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Carotid Blood Flow in Man Determined by Video Dilution Technique: II. Vascular Abnormalities

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Carotid blood flows were evaluated in 31 individuals with vascular abnormalities using the video dilution technique. In patients with stenoses, angiographically estimated at 70%, blood flow was usually, but not always, measured less than normal. The technique proved to be useful in the evaluation of the efficiency of collateral arterial pathways and in the evaluation of superficial temporal–middle cerebral arterial bypass grafts. It was also helpful in estimating contralateral increase in arterial flows with cross compression techniques for the preoperative evaluation of patients subjected to carotid sacrifice. In a limited number of patients video dilution flows correlated with the degree or proximal arterial spasm and were useful in the preoperative study of these patients. The demonstration of flow abnormalities in patients with seizure disorders may be useful in the medical and surgical management of these individuals.

The measurement of carotid blood flows using video dilution technique (VDT) in vitro and in the canine model has been previously described in detail [1–3] and preliminary investigations of normal and pathological carotid blood flow have been reported [4, 5]. An expanded and comprehensive study of normal carotid blood flows in man appeared recently in this journal [6]. Briefly, video dilution technique possesses several advantages in the investigation of carotid blood flow over previously reported techniques [7–11]. These include: (1) low morbidity (only minimally increased contrast, examination time, and radiation exposure); (2) the highest degree of accuracy yet reported (95% confidence limits were −2.8% and +2.4%); and (3) ease of performance without additional cost to the patient, and little cost in additional equipment. This report describes our experiences with vascular abnormalities in man, with particular emphasis on atherosclerotic lesions of the carotid vascular system.

Materials and Methods

Thirty-one patients with primary vascular disease form the basis of this report: 16 men and 15 women, age range, 19–77 years with an average age of 51 years. Angiography was performed in all cases along with the video dilution flow measurements. Because of the hazard of dislodging atheromatous debris in the course of internal carotid catheterization, VDT was limited to the proximal common carotid artery in most cases with atheromatous disease. Although contralateral increased flow with carotid vascular cross compression is a normal physiologic response, it seemed appropriate to include this data, along with several cases of subarachnoid arterial spasm and altered flow states in seizure activity.

The video dilution technique, detailed elsewhere [6], will be restated briefly. During routine cerebral angiography, the fluoroscopic image intensifier is centered and locked in the midline position covering the proximal part of the aortic arch and the main arteries of the neck. The head is in the straight supine position. Video tape records injections of 25 ml meglumine diatrizoate (Conray 60, Mallinckrodt) by pressure injector in the ascending aorta, and 1 ml manual injection of identical contrast medium in the common or internal carotid arteries. The patient's position and respiration are ideally fixed during the study,

TABLE 1: **Carotid Blood Flow as Percentage of Cardiac Output Determined by Video Dilution Technique in 20 Normal Subjects at Rest**

Carotid Artery	Mean	Standard Deviation
Right common	8.5	0.9
Right internal	5.4	0.9
Right external	3.2	0.5
Left common	8.5	0.9
Left internal	5.3	1.0
Left external	3.3	0.4
Right common + left common	17.0	1.6
Right internal + left internal	10.7	1.6
Right external + left external	6.5	0.7

and the radiation intensity and gains of the television chain and recording equipment are constant during the individual injections of contrast material. A videodensitometer produces a mass-time curve when contrast material passes through a carotid artery. The area obtained from this curve is directly proportional to the amount of contrast medium and inversely proportional to the flow at the injection site. Thus, the ratio of carotid artery flow to aortic flow (essentially the cardiac output) is obtained by comparing the mass-time curves recorded from the two contrast injections. A summary of normal carotid blood flow determined by VDT is presented in table 1 [6].

To determine the degree of vascular stenosis, biplane angiographic views of the carotid vasculature were analyzed. An average of the degree of arterial radial stenosis, obtained from the anteroposterior and lateral or oblique projections, was made. This radius was then used to calculate the stenotic cross-sectional area. There are, of course, limitations to these measurements, including the assumption of a perfect cross section cylinder. However, some general results can be obtained by comparing the degree of stenosis to the obtained VDT flows.

Results

The results of carotid flow determinations in 31 patients with vascular abnormalities are considered in six clinically important situations.

Carotid Stenosis

Twenty measurements of VDT carotid blood flow were correlated with angiographic cross-sectional vessel stenosis. The results tend to confirm the previous impressions that significant decrease in flow occurs in the region of 70% stenosis, although a few cases recorded slightly decreased flows at less severe stenotic levels [12-15]. However, in two cases flow was greater than the normal median despite a 70% stenosis (fig. 1).

Case 1 presents an example of stability of internal carotid blood flow in the presence of severe external carotid stenosis. The patient was asymptomatic but had a left carotid bruit discovered on routine examination. The blood flow in the left common carotid artery was 6.2%, equivalent to a normal internal carotid blood flow and correlates with the finding of total external carotid occlusion. Further, despite
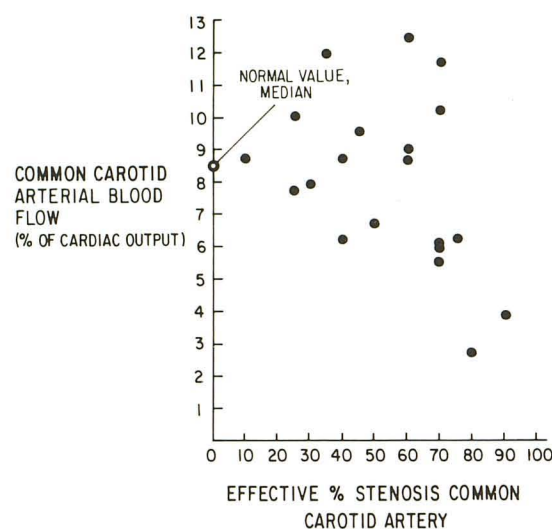
Fig. 1.—Comparison of video dilution technique carotid blood flow and regions of arterial stenosis.

an 85% stenosis of the right innominate artery, normal right common carotid flow (9%) was maintained (Fig. 2).

Case 2 demonstrates increased flow through a "highly" stenotic vessel. In this patient the left internal carotid artery was totally occluded. Seemingly excellent ipsilateral retrograde collateral flow from the left external carotid into the ophthalmic artery was demonstrated by angiography. However, the patient had persistent cerebral ischemic symptoms on that side. The left common carotid flow (essentially external carotid) was 4.3%, only minimally increased above normal external carotid values. The left posterior communicating artery did not fill from the posterior circulation. The right common carotid artery, although 60% effectively occluded, had an increased flow of 11.6% of the cardiac output. As shown by angiography, the latter figure includes cross circulation to the contralateral hemisphere (fig. 3). The combined total carotid flows were 15.9%, still somewhat decreased from an average normal total of 17%. The superficial temporal artery to middle cerebral artery (STA–MCA) bypass procedure resulted in alleviation of symptoms on the left.

Case 3 demonstrates the value of VDT in the evaluation of intracranial stenotic lesions. Although the lateral angiogram demonstrated only mild petrous carotid narrowing, and an angiographically *normal* middle cerebral circulation time, VDT showed a decreased left common carotid blood flow to 5.9%. The anteroposterior view demonstrated a severe stenotic narrowing of the horizontal segment of the middle cerebral artery (fig. 4). After STA–MCA bypass surgery for the stenotic middle cerebral lesion, the patient's ischemic symptoms disappeared. In some institutions, a lateral keyhole view of the neck and skull may be the only angiography performed, or the angiography concentrates on extracranial and not intracranial vessels. This case suggests the fallacy of this practice and demonstrates that VDT may be helpful in indicating the presence of hemodynami-

Fig. 2.—Case 1. Asymptomatic carotid bruits with coronary heart disease. A, Left common carotid arterial injection. Complete occlusion of external carotid artery with multiple areas of stenosis of cavernous and supraclinoid carotid artery (arrows). Flow left common carotid = 6.2%. B, Aortic arch angiogram. High grade stenosis of proximal innominate artery (arrow). Flow right common carotid = 9.0%.

A   B
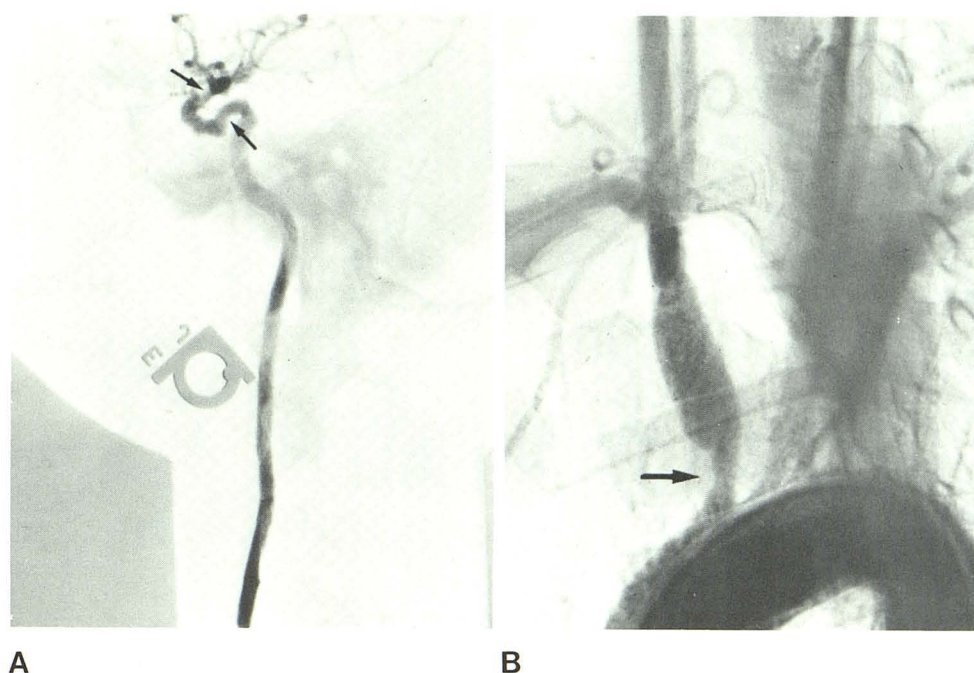
cally significant lesions, as well as the degree of severity in flow reduction when they are not otherwise demonstrated.

Superficial Temporal Artery–Middle Cerebral Artery Bypass

Case 4 shows the effectiveness of VDT in evaluating a superficial temporal–middle cerebral arterial bypass graft in that VDT measurements were consistent with good clinical result (fig. 5). Measurements show a left common carotid flow of 11.7%, and a right common carotid flow (effectively the bypass flow) of 7.8%. This patient did well after bypass surgery. The right common carotid flow is minimally reduced. There was minimal left to right anterior cerebral flow angiographically. The combined carotid flow of 19.5% (normal 17%) suggests an overall adequate supply to both hemispheres.

Case 5 illustrates the value of VDT in the postoperative assessment of superficial temporal–middle cerebral arterial bypass surgery. Angiograms performed in an outside facility demonstrated an almost total occlusion of both the left M1 middle cerebral arterial segment and the proximal external carotid artery. Areas of high-grade stenosis involved the supraclinoid segment of the right internal carotid artery as well as the proximal M1 segment of the right middle cerebral artery (fig. 6). An endarterectomy was successful in alleviating the left external carotid stenosis (fig. 6). A successful left STA–MCA bypass was performed (which was patent angiographically, postoperatively). Some left-to-right intracranial cross filling was observed following surgery. At that time, VDT revealed an increased left common carotid flow (14.0%). A decreased right common carotid flow (6.4%) probably reflects the continued presence of a right intracra-

nial arterial stenosis, as well as left-to-right intracranial cross filling.

Cross Compression Technique

Cross compression technique refers to a maneuver whereby compression of the extracranial part of a common carotid artery may result in ipsilateral intracranial flow from the noncompressed contralateral carotid circulation. Cross compression has been used to assess the ability of the contralateral carotid to supply both cerebral hemispheres if surgical sacrifice of the ipsilateral carotid artery is contemplated [16].

Case 6 demonstrates the increase possible in carotid blood flow contralateral to the side of carotid compression (fig. 7). This patient presented with the clinical suspicion of a recurrent right neck carcinoma without obvious invasion angiographically of the right internal carotid. However, the possibility existed that this vessel might have to be sacrificed at surgery. VDT flow of the left internal carotid artery was 9.0% before cross compression and 20.8% after. Thus, VDT demonstrates doubling of flow in the left internal carotid during this maneuver.

However, the angiographically excellent intracranial cross filling during cross compression does not necessarily mean any real increase in carotid blood flow, as case 7 demonstrates (fig. 8). The angiogram showed slight external carotid irregularities (secondary to previous carcinoma resection), but a patent internal carotid artery, both intra- and extracranially. Some intracranial cross filling and extracranial cross filling, both right to left, through the external system (considered a result of prior surgery on the left neck) was observed. The VDT left common carotid flow was markedly
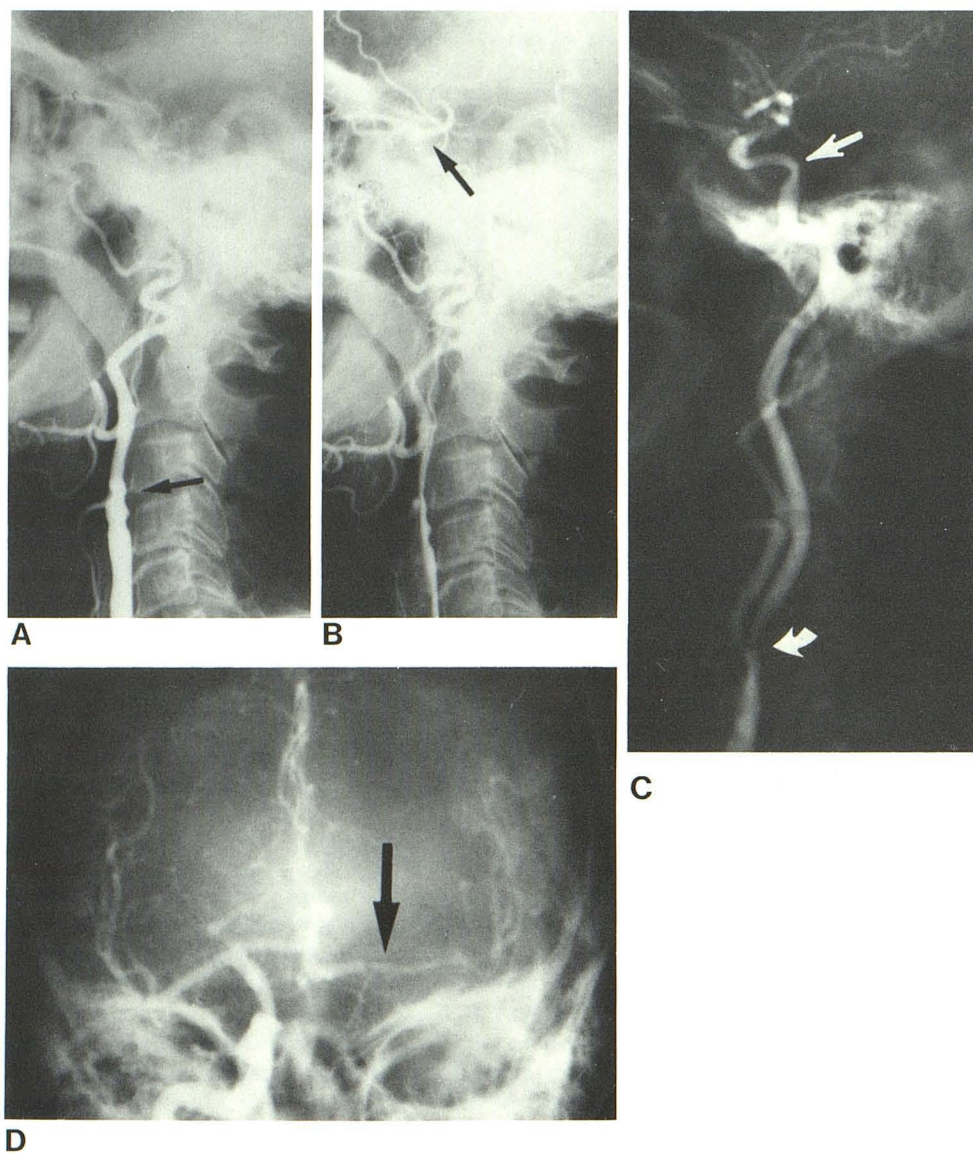
Fig. 3.—Case 2. Hypertension, transient ischemic attacks left hemisphere. **A,** Early arterial phase, lateral left common carotid angiogram. Total occlusion of internal carotid artery (*arrow*). Flow left common carotid = 4.3%. **B,** Late arterial phase. Retrograde filling of left internal carotid artery (supraclinoid segment) (*arrow*) via external ipsilateral collaterals supplies left middle cerebral circulation. **C,** Arterial phase, right common carotid injection. High grade stenosis of carotid bifurcation (*curved arrow*) and moderate stenosis of cavernous internal carotid (*arrow*). Flow right common carotid = 11.6%. **D,** Anteroposterior right carotid angiogram, arterial phase. Cross filling, right to left, into left middle cerebral artery (*arrow*).
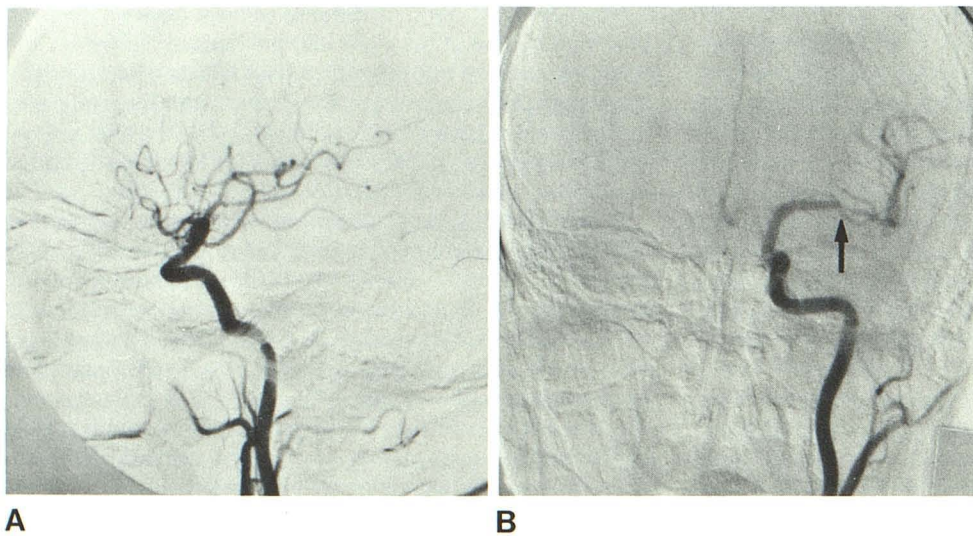

Fig. 4.—Case 3. Transient ischemic attacks, right arm, subacute (1 week). Arteriograms. **A,** Lateral left common carotid. No apparent stenotic lesions. **B,** Anteroposterior left common carotid. High grade stenosis of left M1 middle cerebral arterial segment (*arrow*). A1 anterior cerebral segment is narrowed or congenitally hypoplastic. Common carotid flow: left = 5.9%, right = 14.1%.

Fig. 5.—Case 4. Previous transient ischemic attacks, right hemisphere. **A**, Arterial phase, right common carotid arteriogram. Complete occlusion of right internal carotid artery. **B**, Postoperative superficial temporal artery–middle cerebral artery bypass angiogram, right common carotid. Bypass is widely patent (*arrow*) with excellent filling of middle cerebral artery. Common carotid flow: right = 7.8%; left = 11.7%.

A   B
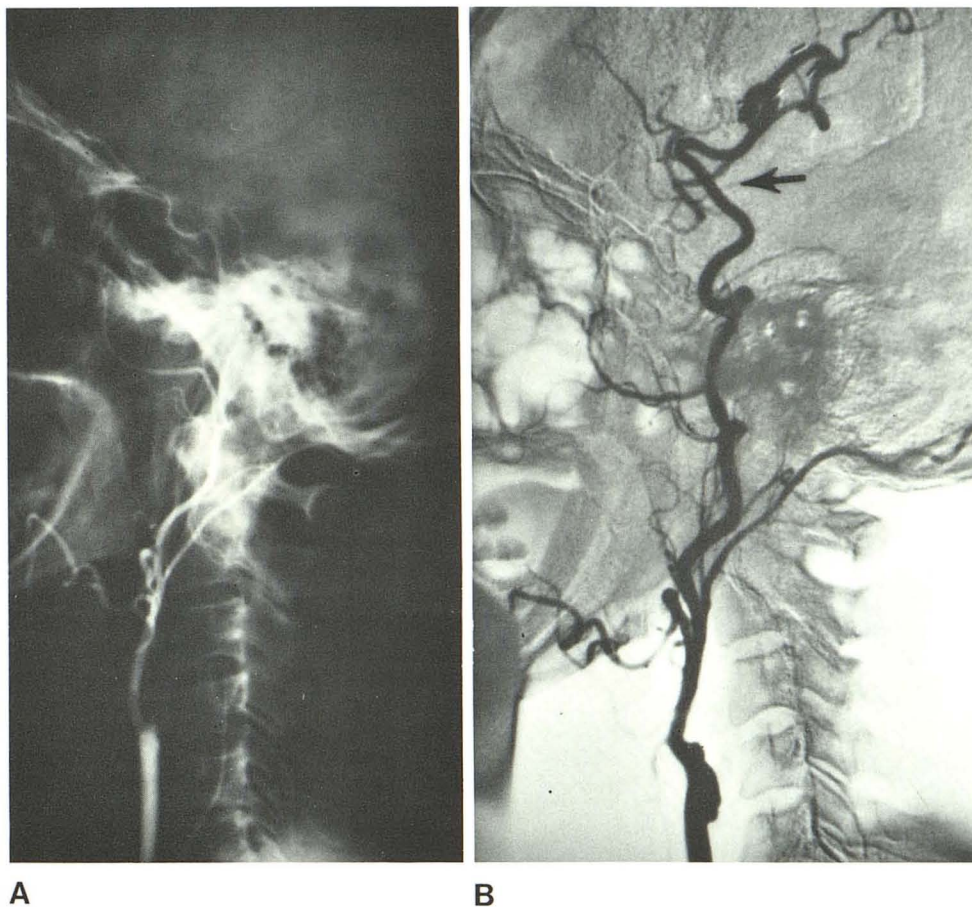
decreased (4.9%), presumably due to lack of significant external flow on the left, and some right to left intracranial flow. Pre- and post-left cross compression, no change in the right common carotid blood flow was observed (15.5%). Thus, this case suggests that the right common carotid was already near peak cross filling capability, or that the left neck compression was inadequate.

Cross compression may demonstrate no cross filling (case 8) but VDT may show some increase in flow after cross compression (10.8% before, 13.3% after carotid compression) (case not illustrated).

Cerebral Infarction

Two cases illustrate the use of VDT in cerebral infarction. Case 9 shows increased internal carotid flow on the side of an acute infarction (fig. 9). Case 10 was an individual with acute right arm transient ischemic attack and a history of multiple old bilateral infarcts. While both CT and angiography were unremarkable for age, both common carotid arterial flows were decreased (right 6.1%, left 5.7%) (not illustrated). Thus, these two cases demonstrate differing results with infarcts of differing ages.

Arterial Spasm

In several cases VDT evaluated cerebral blood flow in the presence of various degrees of arterial spasm secondary to subarachnoid hemorrhage.

At angiography, case 11 had an anterior communicating artery aneurysm with spasm of the left supraclinoid internal carotid artery and less severe involvement of the right supraclinoid segment (fig. 10). A mild right hemiparesis was present. VDT carotid blood flow demonstrated a normal right flow but with a diminished left common carotid flow (6.0%) compatible with the angiographic and clinical status.

Case 12 had subarachnoid hemorrhage in a right middle cerebral aneurysm. Mild middle cerebral arterial spasm was noted bilaterally, right greater than left. The right common carotid blood flow was 6.2% (decreased), the left normal was 8.7% (not illustrated). These two cases demonstrate some correlation between spasm and carotid blood flow.

Seizures

Two cases of seizure disorder are included because seizure disorders in general may occasionally represent a focal disorder in blood flow [17]. Case 13 showed normal CT and
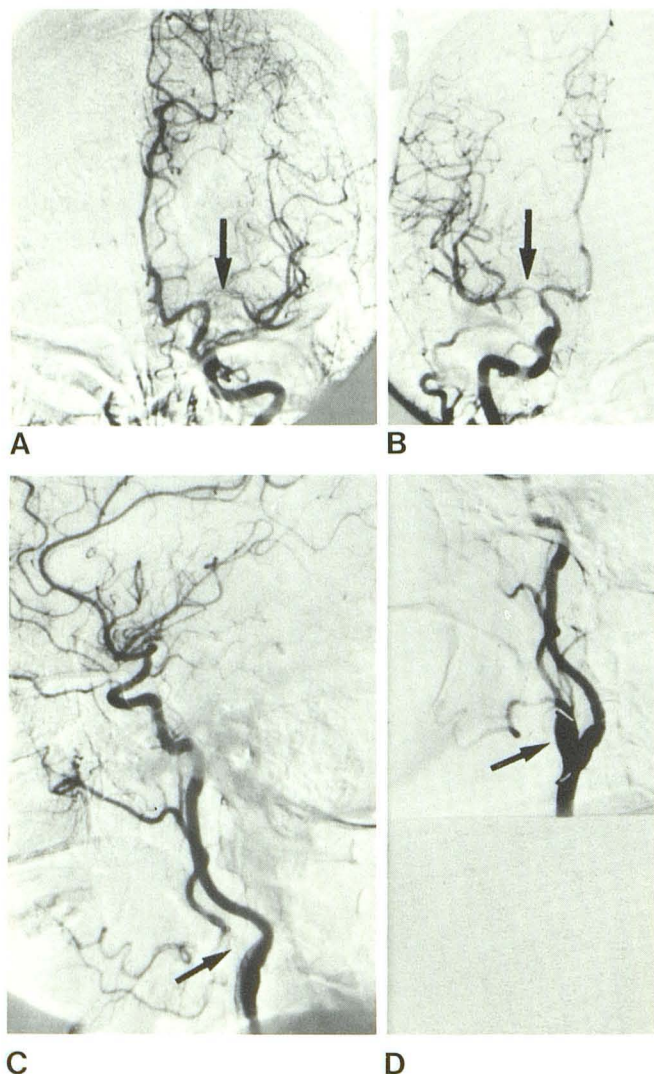
A **B**

C **D**

Fig. 6.—Case 5. Stroke, right arm and leg. Arteriograms. **A,** Left common carotid. High grade stenosis of left M1 arterial segment (arrow). **B,** Right common carotid. Narrowing of supraclinoid internal carotid with area of high grade stenosis of M1 arterial segment (arrow). **C,** Left common carotid. High grade stenosis of proximal external carotid artery (arrow). **D,** Postoperative left lateral view, common carotid. External carotid occlusion has been corrected (arrow). Common carotid flow: left = 14.0%, right = 6.4%.

angiography. The patient suffered from electroencephalo-graphically-determined right temporal lobe seizure and had experienced seizure 1-2 hr before the VDT flows were obtained. The right common carotid flow was increased to 10.0% while the left was markedly decreased to 5.0% (not illustrated).

A second case, case 14, also suffered from right temporal lobe seizures but with some generalized component as well. There was a questionable CT suggestion of atrophy of the right temporal lobe. The cerebral angiogram was itself entirely normal. The patient's general mental level was somewhat confused and slightly retarded. The VDT flows showed bilateral decreased common carotid flow rates (5.1% right, 5.7% left) (not illustrated). This may reflect a generalized pattern of damage at the arteriocapillary level.

Discussion

Part of Poiseuille's law [18] states that the volume of flow in a tube is directly proportional to the fourth power of the radius of the tube. However, Mann et al. [19] showed in 1938 that a 50% stenosis could be present in the canine carotid artery without any reduction in blood flow, and that further a stenosis of up to 90% might be necessary before a 50% reduction in blood flow would occur. Although there has been some continuing controversy on the subject, most authors tend to support the general hypothesis that Poiseuille's law does not apply to measurements in vivo, and that a 50%–90% reduction in the cross-sectional area of a vascular lumen must be present before significant flow decrease is demonstrated [12–15]. Figure 1 and the cases presented demonstrate that one cannot accurately predict a decrease in carotid blood flow from the degree of angiographically demonstrable carotid stenosis. In fact, two cases demonstrated *an increase* in carotid blood flow despite 60%–75% carotid stenosis. The latter phenomenon presumably compensates for even more severely decreased contralateral carotid flow by interhemispheric cross filling.

Estimation of external carotid blood flow in individuals with internal carotid stenosis may aid in assessing the true degree of flow through angiographically demonstrable collateral channels. This in turn may be useful in selecting

Fig. 7.—Case 6. Recurrent right tonsillar carcinoma. Cross compression of right common carotid. Left common carotid injection shows excellent left-to-right intracranial cross circulation. Flow left internal carotid before compression = 9.0%, after = 20.8%.
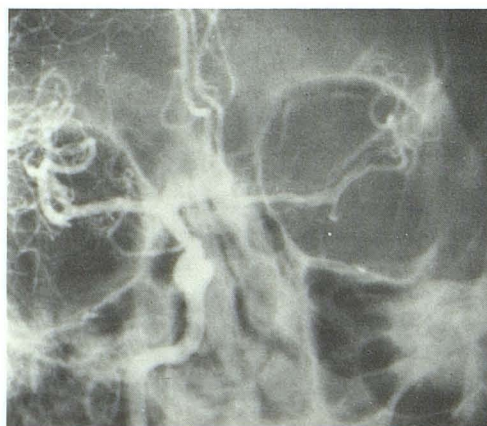
Fig. 8.—Case 7. Left temporal bone carcinoma, recurrent. Cross compression of left common carotid artery during right common carotid arteriogram. Excellent right-to-left intracranial cross circulation. Flow right common carotid before compression = 15.5%, after = 15.5%. Flow left common carotid = 4.9%.

7 **8**

Fig. 9.—Case 9. Right arm/leg transient ischemic attacks. Left middle cerebral infarction. **A**, Left lateral carotid angiogram. Delayed filling of left middle cerebral arterial branches. Internal carotid flow: left = 8.0%, right = 5.9%. **B**, Capillary phase. Delayed retrograde filling of left middle cerebral opercular branches through ipsilateral anterior cerebral arterial supply (*arrows*). Reprinted from [5].
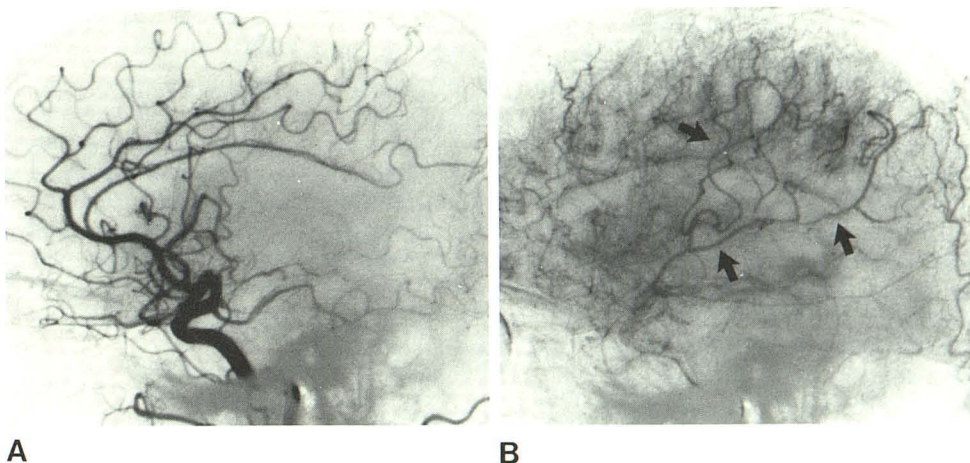

A   **B**

Fig. 10.—Case 11. Acute subarachnoid hemorrhage. **A**, Oblique right internal carotid arteriogram. Spasm of supraclinoid internal carotid artery and M1 segment (*white arrows*). Anterior communicating artery (*arrow*). Flow right common carotid = 8.3%. **B**, Lateral angiogram, left internal carotid. Spasm of supraclinoid internal carotid artery demonstrated. Flow left common carotid = 6.0%.

A   **B**
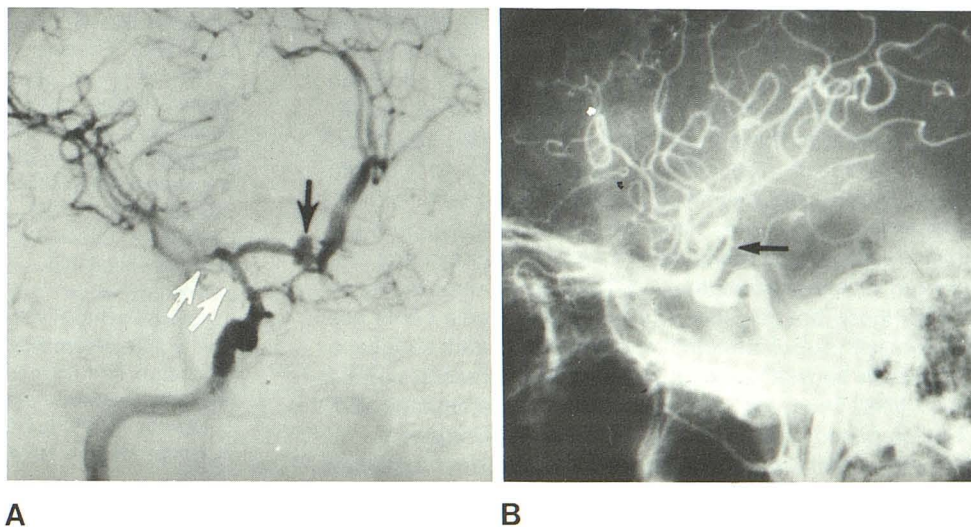
asymptomatic patients for possible superficial temporal artery–middle cerebral artery bypass surgery. Dublin and Richey [20] previously demonstrated false occlusions of superficial temporal artery–middle cerebral artery bypass grafts as a result of arteriographic artifacts. VDT can give an accurate assessment of flow through such bypasses and may be helpful in following such patients postoperatively.

Occasionally, patients with severe cardiac, abdominal, aortic, or peripheral vascular disease may have asymptomatic carotid stenosis. Coronary bypass surgery often results in periods of hypotension that may compromise the brain in individuals with significant carotid stenosis. In such cases, surgeons may endarterectomize the carotid arteries before undertaking coronary bypass surgery [21]. However, this puts the patient at risk for intraoperative cardiac complications. Thus, VDT analysis of angiographically demonstrable carotid stenoses can be useful in helping the surgeon decide whether coronary bypass or carotid endarterectomy should be performed first. An individual in our series had a narrowed right common carotid artery (50% stenosis) but a normal VDT blood flow. Cardiac bypass surgery was performed with excellent results.

Cross compression technique is frequently used to assess the ability of a single carotid artery to supply most supratentorial cerebral circulation, in cases where surgical sacrifice of the contralateral carotid artery is contemplated. What has been assumed, but not known precisely, is whether a noncompressed carotid flow actually does increase during cross compression. In addition, Hieshima has suggested that this method may not be reliable due to variabilities in the efficacy of compression (G. Hieshima, personal communication, 1980). This may be particularly true in cases of postsurgical or irradiated carcinomas, due to overlying scar tissue that prevents adequate compression of the ipsilateral carotid artery. Thus, Hieshima prefers the intravascular balloon occlusion of the carotid vessels to maximally test the brain to withstand sacrifice of the carotid. However, this technique is not without risk, including transient ischemic attack, and embolic complications. VDT represents a safer alternative to evaluate the efficacy of cross compression.

The evaluation of blood flow of affected hemispheres has been undertaken in patients with cerebral infarction [22–24]. Taveras et al. [25] evaluated focal hemispheric blood flow as estimated by angiographic circulation times.

Various patterns were observed including increased circulation times seen 5–29 days after injury (presumably due to arteriolar capillary block) and increased flow, presumably due to the vasodilatation effect of ischemia seen 1–17 days after insult [25]. Case 9 (an acute infarction), demonstrates increased internal carotid blood flow on the side of infarction. This phenomenon probably reflects the so-called "luxury perfusion" described by Lassen [26] and the increased circulation rate described by Taveras et al. [25]. In case 10 (multiple old bilateral infarcts), both common carotid arterial flows were decreased. One might speculate on possible causes of this decreased carotid flow without carotid stenosis. In view of the absence of cerebral atrophy or old infarction on CT (as was the case in our patient), other factors must be considered. Thus again the angiographic evidence may not accurately describe the flow patterns occurring in the carotid arteries.

The angiographic assessment of postsubarachnoid arterial spasm for planning medical management and the timing of surgical intervention has been controversial [27, 28]. There is some evidence that spasm may adversely affect the outcome of surgery due to poor preoperative and intraoperative cerebral perfusion [28]. One author (ABD) has noted that while spasm may indicate a poor prognosis in some cases, this is not always true. Conversely, patients with no evidence of spasm may have decreased angiographic circulation times, increased intracranial pressures, and decreased levels of mentation. VDT offers an opportunity to assess these phenomena. While we have studied only two patients with subarachnoid hemorrhage, the data suggest a correlation between arterial spasm and decreased carotid blood flow. Thus, VDT may aid in the clinical management of these patients and is worthy of further investigation.

Previous authors have reported that seizure foci may show angiographic stain, and arteriovenous shunting shortly after electroencephalography, and/or clinical evidence of seizure activity [29, 30]. In one case of seizure disorder evaluated by VDT, 1–2 hr after an active seizure, increased flow was observed. This finding correlates with suggested angiographic arteriovenous shunting [29, 30]. The second case of seizure disorder was chronic in nature, and demonstrated bilaterally decreased common carotid flows. This case may reflect a generalized pattern of damage at the arteriocapillary level.

The most important observations from the preliminary experience with VDT appear to be as follows.

Generally, a 70% decrease in a cross-sectional area of a vessel produces a decrease in blood flow through the affected lumen. However, *increases* in blood flow were observed with 50%–75% cross-sectional area stenosis, and several cases of 75% or more stenosis had about 75% normal carotid blood flow.

External carotid ipsilateral collateral pathways, in the presence of high grade or total internal carotid arterial occlusion, may not produce sufficient flow rates to compensate for these occlusions, although these collaterals appear to be generous angiographically. In such cases, the degree of VDT flow reduction more closely matched the severity of symptoms.

Manual neck cross compression of carotid vessels has variable effects: little increase in contralateral VDT carotid flow, compatible with the angiographic findings; little increase in contralateral VDT carotid flow, despite excellent angiographic contralateral opacification; or increase in VDT contralateral carotid flow compatible with angiographic cross midline filling.

Decreased carotid blood flows may be observed by VDT that correlate with clinical signs and symptoms, even though the angiographic evidence of vascular occlusion or CT abnormality is lacking.

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