Bilateral Jugular Venous Blood Flow by Thermal Dilution

BY EDWIN M. WILSON, D.SC., AND JAMES H. HALSEY, JR., M.D.

Abstract: Measurements of internal jugular venous flow were made in 12 patients with severe cerebral vascular disease. Flow rates were determined by the thermal dilution method, using room temperature physiological (heparinized) saline as an indicator infused at a constant rate. The major sources of error (indicator mixing) were studied under highly controlled in vitro experiments. Total jugular venous outflow was substantially below mean values of total cerebral flow for normal subjects and somewhat below the mean values for demented patients. Free communication between the two jugular veins via the torcular was observed in all patients. Following unilateral venous compression, the differential shift to the contralateral vein was not always equal to the precompression total flow. This would seem to indicate that this maneuver produces some diversion of flow to other venous channels and suggests that total cerebral blood flow can be obtained reliably only through bilateral measurements.

Additional Key Words: cerebral venous outflow, total cerebral blood flow, indicator dilution, thermistor

This study has been undertaken as part of a continuing effort to develop a system for monitoring the hemodynamic and metabolic alterations in acute progressive stroke, and for their modifications by therapy. Such a system must be continuous or very frequently repeatable for up to 72 hours, without blood loss, and compatible with the care of patients who are in delicate condition and often critically ill.

These considerations have led us tentatively to reject those methods requiring carotid puncture or catheterization. Radioisotope methods based on intravenous injection and inhalation are receiving consideration, but there is some doubt that radiation can be kept within reasonable bounds for the patient and for technical and nursing personnel if the determination is to be repeated hourly for 72 hours or more.

We have found prolonged catheterization of the internal jugular vein to be safe and relatively simple. This permits application of the Kety-Schmidt method for measurement of average cerebral blood flow, and methods for local measurement of jugular venous flow which, if performed bilaterally and simultaneously, would yield an approximation of total cerebral blood flow. We report here our initial experience with the local thermal dilution method of jugular venous blood flow determinations. This has been primarily a feasibility study to explore the possible application of this method to measure total cerebral blood flow, to define its limits of reliability, and to identify methodological problems.

The basic theory of measuring flow rates by indicator dilution methods has been documented. These methods have been applied principally to the measurement of cardiac output and to a lesser extent to the measurement of local or regional flow. The indicator may be introduced either as a bolus

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(single injection) or by continuous infusion.

A variety of indicators has been used including dye, radioactive tracers, and heat (positive or negative).

The thermal dilution method was chosen for these studies of jugular blood flow because its accuracy is comparable to that of other methods and because it permits frequent measurements over long periods of time and yields true volume flow. Since blood withdrawal is not required for measurement or for calibration, and the indicator can be any room-temperature physiological fluid (saline, dextrose in water, etc.), the frequency and cumulative number of measurements that can be made are limited primarily by the patient's ability to handle the fluid load. Continuous infusion was chosen in preference to the bolus input because it facilitates simultaneous bilateral measurements of differential flow changes under transient conditions, instrumentation is simpler, and computation is simpler (measurement of an ordinate rather than an area).

Methods

The general approach in these studies was first to establish basic accuracy by in vitro model experiments under conditions in which various parameters could be individually controlled. This, for example, permits a direct comparison of the relative accuracy of different thermistor catheter configurations. This was followed by in vivo work with experimental animals and later extended to patient studies (fig. 1).

The equations for flow rate by the thermal dilution method can be derived from the laws of conservation of mass and energy. Referring to figure 1, the equation applicable to continuous infusion is restated here for clarity.

\[ F_B = F_I \frac{\rho_B S_B}{\rho_I S_I} \left( \frac{\Delta T_2 - \Delta T_1}{\Delta T_1} \right) \]

where

- \( F_B \) = blood flow rate (cc/min)
- \( F_I \) = injection rate (cc/min)
- \( \rho_B, \rho_I \) = density of blood, injectate (gm/cc)
- \( S_B, S_I \) = specific heat of blood, injectate (cal/gm/°C)
- \( T_B \) = blood temperature (°C)
- \( T_I \) = injectate temperature (°C)
- \( T_M \) = temperature of mixture (°C)

The validity of this equation assumes that (1) there is adequate mixing between inflow (fig. 1 at "a") and sampling site (at "b") such that at any instant there is a uniform temperature at the cross section "b," (2) that the blood temperature \( T_B \) remains constant (or is otherwise known) during the course of a measurement, and (3) that there is negligible net heat exchange from blood mixture to vessel walls between sites "a" and "b."

Temperatures were measured by thermistors incorporated in one leg of a wheatstone bridge as shown in figure 2. Bridge excitation current is limited so that the effects of thermistor self heating (fluid velocity sensitivity) are negligible. Prior to each measurement the bridge is balanced by a ten-turn potentiometer-dial. Blood temperature (\( T_B \)) and thermistor slope (change in thermistor resistance per unit change of temperature) are obtained from a computer tabulation of \( T \) and slope versus resistance. System sensitivity is obtained by observing the recorder deflection (h).
from the momentary insertion of a known resistance (\(R_{\text{cm}}\)) in series with the thermistor. The temperature change which results from a subsequent infusion of room temperature fluid is given by:

\[
\Delta T_1 = \frac{h_{\text{inf(cm)}}}{h_{\text{cm(cm)}}} \times \frac{R_{\text{cm(OHMS)}}}{\text{slope(OHMS/°C)}},
\]

The flow-sensing thermistor probe* was similar to one developed by Dr. Ganz and Mr. Webster for studies on carotid artery flow. Its distal end is S-shaped with the thermistor located midway in the "S" in order to keep it from contacting vessel walls. Injections were made through a teflon catheter (O.D. of 0.060 in. and I.D. of 0.042 in.). Injectate temperatures were measured with a thermistor located near its proximal end as shown in figure 3. The temperature of the injectate rises toward blood temperatures within the intravascular segment (c-c to a-a in figure 1) because of the thermal conductivity of the catheter walls. This temperature change for a particular catheter is a function of catheter length, rate of injectation and velocity of blood past the catheter. Corrections for this temperature change were determined empirically as shown in figure 4. In applying this correction to patient or animal studies, the abscissa, \(T_1-T_1\), is equivalent to the difference between the externally measured injectate temperature and the blood temperature. The thermal loss is then estimated from the rate of injection and a linear interpolation based on the intravascular length of the catheter. The effect of blood velocity on thermal loss was not included in these studies because of the uncertainty of vessel diameter. Over typical ranges of vessel diameters (4 to 10 mm) and mean flow rates (100 to 500 cc/min), in vitro studies have shown that neglecting this correction adds an uncertainty of about ±3% to the caloric input or mean flow calculation.

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In the in vitro studies, thermal dilution measurements were compared with flow rates determined by a turbine flow meter (accuracy ±2%). With primary flow rates ranging from about 100 to 700 cc/min, the effects of varying injection rates and the separation (\(L_1\)) between the thermistor and distal end of the injecting catheter were investigated.

In order to make qualitative assessments of the degree of mixing of injectate with the primary flow, dye was included in the injectate, and the stream patterns along the primary flow path were observed as primary flow rates and injectate rates were varied.

In order to approximate the conditions under which patient measurements were made, two studies were performed on dogs. A carotid artery was cannulated and connected to a syringe and constant speed withdrawal pump. Injecting catheter and thermistor probe were inserted through branch vessels and clamped so that essentially all flow past the thermistor was limited by the syringe withdrawal rate. Thermal dilution measurements were then compared with withdrawal rates measured by timing the syringe barrel position.

Thermal dilution measurements of jugular flow have been made on a total of 12 obtunded or comatose patients with severe neurological disability. Seven of these have been bilateral measurements. In all bilateral patient measurements the injectate temperature was measured unilaterally. The contralateral injectate temperature was assumed equal to this value.

JUGULAR CATHETERIZATION

Catheterization of the internal jugular vein was...
accomplished in each case by percutaneous insertion of an 18-gauge needle-catheter in the midportion of the neck where it lies immediately lateral to the carotid artery. Successful entry is evidenced on aspiration of venous blood, after which the catheter was advanced rostrally as far as possible. Catheter position can be documented radiographically. Fluoroscopy has not been needed in our hands. The only possible malposition is occasional entry of the catheter into the facial vein, which has been easy to recognize by palpation. Apart from inadvertent carotid puncture in a few instances, no complications have occurred. In over 200 jugular catheterizations for periods of up to two weeks, infection has been absent. In this study two insertions in each jugular vein were necessary, one for the injecting catheter and one for the thermistor. The thermistor was inserted through a percutaneously placed catheter which was then retracted along the thermistor after positioning. Relative positioning of thermistor and injecting catheter was determined radiographically in a few instances. It was estimated by comparison of external lengths of injecting catheter and thermistor in all patients studied.

Results

IN VITRO EXPERIMENTS

The total of about 120 in vitro measurements were made comparing thermal dilution flow rates with those obtained from the turbine flow meter. In one set of data with \( L_T = 10 \) cm, injection rate of 24 cc/min, a regression equation of \( Y = 0.943 \bar{X} + 16 \) cc/min, with correlation coefficient \( r = 0.996 \) was obtained (\( N = 24 \), thermal flow \( Y = 416 \) cc/min, turbine flow \( \bar{X} = 422 \) cc/min). In this series all points were within +5\% and −10\% of identity and 22 of 24 were within ±5\% (fig. 5). In another series (fig. 6) with rate = 20 cc/min, and \( L_T \) between 4 and 6 cm, the results were not significantly different (\( Y = 0.946 \bar{X} + 18 \), \( r = 0.992 \), \( N = 28 \), \( \bar{X} = 298 \), \( Y = 302 \)). With \( L_T \) reduced to 2.5 to 3.5 cm, the error magnitude increased to about ±15\% with injection rates in the 20 to 25 cc/min range. With \( L_T \) further reduced to about 1 cm or with much lower injection rates (5 to 10 cc/min), errors up to ±35\% were obtained. With constant rates for primary flow and injection, lateral movement of the thermistor \( (L_T = 1) \) produced large changes in mixture temperature. This was effectively corroborated by visual observation of the dye stream proximate to the orifice.
ANIMAL EXPERIMENTS

The first dog experiment involving eight thermal measurements against timed collections disclosed a large but highly systematic error. The regression equation was \( Y = 0.67 X + 4 \) over a range of 54 to 212 cc/min, but with a correlation coefficient of 0.995. The second dog series involved 15 measurements and showed substantial improvement in absolute accuracy with \( Y = 0.865 X + 15 \) and a correlation coefficient \( r = 0.978 \) over a range of 40 to 220 cc/min.

OBSERVATIONS IN MAN

Unilateral jugular flow measurements on stroke patients showed the following changes in unilateral flow as a result of either contralateral venous compression or head motion.

<table>
<thead>
<tr>
<th>Patient</th>
<th>Mean flow (cc/min)</th>
<th>Mean flow with contralateral compression or head motion (cc/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>100</td>
<td>350</td>
</tr>
<tr>
<td>Case 2</td>
<td>170</td>
<td>490</td>
</tr>
<tr>
<td>Case 3</td>
<td>130</td>
<td>390</td>
</tr>
<tr>
<td>Case 4</td>
<td>185</td>
<td>470</td>
</tr>
<tr>
<td>Case 5</td>
<td>55</td>
<td>140</td>
</tr>
</tbody>
</table>

Where bilateral flow measurements could be made the following data were obtained.

<table>
<thead>
<tr>
<th>Patient</th>
<th>Minimal total flow (cc/min)</th>
<th>Maximal total flow (cc/min)</th>
<th>Peak unilateral flow with contralateral compression (cc/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 6</td>
<td>340</td>
<td>390</td>
<td>400</td>
</tr>
<tr>
<td>Case 7</td>
<td>280 to 330</td>
<td>370</td>
<td>330</td>
</tr>
<tr>
<td>Case 8</td>
<td>570</td>
<td>610</td>
<td>540</td>
</tr>
<tr>
<td>Case 9</td>
<td>250</td>
<td>320</td>
<td>330</td>
</tr>
<tr>
<td>Case 10</td>
<td>605</td>
<td>630</td>
<td>560</td>
</tr>
<tr>
<td>Case 11</td>
<td>270</td>
<td>330</td>
<td></td>
</tr>
<tr>
<td>Case 12</td>
<td>180</td>
<td>225</td>
<td></td>
</tr>
</tbody>
</table>

In some instances, it has been possible to show the effects of flow from the common facial vein. This was done by intentionally locating the thermistor below the facial vein junction and observing the increase in the magnitude of \( \Delta T \) during an infusion as a result of facial vein compression. It was hoped that such a procedure would enable positive location of the thermistor relative to this vein so that repositioning could be made if required. While helpful in some instances, it has not been totally reliable because of uncertainties in occluding this vessel.

A more reliable index of thermistor malposition can usually be obtained from observation of the baseline (preinjection) temperature changes. With the thermistor above the common facial vein, the blood temperature usually remains fairly constant (within \( \pm 0.02^\circ \text{C} \)) over a ten-second to 20-second period. When the thermistor is located below the facial vein junction, the temperature fluctuations increase to some \( \pm 0.2^\circ \text{C} \) or more. This is apparently the result of the cooler facial vein blood having less constant temperature and entering at relatively nonuniform rates. We have also found that occasional bolus injections (0.5 to 1.0 cc) are helpful in determining proper conditions for reliable measurements.

Figure 7 demonstrates the differential shift in flow following a unilateral compression. The "mixing" waves are probably due to relative motion of the thermistor in the imperfectly mixed stream coupled with small flow variations phasic with respiration and heart rate. If these become too pronounced, catheter or thermistor repositioning is indicated.

In some instances, it has been possible to
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In a normal condition the temperature decays to baseline within about four to six seconds. In abnormal conditions such as stagnant flow, clots, or thermistor in contact with vessel walls, the decay to baseline is retarded to some 12 to 15 seconds or more.

Discussion

Mixing Problems

The results of the model experiments showed that the continuous input thermal dilution method used with the instrumentation previously described is sufficiently accurate for the measurement of jugular flow rate in stroke patients. The most critical problem is that of adequate mixing of the indicator with blood. The degree of mixing is increased as the length \(L_T\) between injecting orifice and thermistor sensor is increased. It is also improved with increasing velocity of injectate due to the greater turbulence at the injection site. Visual observation of injectate containing dye showed definite streaming within the first 1 to 2 cm depending on the injectate velocity. This is further borne out by the erratic results of computed flow rate obtained with \(L_T\) in the range of 1 to 2 cm. The computed flow can be either high or low depending on whether the thermistor is located in a stream which is predominantly blood or indicator. The anatomical requirement of injection in or below the jugular bulb and the thermistor above the junction with the common facial vein constrains \(L_T\) to about 3 to 4 cm maximum. Although the dye observations indicated that dye mixing was not quite complete in this region, thermal mixing is relatively greater because it results from both heat conduction and particle dispersion rather than from the latter alone. With injectate rates of about 20 cc/min and \(L_T\) about 3 to 3.5 cm, the method accuracy (in vitro about ±10%) appears quite satisfactory for patient use. A closed-end catheter with lateral holes would improve mixing but could not be inserted by the Seldinger percutaneous technique.

Although the relatively short separation, \(L_T\), results in less than perfect mixing, it does have the advantage of posing negligible heat transfer between vessel walls and blood indicator mixture.

The effect of variation of jugular vein diameter is important only insofar as it affects mixing. For a given flow rate and injection rate mixing is poorer in vessels of large diameter. Most of the in vitro work was done with 6.3 mm (1/4 in.) I.D. tubing. One in vitro study showed a variation of about ±5% in computed flow rates when tubing I.D. was varied from 4 to 10 mm.

Indicator Input

The major source of error in any type of thermal dilution measurement is in the exact quantification of the amount of indicator introduced. Volumes or input rates can be determined with accuracies of the order of ±2%. The effective temperature of the injectate is more difficult to measure accurately. The injectate is warmed as it passes through the intravascular segment of the injecting catheter. The magnitude of this temperature change is dependent on the initial temperature difference between blood and injectate, the thermal conductivity of the catheter, the intravascular length, the velocity of the injectate, and, to a lesser extent, the velocity of blood past the catheter. An intraluminal thermistor mounted close to the distal end (section a-a on figure 1) could very nearly measure the temperature of injectate as it enters the blood. The effective input from a temperature measurement at this point would still have to be corrected to account for the small and poorly mixed input through the catheter walls between sections a-a and b-b. Because of the small size required for this catheter it is not now practical to insert a thermistor probe into it. Because of the need for a wire guide for percutaneous insertion, a catheter with an integrally mounted intraluminal thermistor could not be used. For these reasons we have measured injectate temperature close to the proximal end of the catheter and applied the empirically determined correction for the temperature rise in the intravascular segment.

In Vivo Work

The limited dog experiments were done primarily to demonstrate in vivo feasibility and to provide a comparison against a reasonably known blood flow. A carotid segment was used in lieu of a jugular segment because of its fewer branch vessels and because arterial pressure prevented vessel collapse under conditions of high withdrawal (flow) rates.

The thermal dilution method was used for
measuring jugular flow in a total of 12 patients to date. In five of these, because of various clinical or technical reasons, only unilateral flow measurements could be made. These were of value principally in developing clinical procedures and in demonstrating an increase in unilateral flow as a result of contralateral jugular compression. They also pointed out the need for bilateral measurements from observations of rather pronounced (by a factor of two or three) changes in unilateral flow as a result of changes in head position.

The major problem with the clinical application of this method is the relative positioning of the thermistor probe and injecting catheter. The anatomical and mixing constraints usually require maintaining a separation of 3.0 cm ± 0.5 cm. Spontaneous or forced head motion or unilateral compression frequently make this separation difficult to maintain. Two separate percutaneous insertions are now required for each side. We are currently investigating a dual unit with an injecting lumen and an integrally mounted external thermistor. If the thermal coupling between the injectate and the external thermistor can be kept to acceptable levels, this unit will not only maintain proper separation but will also mean that only one insertion per side will be required.

ANATOMICAL CONSIDERATIONS

In addition to the technical limitations on the accuracy of the determination itself, the relevance of this method to the pathophysiologic problem we are trying to study depends on the extent to which bilateral jugular venous flow represents total cerebral blood flow. Some cerebral venous outflow is via the diploic anastomoses between cerebral venous sinuses and scalp. About 20% of blood in the external jugular vein is of cerebral origin. In addition, Batson's vertebral venous plexus, though also available, probably is of little significance in the absence of bilateral jugular compression or obstruction. Our own data presented here indicate that large shifts in flow via the torcular from one internal jugular to the other occur readily with gentle compression and sometimes even with change in head position. We tentatively conclude that simultaneous bilateral jugular flow measurements somewhat underestimate total cerebral blood flow, the underestimation probably remaining relatively constant for a given subject. The total jugular venous outflow in these patients—a mean of about 390 cc/min—was extremely low as compared with dye dilution measurements of total cerebral blood flow based on internal carotid injection—a mean of about 560 cc/min—for demented patients and 950 cc/min for normal subjects. Our lower results probably reflect in part more severe cerebral vascular disease—all of our patients were hemiplegic or quadriplegic, mentally obtunded or in coma. There may also be some further reduction in the measured result due to partial jugular venous obstruction resulting from the physical presence of two catheters in each jugular vein, thereby diverting some cerebral venous outflow to other channels. We are hopeful that the single catheter unit now being developed will minimize this effect.

It seems likely that the two catheters necessary for the flow measurement produced some obstruction to venous flow. In those cases in which only a unilateral measurement was being made, there appears to have been a significant diversion of flow to the contralateral jugular vein as evidenced by the nearly threefold increase in flow that resulted from compression of the contralateral vein. The extent to which cerebral flow is diverted to channels other than the internal jugular as a result of either the presence of the catheters or unilateral compression is not clear from these limited data.

In cases in which bilateral simultaneous measurements could be made, it appears that flow in a single vein with the opposite vein compressed approximated the total flow measurement with a significant underestimation in some cases. This would raise some doubt about the validity of utilizing the unilateral measurement with contralateral compression as a technical simplification. The principal sources of error would be due to incompleteness of interrupting the contralateral flow, diversion of some cerebral venous flow to other channels, and, if the facial or external jugular veins are also compressed, contaminating the measurement with blood of extracerebral origin.

Additional possible sources of error to consider include erroneous temperature measurements due to thermistor contact with vascular walls, and clotting on the thermistor. The former is largely eliminated by the Ganz-
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Webster S-shaped catheter. Clotting may be minimized by including heparin in the injectate (1 unit per cubic centimeter), and recognized by damping of the output curve. The error introduced by neglecting the correction on thermal loss due to blood flow past the injecting catheter is velocity-dependent. It can be reduced only with some difficulty. Estimation of velocity requires an estimate of vessel diameter by radiographical means as well as an estimate of mean flow rate.

Conclusions

A method is presented for the simultaneous bilateral measurement of internal jugular venous flow based on thermal dilution. Despite the constraints on the separation between injecting and sensing sites, the in vitro and animal studies have shown that indicator mixing can be adequate to give reasonably accurate results. The presence of a catheter in a jugular vein diverts some flow to the contralateral vein. Simultaneous bilateral measurements are needed in order to get a measurement of total jugular flow. In all cases studied there appeared to be free communication between the two jugular veins via the torcular. The degree to which total internal jugular flow is an index of total cerebral flow is uncertain. Further study involving comparisons between this method and other methods for measuring total cerebral flow is indicated.

References

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