Carotid blood flow in man determined by video dilution technique: 1. Theory, procedure, and normal values.

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Carotid Blood Flow in Man Determined by Video Dilution Technique: I. Theory, Procedure, and Normal Values

The blood flows in the common, internal, and external carotid arteries were determined as a percentage of the cardiac output by video dilution technique in 20 normal subjects during routine angiography. Nine women and 11 men, ages 19–63 years, displayed a mean flow in the common carotid of 8.5% (SD ± 0.9%; n = 40); internal carotid, 5.3% (SD ± 1.0%; n = 24); and external carotid, 3.2% (SD ± 0.4%; n = 24). Relative flow is calculated by a modification of the Stewart-Hamilton principle. The technique is fast, simple, highly accurate, and avoids the errors connected with previous videodensitometric mean transit time techniques. The method can be used in routine angiography without prolonging the catheterization procedure or adding to the patient’s risk or cost.

There is currently no accurate clinical technique for measuring blood flow in individual arteries in a noninvasive manner. Numerous experimental methods have been advocated, including electromagnetic flowmeters, radionuclide procedures, Doppler sonographic techniques, and videodensitometry. None is widely accepted and very few have been specifically applied to the determination of carotid blood flow in man.

Review of Previous Techniques

Our present knowledge of carotid blood flow is based mainly on reports of direct electromagnetic flow readings in man during surgery. In the 1960s Hardesty et al. [1, 2] applied electromagnetic flowmeters around the common carotid artery in 11 patients with neck tumors at the time of dissection. The flow readings were obtained during general anesthesia (Fluothane) and with the internal jugular vein ligated on the side of arterial exposure. By clamping the external carotid artery, the mean blood flow of the internal carotid was estimated at 364 ml/min (range, 289–494 ml/min). In four patients, 70% of the common carotid flow went to the internal carotid. Assuming that the blood flow in both vertebral arteries was equal to the flow in one internal carotid, total cerebral blood flow was calculated to be 1,090 ml/min. In a similar study, Kristiansen and Krog [3] estimated the mean common carotid flow in five patients to be 500 ml/min, of which two-thirds went to the internal carotid and one-third to the external carotid. Another study of 18 patients with aneurysms and tumors showed a considerable range of variation of carotid flow in different patients [4].

The supply of the brain by two internal carotid and two vertebral arteries together with the drainage via two jugular veins excludes the application of conventional techniques for blood flow determination in organs supplied by a single artery and vein. In addition, anastomoses between the arteries and mixing of venous blood from different sources in the jugular veins exclude methods that give quantitative results elsewhere.

It is generally assumed that the cerebral circulation takes about 13%–14% of
the cardiac output in the adult man [5, 6]. In a survey of 82 cases examined by the original nitrous oxide technique of Kety and Schmidt [7], Wade and Bishop [5] reported a mean cerebral blood flow of 53 ml/min/100 g brain tissue, corresponding to a total flow of 740 ml/min; the average weight of the brain was taken to be 1,400 g. This in turn would be calculated to be 12.8% of the average cardiac output of 5,800 ml/min in adults. Other investigators, using the Stewart-Hamilton indicator dilution method [8-10] and the Fick principle with external scintillation detectors [11-14], have reported a total cerebral blood flow in the range of 708–1,247 ml/min.

A few radiologic techniques using densitometry have been used in the past. In 1966, Hilal et al. [15, 16] described a new indicator dilution technique for blood flow determination in individual carotid arteries. The optical density of injected contrast medium at constant rate was determined on the radiographs. The concentration of the contrast material in the vessel was calculated from the measured diameter of the artery and from the quantitative comparison of the density of the opaque medium in the artery and that of a set of tubes containing known concentrations of the same contrast medium. In patients older than 50 years, the normal average internal carotid artery blood flow obtained by this method was 331 ml/min and the normal average common carotid artery flow was 516 ml/min, well in agreement with the previous values obtained by electromagnetic flowmeter.

Interest for arterial blood flow determination was renewed with the development of videodensitometry [17]. The high dynamic response of this technique makes it well adapted to study circulatory hemodynamics. The device was used by several groups [18-24] to calculate blood flow according to the transit time technique. Their interest was exclusively directed toward the coronary blood flow and no estimates of carotid flow were reported. The transit time technique has three major disadvantages compared with the video dilution technique. First, it requires accurate measurement of the arterial segment volume. Inaccuracies of magnification, vessel diameter, segment length, and, to a lesser extent, deviations of the vessel out of the fluoroscopic plane lead to severe errors of calculated flow. Second, the transit time technique assumes that the flow in the artery is constant, which is clearly not true. Measurements obtained vary depending on what phase of the cardiac cycle was used. Transit time measured during a complete cardiac cycle would avoid this problem, but only a segment of thoracic aorta is large enough to contain the flow of a complete cardiac cycle. The capacity of all other peripheral arteries restricts the transit time in the segment of the fluoroscopic field to well under one cardiac cycle. Third, clinical interpretations of blood flow expressed in absolute units of milliliters per minute is difficult. It varies with parameters such as the patient’s weight, height, and body surface. Flow through an individual artery is evaluated most easily as a fraction of a common patient denominator such as the cardiac output. Hence, the transit time technique has not achieved general clinical acceptance.

Video dilution technique offers clear advantages over all previous techniques in being a fast, simple, and highly accurate method of determining carotid blood flow that can be performed during routine angiography. It has been developed and thoroughly tested in a hydrodynamic flow model [25, 26] and extensively validated in the animal model [27] before being applied to the clinical setting.

METHODS

By the video dilution technique, it is possible to estimate the blood flow in any selectively catheterized artery as a percentage of a reference flow. It is performed during fluoroscopy by recording two consecutive injections on videotape. The method is an indicator dilution technique building on the Stewart-Hamilton principle where the sampling catheter has been replaced by a videodensitometric window. The integrated densitometric area of the dilution curves represents a mass-time curve in contrast to the concentration-time curve obtained by conventional indicator dilution techniques. The area, A, is directly proportional to the amount of injected contrast medium, M, and inversely proportional to the flow, Q, at the site of injection. Thus, \( A = k(M/Q) \), where k is a proportionality constant affected by the radiation intensity and the gains of the television chain and recording equipment. Fortunately, k need not be determined as it will eventually cancel out in subsequent calculations.

If two contrast injections are made in a circulatory system and the dilution curves recorded downstream over the same cross section of a selective artery, then the flows at the two injection sites can be calculated according to \( Q_1/Q_2 = (M_1 - A_2)/(M_2 - A_1) \). This relationship has been extensively studied in a hydrodynamic flow model where the ratio \( Q_1/Q_2 \) has been determined by video dilution technique and compared with volumetric flows [25, 26]. The technique has been validated in an animal model (20 dogs, 389 measurements) comparing the video dilution technique and electromagnetic flow readings [27]. A nested random effects analysis gave a correlation coefficient of 0.99 (\( r^2 = 0.98 \)). The 95% confidence limits for the combined data were –2.8% and +2.4% [27].

Video dilution technique is currently used as a standard procedure performed in conjunction with routine angiography in our institution. Over the past year more than 100 patients undergoing neuroangiography have had carotid flow measured. The technique [28-30] will be reviewed briefly.

By percutaneous technique (Seldinger) in the groin, a standard cerebral catheter (5 French JB 2, Cook Co.) is placed with the tip of the catheter in the ascending aorta under fluoroscopic control 2–4 cm beyond the aortic valve. The image intensifier is then centered and locked in a midline position covering the proximal part of the aortic arch and the main arteries of the neck with the head in a straight supine position (fig. 1). An injection of 20–30 ml regular cerebral contrast medium (meglumine diatrizoate, Conray-60, Mallinckrodt) by pressure injector with highest allowable injection rate is recorded on videotape during fluoroscopy with locked voltage and amperage. During the recording, the patient holds his breath. Then the catheter is positioned with the tip in the left common carotid artery and a manual injection of 1 ml contrast material is recorded. With the same position of the image intensifier and the patient (position 1), the catheter is now placed in the right common carotid artery for recording of a 1 ml manual injection of contrast. Dilution curves obtained by the densitometric window covering sections of the left and right common carotid arteries may be obtained on line or after the procedure by replaying the tape. An estimate of the left common carotid flow as a fraction of the cardiac output is seen in figure 1. The position of the densitometric window over the left common carotid artery has to be the same during the aortic arch and the selective injection. The same reference injection in the arch is used for calculation of the flow in the right common carotid.
Determination of the right internal carotid flow as a fraction of the right common carotid flow is illustrated in figure 2. The image intensifier is moved to position 2 and 1 ml of contrast material is injected twice into both common carotid and internal carotid arteries, respectively. Both dilution curves are recorded with the window covering a cross section of the internal carotid artery. Flow of right internal carotid/right common carotid is then 15.9/25 x 100 = 63.8%.

Fig. 2.—A, right common carotid flow measured over right internal carotid after 1 ml injection into right common carotid is calculated as 25.0 in arbitrary units. B, Right internal carotid flow at same site after 1 ml injection into artery is calculated as 15.9 in arbitrary units. Flow ratio of right internal carotid/right common carotid is then 15.9/25 x 100 = 63.8%.

Materials

Normal values of blood flow in the common, internal, and external carotid arteries were obtained from patients undergoing routine angiography who met the following criteria: (1) normal angiogram (and CT if applicable), (2) negative laboratory findings, (3) no neurologic symptoms at the time of examination or when discharged, and (4) clinically judged as normal. Nine women and 11 men 19–63 years of age were examined by video dilution technique. Some of the patients were admitted in connection with traumatic accidents, others for neurological workup after previous neurologic symptoms. In all patients, angiography was requested and the flow studies performed as a complementary procedure with the patient’s consent. All patients were examined in the supine position in a conscious state with mild sedation (Demerol, 50 mg) preceding the angiographic procedure. No complications were seen during the procedure or during hospitalization. The entire time for the flow study did not usually exceed 10 min, with additional fluoroscopic time not more than 100 sec. Additional contrast material used for the flow studies was within the range of 25–35 ml. In only eight patients, the common carotid artery flow was determined as a percentage of the cardiac output. In another 12 patients, a complete workup was obtained with flow determination of the common, internal, and external carotid arteries. The external carotid flow was calculated from the difference between the common and internal carotid flows.

Results

Individual estimates in 20 normal subjects are displayed in figure 3 and table 1. No differentiation by age group or gender was determined. The mean blood flow in the right common carotid (n = 20) and the left common carotid (n = 20) was equal to 8.5% of the cardiac output (SD ± 0.9). A slightly larger flow was obtained in the right internal carotid, 5.4% (SD ± 0.9), compared with the left side, 5.3% (S.D. ± 1.0), in 12 patients. However, the difference was not significant (p < 0.01). The combined flow of the right
and left common carotid arteries in 20 patients was 17.0% (SD ± 1.6) and the corresponding combined figure for the right and left internal carotid arteries in 12 patients was 10.7% (SD ± 1.6).

The mean common carotid blood flow calculated from 40 individual estimates bilaterally in 20 patients was 8.5% of the cardiac output (SD ± 0.9). The corresponding figure for all internal carotid arteries \(n = 24\) was 5.3% (SD ± 1.0) and for the external carotid arteries \(n = 24\), 3.2% of the cardiac output (SD ± 0.4).

**Discussion**

In our estimates, the carotid blood flow was expressed as a fraction of the cardiac output. Since the reference injection for cardiac output was performed in the ascending aorta 2–4 cm from the aortic valve, the assumption is made that this flow is equal to the left ventricular output. This is not strictly true as the coronary blood flow of about 4% has been neglected. Some of the pressure-injected contrast material in the ascending aorta will probably mix in the coronary sinus. Our estimate of cardiac output might then be about 2% less than the true left ventricular output giving a corresponding overestimate of the carotid flows. A 2% correction of this error would give a blood flow in the internal carotid of 5.2% instead of the reported 5.3%. This small error has here been neglected assuming that the cardiac output is equal to the flow in the proximal part of the ascending aorta.

The mean blood flow through the common carotid, 8.5%, internal carotid, 5.3%, and external carotid, 3.2% of the cardiac output, would correspond to the absolute amount of 493, 307, and 186 ml/min, respectively, assuming the average cardiac output in man to be 5,800 ml/min. These figures correspond reasonably well with previously reported figures obtained by the electromagnetic flowmeter [1–4] and by the technique described by Hilal et al [15, 16]. In our study, the internal carotid received 62.4% of the flow in the common carotid. This also agrees with previous reports [1–3, 15, 16].

The total blood flow through both internal carotids in 12 patients was 10.7% (SD ± 1.6) of the cardiac output. This figure reflects only a part of the cerebral circulation. Additional supply is provided by both vertebral arteries, presumably to a lesser extent. In addition, both internal carotid and vertebral arteries give off extracerebral branches. The internal carotid supply the ocular muscles, the lacrimal gland, the nasal mucosa, and the neural tissue of the orbits via the ophthalmic artery. The vertebral arteries similarly have several small branches supporting the neck before entering the skull. However, these extracerebral branches are not likely to carry a significant amount of blood [6]. From preliminary estimates, the flow in each of the vertebral arteries has been calculated to be 1.9% of the cardiac output (Lantz BMT, Link DP, Holcroft JW, Foerster JM, unpublished data). This means that the total inflow of blood to the skull through both internal and vertebral arteries would be 14.5% of the cardiac output under normal resting conditions. Thus, the blood supply of the brain with exclusion of extracerebral branches of the internal carotid and vertebral arteries would amount to about 12%–14%. This figure corresponds very well to data published on total cerebral blood flow [5, 6]. Total cerebral blood flow estimated by indicator dilution methods [8–10] and by external scintillation detectors [11–14] is reported in absolute units to be 708–1,247 ml/min. Converted to relative measures of the average cardiac output of 5,800 ml/min, the corresponding fractional cerebral blood flow would be 12.2%–21.5%. The total cerebral blood flow of 14% of the cardiac output estimated by the video dilution technique would amount to 812 ml/min in the average adult patient.

Absolute flow estimates in milliliters/time unit is not possible with the video dilution technique. However, this is the strength of the method, as the absolute flow estimates have no clinical relevance unless related to other patient parameters such as weight, height, or body surface. It expresses regional artery blood flow as a percentage of cardiac output. The data show that the estimates of flow at rest in the carotids are fairly constant in a normal population with small deviations from the mean value. Experience is still too small for differentiation of flow data in regard to gender and age groups, but preliminary results suggest no significant difference in this regard. A continuous accumulation of data will answer these questions.

When using the video dilution technique in the clinical setting, several sources of error should be considered regarding the effect of contrast material on circulation, mixing of contrast with blood, and the recording technique. These issues were addressed thoroughly in a recent review [31]. However, practical advice when using the video dilution technique is outlined briefly.

It is well known that angiographic contrast media have effects on the cerebral hemodynamics [32–34]. This effect is transient and the blood flow usually returns to normal within 30–60 sec. To avoid local and general effects on circulatory hemodynamics, it is advisable to wait about 2 min before an injection is repeated. It is also preferable that
the patient hold his breath during contrast recordings to avoid cyclic fluctuations of the densitometric baseline. It is extremely important that two consecutive recordings are made with the densitometric window over the exact same cross section of the artery without movement of the patient or the image intensifier in between. The only disadvantage of the technique seems to be the requirement of patient cooperation. In our experiments, about 2% of all recordings have to be deleted for this reason.

Recirculation of contrast material through the venous system can be avoided by repositioning the electronic window. Also, spillover of contrast material from the selective artery in the aorta can be checked easily by replaying the tape. In those instances, the recordings should be deleted.

Contrast injections in the aorta are performed in a direction opposite to the flow. Good mixing of contrast material with blood is anticipated. However, with selective injection, the contrast material is injected in the same direction as the flow and perfect mixing is not anticipated. The latter does not seem to play an important role, as the densitometric window is covering a complete cross section of the artery, recording the total amount of passing contrast material. This function has been studied by comparing a series of injections in the superficial femoral artery in dogs in the same and the opposite direction of the flow [31, 35]. There was no significant difference between the techniques (p < 0.01). As a precaution, we have usually maintained a distance of at least 2 cm between the catheter tip and the window and at least 3 cm between the catheter tip in the common carotid and the carotid bifurcation.

By determining blood flow in individual carotid arteries, the video dilution technique is capable of giving important physiologic information in a variety of clinical situations. The extent of cerebral ischemia caused by arterial obstructive disease, intracranial aneurysms, and emboli can be evaluated before surgery. Also in the treatment of stroke and brain injury and in determining the prognosis in comatose patients, the video dilution technique may be of great importance. It can be performed in any angiographic suite with the addition of a videodensitometer. The technique is highly accurate and gives information about hemodynamics that cannot be obtained easily by any other means. It does not contribute to the patient’s risk or cost and there are no contraindications other than those for angiography.

Further papers in this series will deal with the influence of vascular disease and intracranial mass effects upon the carotid blood flow.

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