Intraoperative Measurement of Javid Shunt Flow With Transit-Time Ultrasound

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Transit-time ultrasound methods were used to measure blood flow in 37 patients undergoing carotid endarterectomy. Internal carotid flow before (ICF^{bef}) and after (ICF^{aft}) endarterectomy was measured with a 6 mm perivascular probe, and Javid shunt flow (SF) was measured with a clamp-on probe. For the entire group ICF^{bef} averaged 117 ± 67 ml/min and ICF^{aft} was 173 ± 67 ml/min. Shunt flow averaged 123 ± 51 ml/min. The differences between ICF^{bef} and ICF^{aft} and between SF and ICF^{aft} were significant (ANOVA, $p < 0.01$) but the difference between ICF^{bef} and SF was not. The relationship between ICF^{bef} and SF appeared to define two groups of patients. Those in whom SF was greater than ICF^{bef} (SF > ICF^{bef}) had more stenosis evident on preoperative arteriograms (64.7% ± 14.55% maximum single diameter stenosis) and a greater average increase in ICF (151% ± 159%) than those with SF ≤ ICF^{bef} (43.3% ± 20.9% stenosis and 34% ± 54% increase in ICF), suggesting that the relationship between SF and ICF^{bef} defines groups with different hemodynamic responses. The similarity between SF and ICF^{bef} indicates that Javid shunt flow offers adequate protection from cerebral ischemia. A practical benefit of the shunt clamp-on flow probe is the ability afforded to recognize shunt occlusions. (Ann Vasc Surg 1994;8:571-577.)

Common carotid to internal carotid shunts are commonly employed during carotid surgery based on the principle that during carotid clamping shunts maintain adequate cerebral perfusion to protect against ischemic cerebral injury.[1,2] Despite many clinical studies employing EEG monitoring to support this hypothesis, few studies have directly measured intraoperative shunt or carotid flow, and the hemodynamic evidence that cerebral perfusion is adequately maintained by shunting has depended on indirect measurements with ^{133}Xe washout measurements of regional cerebral perfusion[3,4] or duplex ultrasound assessment of middle cerebral artery flow velocities.[5,6] These techniques are difficult to apply and have not been widely adopted for monitoring flow during carotid surgery. Because of the paucity of studies and the inaccuracy of techniques available in the past, there are no widely accepted values for blood flow (ml/min) during carotid surgery. Some have suggested that the Javid shunt may actually limit flow in the manner of a critical stenosis because of its dimensions,[7] thus compromising the goal of cerebral protection. Inasmuch as the Javid shunt is probably the most commonly employed shunt in the United States (Walcott C. Personal communication, 1993), its hemodynamic performance is of practical importance.

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MATERIAL AND METHODS

Taking advantage of the ability to measure bulk flow with the relatively improved technique of transit-time ultrasound,[8] we measured flow in the internal carotid artery and Javid carotid shunts during surgery with the aim of characterizing the performance of the shunt and the relation between shunt and internal carotid flow before and after endarterectomy. Patients undergoing carotid endarterectomy had flow in the internal carotid artery measured with perivascular transit-time probes before and after carotid reconstruction. Flow in the Javid carotid shunt was measured with clamp-on probes specifically engineered for this purpose.

All patients were from the Vascular Surgery Service of the Veterans Administration Medical Center, Long Beach, California, and were studied using a protocol approved by the institutional review board. Between April 1991 and May 1993, thirty-three patients underwent a total of 37 carotid endarterectomies for either critical stenosis or embolic phenomena. Each patient underwent preoperative contrast arteriography of the cerebral circulation. In four patients the operation was performed to correct an asymptomatic stenosis and in nine (24.3%) large ulcerated plaques were detected by arteriography in the absence of significant stenosis but in the presence of symptoms. General anesthesia and standard endarterectomy techniques using a longitudinal incision from the common carotid into the origin of the internal carotid artery were employed. A Javid shunt (C.R. Bard, Inc., Billerica Mass.) was placed in each patient. Patch angioplasty was not used as the caliber of the internal carotid artery and bulb was large enough to accept a shunt, eliminating concern that a stenosis would be created by the closure of the arteriotomy. Internal carotid flow (ICF) was measured with a T207 flowmeter and an S series 6 mm diameter perivascular probe (Transonic Systems, Ithaca, N.Y.). The perivascular probe was applied to the site dissected on the internal carotid artery for vascular clamp application to measure flow before cross-clamping (ICF^{bef}) and again after completion of the endarterectomy and removal of clamps (ICF^{aft}). The ICF^{aft} measurement was performed when the patient was hemodynamically stable and at least 5 minutes after restoration of carotid flow to allow cerebral autoregulatory responses to stabilize. A specially designed transit-time clamp-on probe was applied to the shunt to measure shunt flow (SF). In the early part of this series the probe was clamped to the shunt prior to insertion. This moderately increases the difficulty of shunt insertion because of the cable that connects the probe to the flowmeter, and our current practice is to apply the probe to the shunt only after flow is established.

Sterile gel (Aquasonic 100, Parker Laboratories, Orange, N.J.) was used as an acoustic medium between the arteries or the shunt and the probe. Flow measurements were permanently recorded with the use of an IBM 286 microcomputer connected to the flowmeter in conjunction with a software program supplied by the company. The peak flow found over 30 seconds with the 0.1 Hz flowmeter output was later printed out to determine flow based on analysis of the printed waveforms. Because transient hyperemic elevations were often seen in the initial SF measurement found immediately after shunt placement and restoration of distal carotid flow, the SF measurements chosen for analysis were always taken from the period immediately before removal of the shunt when a stable equilibrium was present. The percentage change in internal carotid flow (%ΔCF) achieved by endarterectomy in individual patients was calculated as $100 \times (ICF^{aft} - ICF^{bef})/ICF^{bef}$.

The perivascular probes and clamp-on probes were calibrated with a bench-top continuous-flow circuit using water. True flow was measured v[illegible] a graduated cylinder and stop watch and co[illegible]pared to the 0.1 Hz flowmeter measurement. The maximum single diameter stenosis affecting the internal carotid artery present in each patient's preoperative arteriogram was calculated by measuring the smallest diameter involving the carotid bulb or proximal internal carotid artery and the diameter of the normal internal carotid artery distal to the stenosis and any poststenotic dilatation.[9] The statistical significance of differences between groups was determined with ANOVA using a microcomputer program (GraphPAD Instat, San Diego, Calif.).

RESULTS

The 6 mm perivascular probes and the clamp-on Javid shunt probes were supplied after calibration by the manufacturer. Our bench-top flow circuit calibration confirmed that the correlation between true and measured flows was good enough to use the transit-time measurements without adjustment (Fig. 1). Fig. 2 represents typical flow tracings recorded during an endarterectomy. Both pulsatile flow vs. time waveforms and time-averaged flow tracings are shown.

The results of ICF^{bef}, ICF^{aft}, SF, %ΔICF, and percentage stenosis for all 37 patients are sum-

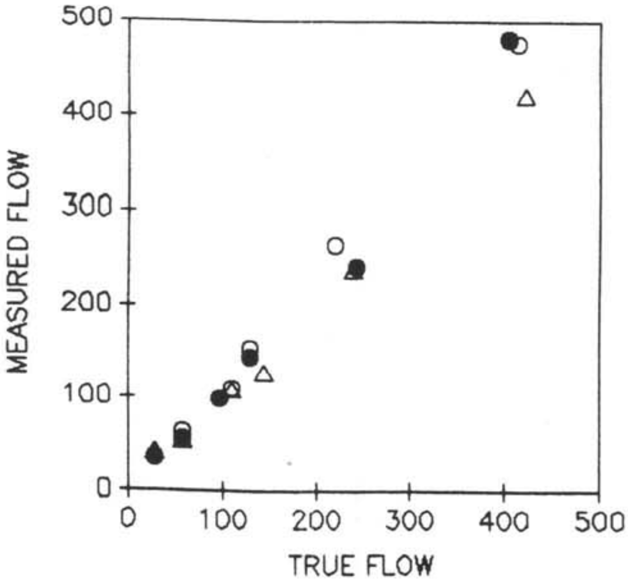

Fig. 1. Calibration data for clamp-on transit-time shunt probes. Three different probes (closed circles, open circles, and triangles) underwent comparison of true and measured flows. The slope of the line that best fits all data points by linear regression analysis is 1.1 with a correlation coefficient of 0.99.

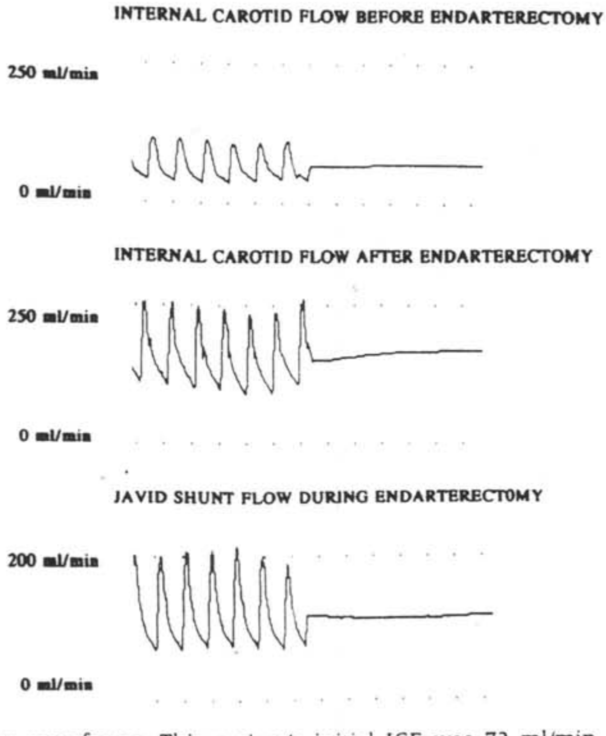

Fig. 2. Typical flow waveforms. This patient's initial ICF was 72 ml/min, final ICF was 165 ml/min, and initial SF was 195 ml/min falling to the equilibrium value of 115 ml/min. One second elapses between each dot with the bottom row corresponding to 0 flow and the top row to a preset value (250 ml/min for the 6 mm probe and 200 ml/min for the clamp-on probe).

Table I. Summary of results for all 37 patients

Group	ICF^{bef}	ICF^{aft}	SF	% Increase ICF	% Stenosis
All	117 ± 67	173 ± 67	123 ± 51	97 ± 135	54.8 ± 20.9
$SF > ICF^{bef}$	86 ± 55	152 ± 41	142 ± 56	151 ± 159	64.7 ± 14.55
$SF \leq ICF^{bef}$	155 ± 62	197 ± 82	101 ± 35	34 ± 54	43.3 ± 20.9

marized in Table I. For the entire group the mean value for ICF^{bef} was 117 ± 67 (SD) ml/min with a low value of 10 ml/min and a maximum value of 300 ml/min. ICF^{aft} was 173 ± 67 ml/min with the lowest flow observed being 60 ml/min and the highest being 400 ml/min. SF was 123 ± 51 ml/min for the entire group (minimum 45, maximum 280). For the entire group the difference between ICF^{bef} and ICF^{aft} was highly significant ($p < 0.001$), as was the difference between SF and ICF^{aft} ($p < 0.01$). The difference between ICF^{bef} and SF was not significant (uncorrected $p = 0.727$). The percentage change in ICF determined by averaging the %ΔICF for each patient was 97 ± 135 as opposed to an increase of 47.9% based on the aggregate means of ICF^{bef} and ICF^{aft}. ICF increased in 30 patients and decreased in only seven. Among patients in whom decreased ICF was observed, the maximum decrease was 34.6% (190 ml decreasing to 128 ml/min). None of these seven patients developed a neurologic deficit. The average preoperative maximum single diameter stenosis evident on the preoperative arteriograms was 54.8% ± 20.9% for the entire group.

When the data were analyzed based on the relationship between ICF^{bef} and SF, the patients were divided into two groups of comparable size; 20 patients in whom SF was greater than ICF^{bef} ($SF > ICF^{bef}$) and 17 in whom SF was less than or equal to ICF^{bef} ($SF \leq ICF^{bef}$). Table I also shows the average flow measurements and stenosis for these two groups. Two statistically significant distinctions between the $SF > ICF^{bef}$ and $SF \leq ICF^{bef}$ groups are discerned. The lower value for ICF^{bef} observed in the $SF > ICF^{bef}$ group was significantly lower than that of the $SF \leq ICF^{bef}$ group (86 ± 55 ml/min vs. 155 ± 62 ml/min, $p < 0.05$). In addition, the normalized percentage increase in ICF (%ΔICF) was much greater in the $SF > ICF^{bef}$ group than in the $SF \leq ICF^{bef}$ group (151% ± 159% vs. 34% ± 54%, $p < 0.001$). Although the $SF > ICF^{bef}$ group tended to have more arteriographic stenosis (64.7% ± 14.55%) than either the entire group (54.8% ± 20.9%) or the $SF \leq ICF^{bef}$ group (43.3% ± 20.9%), the differences were not significant.

In 18 of the 37 patients we recorded the initial shunt flow to compare with the final shunt flow present after initial autoregulatory responses had subsided. The average initial shunt flow was 162 ± 88 ml/min (minimum 45, maximum 400) compared to 124 ± 51 ml/min (range 75 to 280 ml/min) for the equilibrium shunt flow observed at the conclusion of the endarterectomy in these 18 patients. We noted that the decrease in the initial shunt flow was gradual and generally equilibrium was not reached for at least 5 minutes. Initial shunt flow was significantly greater than equilibrium flow ($p = 0.0136$, two-tailed paired t test) and in only four patients was the initial shunt flow less than the final flow.

Performance of these flow measurements erally added approximately 10 minutes to the endarterectomy procedure. There were no infections, no deaths, and one minor stroke within 30 days, and one patient had permanent monocular blindness after an emergency operation for crescendo amaurosis. The two neurologic complications were attributed to embolic phenomena inasmuch as flow values were high at the conclusion of the surgery and subsequent duplex ultrasound examinations revealed no technical problems.

In one patient the initial shunt flow measurement showed only intermittent flow and the displayed waveform demonstrated wild fluctuations. We attributed this to the tip of the shunt being intermittently occluded when it was pressed against the distal artery wall. The flow abnormality was easily corrected by repositioning the tip of the shunt. In the remainder of the patients decreases in flow were occasionally detected when shunts were transiently kinked or sharply bent. These decrements in shunt flow never persisted because shunt flow was monitored continuously.

DISCUSSION

Our experience indicates that Javid shunt flow and internal carotid flow can be measured without adding to the technical difficulties of endarterectomy and with only minimal prolongation of surgery. The safety of endarterectomy may be enhanced inasmuch as shunt occlusions should be preventable with this technique, although our complication rate was no better than that reported with other methods of cerebral monitoring or technical evaluation of arterial reconstructions.[3,9,10] Shunt occlusions do occur[11,12] and in this series we observed one initial occlusion, which was easily recognized and corrected. Others have suggested that the ability to monitor shunt flow during surgery would be of practical benefit, and a shunt with a built-in Doppler probe has undergone preclinical testing and development.[13] Whether adding routine transit-time ultrasound shunt flow monitoring to carotid endarterectomy will actually improve its safety or is of practical value is a question that cannot be answered based on our experience. The fact that it can be done does not necessarily justify the procedure, particularly since most strokes resulting from carotid surgery are probably due to intraoperative embolism or postoperative thrombosis rather than to shunt occlusions; perhaps a ›perative study involving multiple centers could address this issue.

In a previous study in which ICF was measured with electromagnetic flowmeter methods, ICF^{bef} averaged 133 ml/min and increased to 212 ml/min after endarterectomy.[14] Others have found ICF^{aft} to be 164 ml/min[15] and 254 ml/min (this latter measurement may not be directly comparable because the external carotid artery was clamped during the measurement.[16] ^{133}Xe measurements of regional cerebral flow are difficult to directly correlate with flow, but assuming there is no collateral flow to the ipsilateral hemisphere when the internal carotid artery is open and the cerebral hemisphere weight is 500 gm[17] and regional cerebral flow is 50 ml/100 gm/min, internal carotid flow should be 250 ml/min. Duplex ultrasound studies have yielded a higher value of 286 to 330 ml/min for normal volunteers.[18,19] Our measurement of 173 ml/min as the mean internal carotid flow after endarterectomy is in fair agreement with these data, given that electromagnetic and duplex ultrasound methods are difficult to calibrate in clinical settings. The accuracy and validity of transit-time measurements are supported by several studies[20-22] and these measurements have become standard in physiologic studies in animals.

The average value for maximum single diameter stenosis of 54.8% that we measured in our patients' arteriograms is somewhat lower than most vascular surgeons expect to find. Given the fact that veterans tend to have more severe vascular disease than the general community population, we believe this discrepancy is due not only to the high frequency of symptomatic carotid ulceration without significant stenosis that we found but also to the stringent method we use to measure stenosis. Our measurement compares the smallest diameter in the path from the common carotid to the internal carotid artery and compares it to the normal caliber internal carotid artery distal to the lesion. Comparisons of the smallest diameter to other portions of the flow path such as the bulb will invariably exaggerate the degree of stenosis believed to be present.

The observation that flow actually decreased in 7 of 37 patients deserves comment. We attribute this to a combination of factors. First, several physiologic variables such as cardiac output, arterial P_{CO_2}, and cerebral collateral flow may vary during the operation between measurements of ICF^{bef} and ICF^{aft} and lead to a decrease in flow despite correction of stenosis. These physiologic variables may outweigh the influence of increased carotid diameter, particularly in patients operated on for ulceration or only moderate stenosis. Second, in some cases the carotid reconstruction may lead to unrecognized or unintentional stenosis. Third, the transit-time flowmeter methodology has some imprecision (15% for the S series probes employed), which may occasionally lead to inaccurate comparisons. Of greatest interest is the frequency with which a stenosis is created rather than relieved. We are planning future studies with completion arteriography and serial duplex ultrasound measurements to help distinguish between these variables.

Javid shunt flow in an artificial circuit reportedly varies from approximately 100 to 200 ml/min as the driving pressure increases from 60 to 80 mm Hg,[17] which is in agreement with our findings. Electromagnetic flow measurements in goats showed baseline flow in the internal carotid artery to be approximately 640 ml/min with flow through the Javid shunt being 340 ml/min compared to 470 ml/min for the largest bore shunt employed.[23] This latter study indicates that under certain circumstances Javid flow values are higher than those we observed and shunt dimensions are unlikely to critically limit cerebral perfusion.

^{133}Xe measurements of cerebral perfusion under halothane anesthesia during carotid endarterectomy as analyzed by Sundt et al.,[4] are consistent with our shunt flow measurements. Carotid clamping caused mean cerebral perfusion to fall an average of 40% from a baseline value of 55.7 ml/100 gm/min. Patients with critical decreases in cerebral perfusion had shunts placed, resulting in partial restoration of perfusion to 45.6 ml/100 gm/min. If selectively shunted patients had an average perfusion of 20 ml/100 gm/min, then shunt flow would have been approximately 125 ml/min, assuming all internal carotid flow was directed to the ipsilateral hemisphere.

It should be noted that direct measurements of shunt or native artery flow do not simply correlate with cerebral perfusion because of the unpredictable nature of both the cerebral hemodynamic response to transient carotid occlusion and the quality of collateral pathways that may supplement cerebral perfusion when native inflow is perturbed. Measuring flow in the shunt is not a practical substitute for selectively deciding whether to place a shunt based on monitoring markers of cerebral perfusion such as the EEG. It would be of value to perform either EEG monitoring or ^{133}Xe measurements of cerebral perfusion in conjunction with carotid artery and shunt flow measurements to allow direct correlation of extracranial flow with cerebral perfusion.

Our finding that Javid shunt flow is similar to baseline flow indicates that adequate cerebral perfusion is maintained. Additional confirmation comes from our observation that initial shunt flow fell gradually, consistent with typical hyperemic responses to transient arterial occlusion. Hyperemic flow falls from an initial high level as an initial ischemic debt is paid. If shunt flow is found to be inadequate, hyperemic responses should not be observed. An early report of changes in ocular pressure with pneumoplethysmography during carotid surgery suggested that the Javid shunt limits flow in a manner resembling 75% stenosis.[7] The ability of the cerebral circulation to autoregulate must be considered, however. If the brain sufficiently lowers resistance in response to the pressure gradient induced by a shunt, cerebral perfusion will be unchanged. Our demonstration that shunting maintains internal carotid flow at a level close to baseline values during carotid surgery is a more direct representation of the effects of shunting on cerebral perfusion than pressure observations.

The relationship between preoperative stenosis and whether shunt flow is higher or lower than initial internal carotid flow may be important. Although the difference in stenosis found between $SF > ICF^{bef}$ patients and $SF \leq ICF^{bef}$ patients was not statistically significant, the data are consistent with the expectation that patients with more severe stenosis have lower baseline flow. Such patients may have more complete protection of cerebral perfusion by shunting. Are patients with less severe stenosis in whom shunt flow is less than baseline flow more likely to have critically decreased cerebral perfusion because of the discrepancy between shunt and native artery dimensions? A confounding factor is the role of the collateral cerebral circulation. If the severity of the stenosis in the internal carotid artery correlates with more diffuse cerebrovascular disease, then patients with less stenosis may have lower shunt flow because they have better collateral circulation. Our observation that ICF^{bef} and $\%\Delta ICF$ differ significantly between the $SF > ICF^{bef}$ and $SF \leq ICF^{bef}$ groups suggests that preexisting stenosis may be a determining factor in hemodynamic responses to shunt insertion, but further studies employing stump pressure measurements to measure the pressure gradient created by the shunt and characterize shunt vs. intracerebral resistance will be necessary to further elucidate these relationships.

CONCLUSION

Transit-time ultrasound instrumentation allows accurate measurement of internal carotid and Javid shunt flow during carotid surgery. Occlusions in the shunt can be easily detected by monitoring flow in the shunt with a clamp-on probe. Shunt flow values are in the physiologic range defined by internal carotid flow measurements and are sufficient to maintain cerebral perfusion.

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