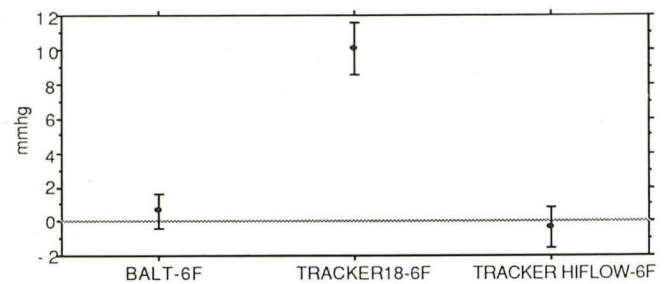

Fig. 2.—Summation of differences in mean pressures between microcatheter and guiding catheter. The mean difference in actual pressure measurements was 0.61 mm Hg for the Balt 1.8-French catheter and 6-French (6F) guiding catheter, 10.09 mm Hg for the standard Tracker-18 and 6-French, and −0.37 mm Hg between the Tracker Hi-Flow and 6-French. Error bars represent 1 SD.
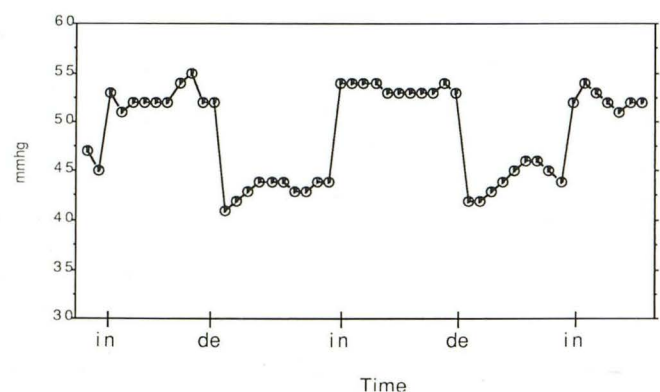
Fig. 3.—Graphic display of pressure changes in the external carotid artery via a 6-French guiding catheter with inflation (in) and deflation (de) of an occlusive balloon in the internal maxillary artery.

Tracker-18, Tracker-18 Hi-Flow, and Balt 1.8-French microcatheter systems. The microcatheters were placed in the internal maxillary arteries of the experimental animals, along with a 6-French guiding catheter in the common carotid artery.

Fig. 4.—Case 1.
A-C, Anteroposterior (*A*), early arterial lateral (*B*), and late arterial lateral (*C*) views of right internal carotid injection. Arteriovenous malformation (AVM) in right temporal lobe is being fed by anterior temporal branch. Selected pressure measurements (in mm Hg) on anteroposterior view are superimposed over locations where they were obtained.

D, Superselective injection of AVM feeder. Pressure at this point was 45 mm Hg less than that obtained from the 6-French catheter in the internal carotid artery.

A

B

C

D
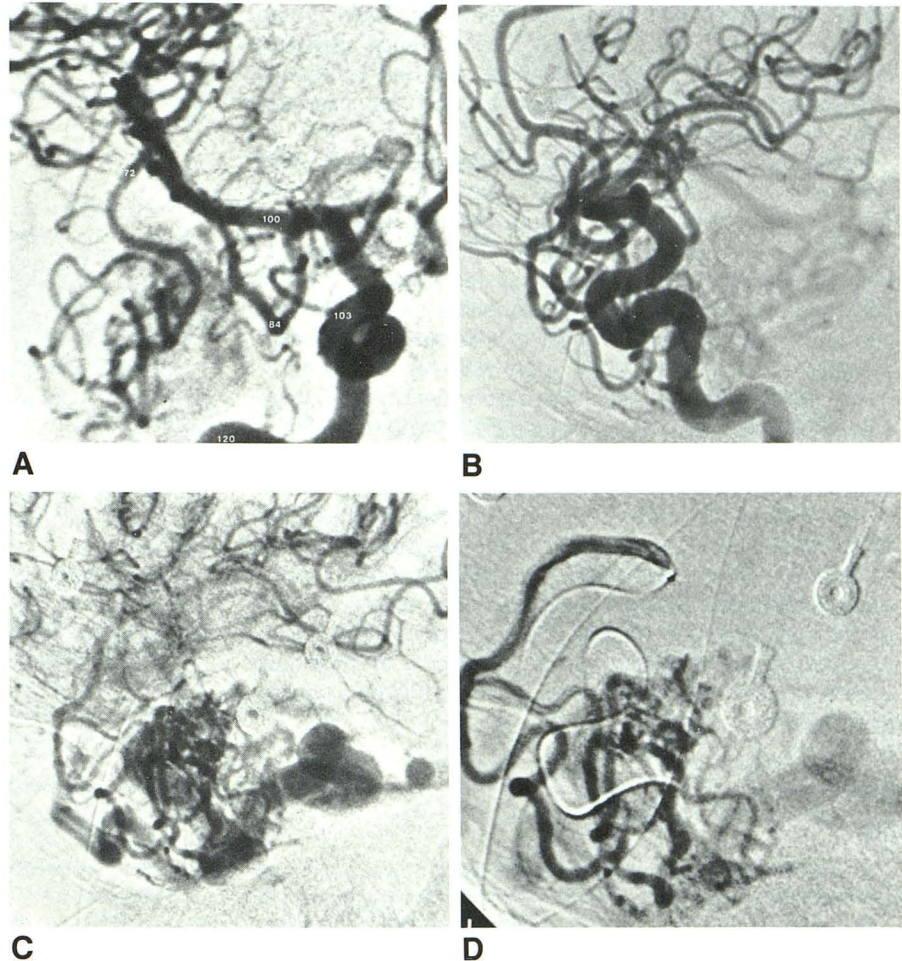
Initial mean pressures were obtained before and after coaxial placement of the microcatheters, which confirmed that there was no damping of the mean pressures measured from the guiding catheters by coaxially placed microcatheters. Simultaneous measurements of the mean blood pressures from both catheters were then recorded over a range of approximately 30–130 mm Hg. Figure 1 is a graphic display of one experiment (Tracker Hi-Flow vs 6-French data). In earlier experiments, systolic and diastolic pressures were obtained. However, when compared with the corresponding measurements from the guiding catheters, the systolic pressure was decreased and the diastolic pressure was elevated; that is, pulse pressure amplitude was reduced. This result was probably due to the restricted diameter of the microcatheters. Because of this, mean pressures were followed instead of pulse pressures.

The net difference in mean pressure measurements between the microcatheters and 6-French guiding catheter was calculated for each observation. The means and standard deviations of these net values were then calculated. The mean difference between the Tracker-18 and the 6-French catheters was 10.09 mm Hg (SD = 1.55). Although the Tracker-18 catheter did not measure the same pressure as the 6-French, the net difference between the two catheters remained the same as blood pressure was varied. It is therefore valid to
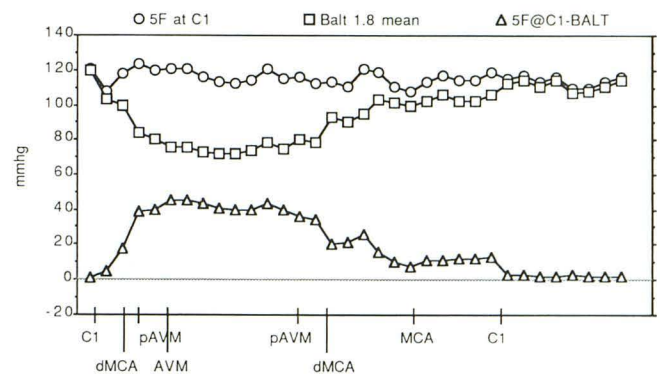

Fig. 5.—Case 1: Mean blood pressure measurements from the Balt 1.8-French catheter as it approached and retreated from the arteriovenous malformation (AVM), mean blood pressure from the 5-French (5F) catheter at the C1 level, and net pressure difference between 5-French and Balt 1.8-French catheters as Balt position was changed. C1 = level of anterior arch of C1; dMCA = middle cerebral artery distal to feeder; pAVM = AVM feeding vessel proximally (anterior temporal branch of MCA); AVM = AVM feeding vessel distally; MCA = middle cerebral artery at trifurcation.

use this catheter to assess changes in mean blood pressure. For the Balt 1.8-French vs the 6-French catheters, the mean difference was 0.61 mm Hg (SD = 1.02). For the Tracker Hi-Flow vs the 6-French catheters, the mean difference was

−0.37 mm Hg (SD = 1.15). These differences between the Tracker Hi-Flow, Balt 1.8-French, and 6-French catheters were not significant (Fig. 2). Therefore, the Balt 1.8-French and Tracker Hi-Flow catheters can be used to accurately measure mean blood pressure.

During the second phase of the animal studies, selective balloon occlusion and deocclusion (reperfusion) were performed while regional blood pressure was monitored [5, 15–17]. One experiment is depicted in Figure 3. By using an Ingenor 4/2-French microcatheter system mounted with a Debrun latex balloon in the internal maxillary artery, the balloon was serially inflated and deflated while the mean pressure changes in the external carotid artery were recorded via a 6-French guiding catheter. When the balloon was inflated, there was an initial prompt rise in the blood pressure in the external carotid artery followed by a gradual stabilization of the pressure at levels higher than preinflation pressures. With deflation of the balloon, there was a drastic reduction in the blood pressure, with subsequent stabilization of the pressure closer to, but still distinctly less than, the original pressure. Therefore, we have documented that even normally reactive vessels may have changes in pressures during embolotherapy. These regional changes in pressures after occlusion of large-flow vessels can be identified and the pressure changes can be substantial.

Case Reports

Case 1

A superselective Wada (Amytal injection) test [18] was performed in a left-handed patient being evaluated for function in the region of a right temporal AVM fed by middle cerebral artery (MCA) branches (Fig. 4). Figure 5 shows the results of this experiment. The Balt 1.8-French catheter was used. A 5-French catheter was placed in the high cervical internal carotid artery at the level of the anterior arch of the first cervical vertebra (C1). Pressure measurements were obtained when the Balt 1.8-French catheter was passed from the 5-French guiding catheter toward the AVM, and again when the 1.8-French catheter was withdrawn from the AVM. There was a significant drop (45 mm Hg) in the mean blood pressure at the AVM as compared

with that at the guiding catheter at the C1 level. As expected from the animal experiments, when the Balt 1.8-French catheter was placed at the level of C1, the Balt 1.8-French catheter and the 5-French guiding catheter measured equivalent mean blood pressures.

Case 2

A similar study was performed in a right-handed patient with a left temporal lobe AVM who was being studied with a superselective Wada test. The graphic data from mean pressure measurements taken via a Balt 1.8-French catheter as compared with a 6-French guiding catheter at the level of C1 are shown (Fig. 6). The Balt 1.8-French catheter was advanced from C1 to the MCA trifurcation, to the proximal AVM feeder (the anterior temporal branch), to the distal AVM feeder, back to the MCA, then to the angular artery, then to the MCA trifurcation, then back to the anterior temporal AVM feeder, then to the cavernous and petrous carotid arteries, and finally back to C1. As was seen in case 1, there was a significant drop in blood pressure as the AVM was approached. The difference in pressure
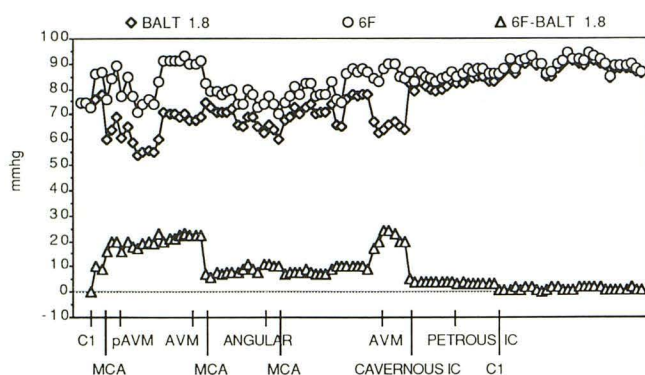

Fig. 6.—Case 2: Mean pressures from the Balt 1.8-French and 6-French (6F) catheters and net pressure difference between the 6-French guiding catheter and Balt 1.8-French catheter as arteriovenous malformation (AVM) is approached with microcatheter, which is then withdrawn and reinserted. C1 = level of anterior arch of C1; MCA = middle cerebral artery at trifurcation; pAVM = AVM feeding vessel proximally (anterior temporal branch of MCA); AVM = AVM feeding vessel distally; ANGULAR = angular artery; CAVERNOUS IC = cavernous segment of internal carotid; PETROUS IC = petrous segment of internal carotid.

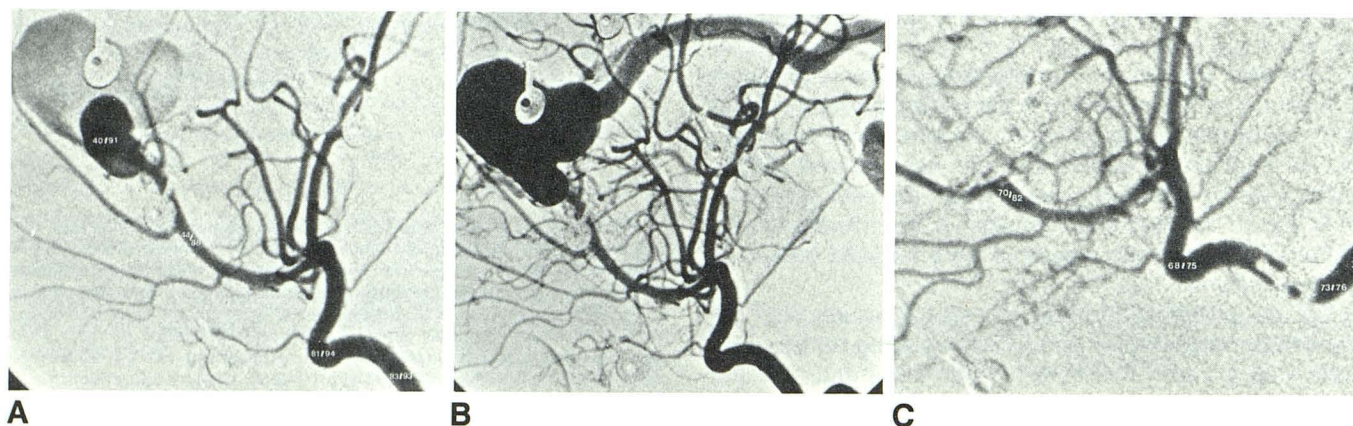**A**   **B**   **C**

Fig. 7.—Case 3.
A and *B*, lateral angiograms of right internal carotid injection.
C, Postembolization lateral right internal carotid injection.
Superimposed over preembolization (*A*) and postembolization (*C*) angiograms are pressures (in mm Hg) obtained at those points (vessel pressure/simultaneous 6-French pressure at C1).

between the two catheters measured at the same location was analyzed again, with results similar to those in case 1. The mean difference between the Balt 1.8-French and the 6-French catheters was 1.12 mm Hg (SD = 0.522). This is similar to the data obtained with the animal experiments.

Case 3

A 6-year-old girl presented with a subarachnoid hemorrhage. Angiography showed an AVF fed primarily from the right pericallosal artery (Figs. 7A and 7B). Under general anesthesia, a Balt 1.8-French catheter was advanced into the fistula. A superselective Wada test, performed with EEG and evoked potential analysis, was negative (no electrophysiologic changes after injection of 30 mg of sodium amobarbital) [18]). As the Balt catheter was pulled away from the fistula, pressure measurements were obtained. These measurements were obtained at the level of the venous pouch, pericallosal artery at the level of the fistula, proximal pericallosal feeder, cavernous carotid artery (two measurements), petrous carotid artery, and level of the guiding catheter (6-French) at C1. Subsequently, a Tracker Hi-Flow catheter mounted with a Hieshima balloon (Interventional Therapeutics Corp., San Francisco, CA) was placed into the feeder just proximal to the fistula. After balloon detachment, measurements were obtained at the pericallosal stump, cavernous carotid, petrous carotid, and C1 (Fig. 7C). These data are graphically displayed in Figure 8. At the level of the feeder, there was a change in net mean blood pressure of 32 mm Hg. The patient did well after the procedure and experienced no complications.

The study in this patient confirmed the observations seen in our animal experiments and the studies of Hassler and Steinmetz [12], Nornes and Grip [13], and Jungreis et al. [14]. When a high-flow vessel was occluded, significant changes in intravascular pressures were seen. In this patient, although the mean pressure increased by 32 mm Hg, no complications of NPPB were seen. As demonstrated in Figure 8B, there was also a significant increase in the regional net mean pressures as measured in the cavernous carotid (6 mm Hg) and petrous carotid (7 mm Hg) arteries. This may have significant implications during therapy, as suggested by Spetzler et al. [4]. In addition, if there should be a second vascular malformation or aneurysm, this abrupt elevation in regional pressure could lead to hemorrhage [4, 6, 7].

Case 4

The utility of pressure monitoring during endovascular therapy was demonstrated in this patient. A spontaneous dural AVM of the sigmoid and transverse sinuses was filled primarily by occipital branches of the external carotid artery, but there was significant supply from other meningeal branches of both the external and internal carotid arteries. A 5-French catheter was placed in the external carotid artery with a coaxial Tracker Hi-Flow catheter placed in the occipital artery and a Tracker-25 catheter introduced from the left femoral vein into the right transverse sinus via the left jugular vein (Fig. 9). Pressure measurements were obtained from all three systems during the embolization procedure. Before the start of the embolization procedure there was elevated pressure (51 mm Hg) and reversal of flow in the right transverse sinus because the right jugular vein was occluded. The occipital supply to the fistula was then embolized with the Tracker Hi-Flow, using polyvinyl alcohol particles (Ivalon, Ingenor) and Avitene (microfibrillar collagen, Alcon Laboratories, Inc., Fort Worth, TX) [19]. Substantial reduction in flow was observed angiographically, although there was no significant pressure change in the occipital artery compared with the external carotid artery. However, in the same period of time, the pressure measurements from the
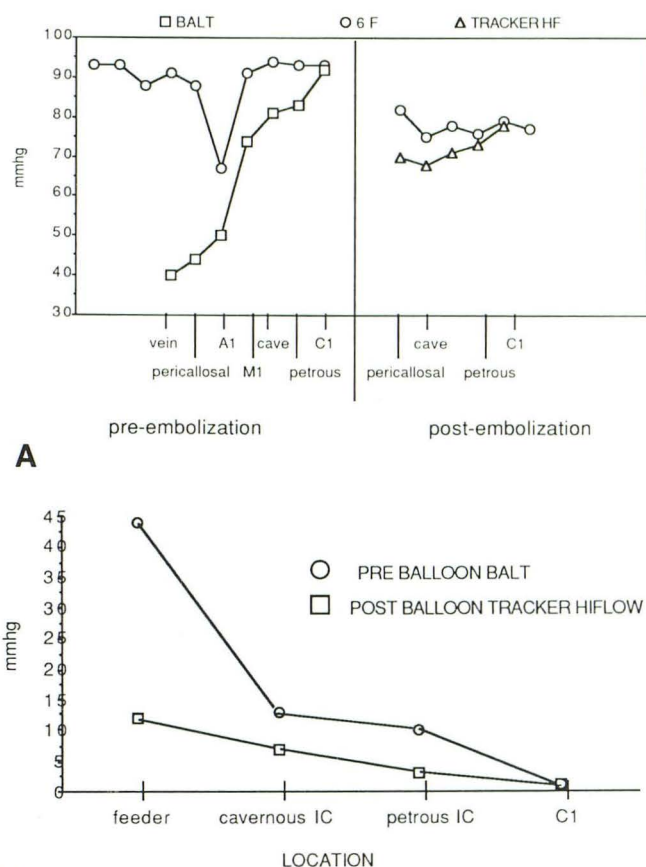
A, pre-embolization   post-embolization

B,

Fig. 8.—Case 3.

A, Simultaneous measurements of mean blood pressure from 6-French (6F) guiding catheter at C1, compared with Balt 1.8-French catheter from venous outlet to C1 and Tracker Hi-Flow (HF) from arteriovenous malformation (AVF) feeder to C1. Tracker measurements were obtained after balloon embolization of pericallosal AVF. As noted previously, Tracker Hi-Flow and Balt 1.8-French pressure measurements were not significantly different from those of the 6-French catheter when measurements were made at the same level (C1).

B, Net mean blood pressure measurements before and after balloon embolization. Data were obtained by subtracting pressures obtained with microcatheter from those obtained with 6-French guiding catheter (at level of C1). Net change in mean blood pressure at level of pericallosal feeder is 32 mm Hg.

vein = venous outlet; pericallosal = pericallosal feeder to AVF; A1 = A1 segment of anterior cerebral; M1 = M1 segment of middle cerebral; cave = cavernous internal carotid; petrous = petrosal segment of internal carotid; C1 = internal carotid at anterior arch of C1 vertebral body; IC = internal carotid artery.

transverse sinus showed substantial reduction in venous pressure. This was presumed to be the result of decreased arterial inflow. Because there was still extensive supply from the internal and external carotid system and an arteriovenous gradient was still present, transvenous embolization was performed using minicoils (Cook, Inc., Bloomington, IN) via the Tracker-25 catheter [20]. During the embolization, pressure measurements were obtained from the Tracker-25 catheter with corresponding angiograms and venograms. There was a consistently steady rise in the venous pressures to the point of equalization of venous and arterial pressures. At the point of equalization of the pressure gradient, angiography showed that there was no flow into the vein from the arterial side (Figs. 9D and 9E). The measurements with the Tracker-25 catheter were always obtained with the tip of the catheter at the sigmoid-transverse junction. Figure 10 graphically displays the data.
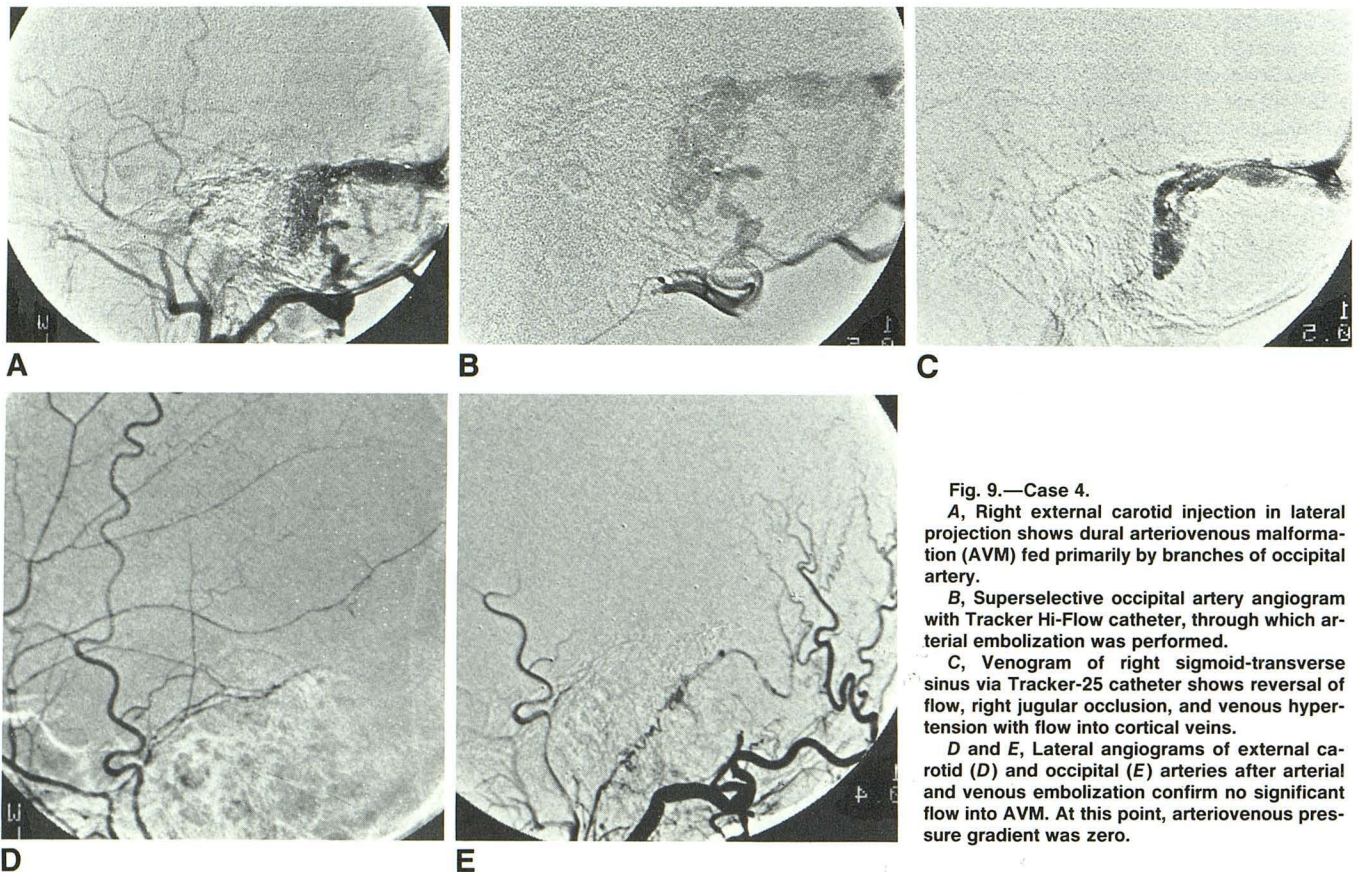
A **B** **C**

D **E**

Fig. 9.—Case 4.

A, Right external carotid injection in lateral projection shows dural arteriovenous malformation (AVM) fed primarily by branches of occipital artery.

B, Superselective occipital artery angiogram with Tracker Hi-Flow catheter, through which arterial embolization was performed.

C, Venogram of right sigmoid-transverse sinus via Tracker-25 catheter shows reversal of flow, right jugular occlusion, and venous hypertension with flow into cortical veins.

D and *E*, Lateral angiograms of external carotid (*D*) and occipital (*E*) arteries after arterial and venous embolization confirm no significant flow into AVM. At this point, arteriovenous pressure gradient was zero.
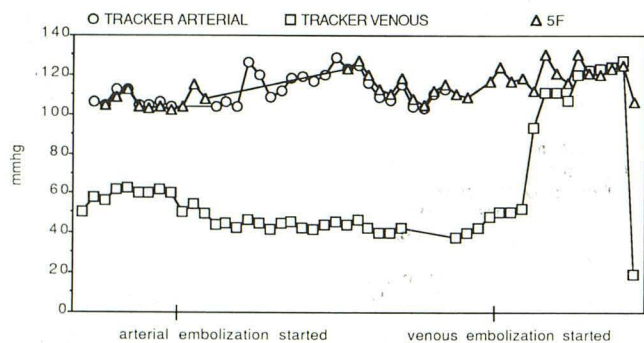

Fig. 10.—Case 4: Data from 5-French (5F) guiding catheter in external carotid artery, Tracker Hi-Flow in occipital artery, and Tracker-25 in sigmoid-transverse sinus during arterial, then venous, embolization. Venous pressures dropped during arterial embolization, then rose during transvenous embolization. The last data point on the venous pressure curve represents the mean pressure from the contralateral jugular bulb after embolization, representing the apparent normal pressure in the venous system (19 mm Hg).

Discussion

Accurate endovascular pressure measurements can be obtained with microcatheter systems. Both in the animal studies and clinical cases, there was excellent correlation between pressure measurements from the microcatheter systems and the larger coaxial catheters. When they existed,

measurement differences between the microcatheter and guiding catheter were constant in both the experimental and clinical studies. The Balt and Tracker Hi-Flow systems measured mean pressures equivalent to those obtained through larger catheters, while the Tracker-18 microcatheter measured means systematically 10 mm Hg above mean pressure from the guiding catheter. It is unclear why this occurred. The Balt catheter is constructed from a proximal 3-French metal–braided polyurethane compound attached to a distal tapered 2.5- to 1.8-French Pursil material (polyurethane-Silastic compound). The Tracker catheters are constructed from a poly-ethylene-polypropylene mixture. The Tracker Hi-Flow catheter tapers from an outer diameter of 3.2- to 2.8- to 2.2-French, while the Tracker-18 tapers from 3.0- to 2.2-French. Both are 2.7-French at the distal tip, which has a platinum coil for radiopacity. Perhaps the difference in the mean pressures obtained from the Tracker-18 is due to a difference in the diameter and/or construction materials. However, this is relatively unimportant, since pressure changes are probably the most critical variable to follow during endovascular therapy, and all three catheters are accurate for these measurements.

The measurements of endovascular pressures are reliable through a wide range of blood pressures. In the animal studies, mean pressures were manipulated with dopamine and nitroprusside. The microcatheter systems showed an equivalent response to these blood pressure changes when compared with larger coaxial 5- to 7-French catheters. In this study, we followed mean blood pressure rather than systolic

or diastolic pressure because the microcatheters do cause some damping of the pressure waveform as compared with the guiding catheter. This effect is probably due to the small diameter and long length of these microcatheters. However, the relative importance of the mean vs systolic or diastolic pressure is unclear at this time.

Correlation of the angiogram with the pressure measurements may provide greater understanding of the physiology of these lesions, which in turn can affect therapeutic decisions. In the case of the dural AVM (case 4), adequate therapy of the AVM was not achieved during arterial embolization. Since an arteriovenous pressure gradient still existed after occlusion of the occipital artery, the dural AVM recruited arterial supply from other branches of the external and internal carotid arteries. To eliminate that gradient, the distal transverse and sigmoid sinuses were occluded [5, 21]. With the elimination of the pressure gradient, there was no longer any angiographic evidence of inflow from the arterial feeders, and only then was the lesion sufficiently treated. The pressure measurement system, therefore, was valuable in determining the end point of therapy, as well as in deciphering the hemodynamic changes occurring during embolization. During embolization, pressure changes were identified prior to angiographically visualized changes in flow. Similar findings were seen by Jungreis et al. [14]. Pressure monitoring, therefore, may be important in the evaluation of the effectiveness of endovascular therapy. In the case of the brain AVF (case 3), pressure analysis confirmed the results seen in prior intraoperative experiments. These data can have important therapeutic implications, especially in the postprocedure management of systemic blood pressure.

Intracranial hemodynamic changes can be observed and monitored during diagnostic and therapeutic endovascular procedures. This may have important implications in evaluating the NPPB phenomenon. Although none of our patients had subsequent hemorrhage related to the endovascular procedure, it is possible that future studies may identify safe pressure changes that may be tolerated by surrounding brain tissue. In the one patient with a brain AVF, a net change of 32 mm Hg was seen after embolization. Fortunately, this did not lead to hemorrhage. Only with continued monitoring during endovascular procedures will adequate data be generated to verify the NPPB phenomenon, and possibly predict thresholds of pressure tolerance.

With the use of these new microcatheter systems, the field of neurointerventional procedures has expanded greatly. These catheters enhance our ability to treat aneurysms, AVMs, and AVFs. There has been a long-held belief that embolization procedures for AVMs are risky because of the NPPB phenomenon [4, 6]. However, by using microcatheters to directly measure the intravascular pressures, it is hoped that data can be generated to objectively evaluate the true nature of this phenomenon and the hemodynamic changes responsible for this complication of therapy. Although some physiologic information can be obtained by studying the anatomy, we need to go beyond this and acquire the quantitative physiologic data necessary to fully understand these lesions.

With the data we have obtained so far we believe it is essential to measure endovascular pressures during therapy, as it provides important insights into the progress of the treatment and the nature of the disease.

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