An Electromagnetic Catheter-Flowmeter


ABSTRACT

An electromagnetic flowmeter incorporated into a catheter is described. The catheter is introduced into the aorta via the femoral artery. The flow sensor is located some distance below the catheter tip and is sensitive to flow at right angles to the catheter. A crater-like elevation at one end of the transducer lumen permits funnel-like connection of the transducer to the ostium of an aortic branch. The transducer thus measures the blood flow through a selected branch of the aorta. It is pressed against the branch artery by arching the catheter by means of a pull-wire. A reliable and readily reproducible zero-flow baseline is obtained by slightly withdrawing the lumen of the transducer from the branch ostium, thus closing the lumen by the aortic wall. Records of phasic blood flow in the left renal and superior mesenteric arteries of a dog are presented. The calibration was accomplished by comparison with a calibrated noncannulating electromagnetic flow transducer. Reliable calibration can also be performed in vitro.

ADDITIONAL KEY WORDS

renal arterial flow dog superior mesenteric artery flow

Several attempts have been made in the past to measure blood flow in the major arteries by means of a flow sensor attached to the tip of a catheter. Pieper (1) succeeded in obtaining blood flow recordings by means of a differential transformer transducer at the tip of a catheter centered in the aorta by means of an "umbrella skeleton" device. He also succeeded in obtaining coronary flow records with a similar transducer monitoring the flow through a hollow catheter tip inserted into the opening of the main coronary artery (2). Blood flow records have also been obtained with catheter-mounted thermistor flow sensors (3). Mills attempted to accomplish the same thing by means of an electromagnetic flowmeter attached to a catheter tip intended for use at the center of a major vessel (4). His flow sensor was unconventional in that the magnet was enclosed in a plastic cylinder capped by hemispheres at both ends. It was oriented parallel to the flow axis, and the electrodes were located on the periphery of the cylinder along a line transverse to the magnetic field. This configuration is extremely unfavorable since the short-circuiting effect of the fluid surrounding the electrodes greatly lowers the sensitivity as compared to the conventional configuration at equal inter-electrode distance and magnetic field intensity where the electrode tips are insulated from the surrounding fluid by a plastic sleeve. The paper did not give any data on experimental calibration and presented no flow records.

In a preliminary paper (5), one of us has shown how an electromagnetic catheter-flowmeter can be used for quantitative determination and recording of the volume rate of arterial flow in branches of the aorta. The objective of this publication is to describe an improved modification of the device and to show that it has some advantages over the conventional electromagnetic flow transducer applied externally to intact arteries. The electronic system we use in connection with the catheter transducer is identical with the 400-

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cps gated sine-wave system employed with conventional flow transducers as previously described (6). The approach to the solution of our objective deviates from the conventional mode of application of catheter flow-velocity transducers. The flow-sensing element is not located at the catheter tip, and instead of being sensitive to flow parallel to the catheter axis, the transducer is sensitive to flow perpendicular to the catheter axis. It thus displays zero sensitivity to the axial flow in the aortic trunk when placed along the aortic axis. To measure the flow through an artery branching off the aorta, the transverse opening of the flow transducer near the tip of the catheter is pressed against the periphery of the aorta at the point of origin of the selected branch artery as described below.

The Flow Sensor

The application of the flow sensor in funnel-like fashion to the ostium of a branch of the aorta is equivalent to measuring the branch flow with a cannulating flowmeter (i.e., without an intervening blood vessel wall separating the blood from the electrodes). Any conventional cannulating flow transducer would, in principle, be suitable for this purpose. Actually, however, the introduction of the transducer through the lumen of an artery, such as the femoral or the carotid, imposes limitations upon the cross-sectional area of the flow sensor. It must be at least slightly larger in diameter than the ostium of the internal artery in which the flow is to be measured but no larger than the diameter of the slightly stretched peripheral artery through which it is introduced with the attached catheter. We have chosen a design (5) that permits reducing the cross section of the transducer to a minimum and made modifications, described below, that further reduce its diameter without reducing its mechanical strength or sensitivity.

Figure 1, upper left, is a cross-sectional view of the flow transducer looking into the lumen, L, which is approximately square. Its side walls are platinum sheets, P1 and P2, ¾ mm thick, insulated with a layer of Epoxylite 1/3 mm thick. The insulation is removed inside the lumen over an approximately circular area ¾ mm in diameter to create the two recessed electrode spots, E1 and E2, contacting the blood. The electrode plates, P1 and P2, are cemented with Hysol epoxy to the Hysol epoxy frames, F1 and F2, to form a rigid structure that supports and centers the cylindrical permalloy cores, I1 and I2, which fit into cylindrical depressions in the frames, F1 and F2. Coils, C1 and C2, are wound about the cores, I1 and I2 (1.25 mm in diameter, 5 mm long), with 75 turns of 32-gauge Gripeze insulated copper wire. A magnetic field of 170 gauss is generated at the center of the lumen, L, at the normal operating current of 0.8 amp. The electrode wires, W1 and W2, are soldered to the plates, P1 and P2, and are guided symmetrically toward the catheter, C, with a tight twist along the surface of coil C2 as shown. Just beyond coil C2 wires W1 and W2 enter the grounded metal braid, B, which serves as a shield.

The coils, C1 and C2, are connected in series by wire Wc. Wires W7 and W8 (Teflon-insulated copper wire, gauge 7/40) convey the 400-cps current energizing the magnet coils. They are twisted and run parallel to wires W1 and W2 through the catheter toward
the plug which is attached to the opposite end of the catheter. The radiopaque catheter (United States Catheter Co. 5264-8F) is made of a nylon tube reinforced with woven dacron coated on the outside with a radiopaque resin. It is cemented with Hysol epoxy to the transducer body which is completely encapsulated in Hysol epoxy (C9-4206) by dipping and subsequent exposure to infrared radiation. A layer of Silastic silicone rubber (General Electric, RTV-112) is coated over the epoxy seal at S for added protection against leakage.

The transducer body is not symmetrical in side view (Fig. 1, upper right). Its lumen (indicated by horizontal dashed lines) terminates in a crater-like protrusion on the left side. This protrusion facilitates application of the transducer lumen to the ostium of the arterial branch, making the protrusion "snap" into the arterial lumen in press-button fashion.

When the diameter of the ostium of the artery to which the flow-sensing catheter is to be applied exceeds the diameter of the flow sensor, leakage of blood around the

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**FIGURE 2**

Catheter flowmeter. At left, catheter is unarched; at right, it is arched by tension applied to wire, W, to make the crater on the left side of the flow transducer snap into the ostium of artery branch, B. The center drawing shows the device for application of wire tension. C = catheter; B = branch of the aorta; T = tail portion of the catheter cemented to the transducer; L = transducer lumen; W = pull wire; S = emergence point of the pull wire; t = stainless steel tubing harboring the pull wire; H = hole for attachment of pull wire; LO = end wire loop; P = stainless steel tubing for intra-arterial injection; ST₁; ST₂ = syringe needle hafts; PL = transducer plug; SL = slide; A = spring actuator; SS = set screw; Sp = spring; SC = scale; I = index; W = pull wire; b = aluminum body; N = nipple.
flow sensor could occur, and the transducer would thus measure a fraction of the flow passing through the artery branch. Such flow leakage can be prevented by the slight modification shown in Figure 1, lower left. A silicone rubber washer, W, 0.25 mm thick and perforated at the center by an opening equal in diameter to the diagonal of the lumen, L, is cemented by Silastic to the body of the probe, allowing the crater1 to protrude. The cemented area is indicated by the shaded area, CP, which surrounds the opening, L, and extends beyond the ends of the vertical diameter of the washer, W. If we allow the vertical washer to wrap itself once around the transducer (which happens when the transducer is introduced through a narrow artery into the aorta), we can use a washer approximately 9 mm in diameter for a transducer 3 mm in diameter. Usually, the diameter of the artery ostium will not surpass the diameter of the transducer by such a large factor. Consequently, a washer with a considerably smaller diameter will suffice for most practical purposes.

In view of the tendency of a hard epoxy crater to injure the aortic intima as it is moved in and out of the branch ostium to secure a zero flow baseline, we recommend that the crater edge be covered with RTV-112 Silastic, which reduces or eliminates this hazard. At the same time, the fibrin film, which tends to form on an epoxy crater, is avoided.

The use of a square transducer lumen permits reduction of the outer transducer dimensions to a minimum, since the electrodes now also serve the structural function of side walls, which, being made of metal, are strong though very thin. Suitability of rectangular lumens for electromagnetic flow transducers has been pointed out by Shercliff (7). The sensitivity and linearity of this transducer are comparable to the performance of a transducer with a circular lumen of corresponding dimensions.

FIGURE 3

Left, frontal view of the catheter-flowmeter depicting the lumen of the transducer and the catheter sections adjacent to it. The catheter is unarched in the abdominal aorta of a dog. Right, lateral view of the catheter flow transducer (lumen not shown). The catheter is arched in the abdominal aorta of a dog and is positioned to measure the blood flow in the left renal artery running from the transducer to the kidney. The renal artery (between white arrows), ureters, and kidneys have been opacified by the injection of contrast material through a small catheter introduced percutaneously into the aorta. The black arrow points to the tip of this catheter, from which a stream of radiopaque material passing downward obscures the lower section of the catheter-flowmeter.
Flow-Sensing Catheter

Figure 2 shows the incorporation of the flow transducer into the catheter flow sensor as well as some details omitted in Figure 1. For pharmacological studies, it is convenient to have a means of injecting drugs into the artery through which the blood flow is being recorded. For this purpose, 26-gauge hypodermic tubing is run through the catheter. It emerges at point P and is bent to inject into the transducer lumen, L.

In principle, radiopaque material could be injected in the same fashion to visualize the artery by x-rays and to delineate the distribution of the blood passing through it. Actually, however, the high viscosity of the contrast material does not permit sufficient influx. For best results, a radiopaque catheter is introduced percutaneously into the aorta via the contralateral femoral artery. By intermittent hand injection of contrast material, the desired artery can be readily located, permitting the catheter flow sensor to be positioned quickly and easily. Figure 3, left, is a roentgenogram of the catheter with the transducer lumen facing the observer, before injection of the contrast material. The roentgenogram on the right shows the catheter with the transducer lumen oriented coaxially with the entrance section of the renal artery after injection of the contrast material. The kidney, ureters, and left renal artery are clearly depicted.

For proper operation of the transducer to measure the entire blood flow entering a given artery from the aorta, the left opening of the lumen, L, must be pressed against the point from which the artery branches off, as shown in the right-hand diagram of Figure 2.

Application and Performance of the Catheter-Flowmeter in the Living Animal

The flow sensor, perforated by the lumen, L, is located between two sections of the catheter, which can be arched into the shape of a bow between points H and S, as shown in the right-hand diagram of Figure 2. This is accomplished by application of tension to the wire, W, which is attached to the catheter tip at point H and dives into the catheter interior at point S. This point is a terminal of a 26-gauge stainless steel tube, t (left-hand diagram, Fig. 2), which traverses the catheter to emerge about 100 mm from the plug, PL, which supplies the power to the transducer electromagnet and conveys the flow signal from the electrodes to the amplifier. Figure 2 shows the catheter in the straight position before application of tension to the wire, W (left diagram), and in the arched position (right-hand diagram). Figure 3 shows the two positions of the catheter in anesthetized dogs. In Figure 3 (left) the transducer is oriented to show its lumen. On the right, the catheter is suitably arched and the transducer is properly positioned for recording left renal artery flow.

It is hazardous to apply tension to the wire, W, directly by hand. It can be overstressed and broken. To avoid this, the pull is transmitted to the wire by means of a spring, SP (Fig. 2), which is housed in a hollow cylindrical spring “actuator,” A, which can be pulled upward, thus shortening the spring and exerting a pull on the wire, W, which enters the tubing, t, through the syringe needle haft, STj. The actuator slides in an outer hollow cylindrical body, b, and can be fixed in position relative to it by a set screw, SS, thus securing action of a constant spring tension upon the wire, W, and consequently providing a constant force pressing the crater of the transducer lumen into the ostium of the artery under investigation. Compression of the spring, by pressing the slide, SL, inward, diminishes the tension of the wire and allows a temporary complete or partial relaxation of the spring and a consequent straightening of the catheter. This is done to facilitate frequent in-and-out movement of the catheter in the aorta.

We have tested the performance of the catheter-flowmeter in several branches of the abdominal aorta of large dogs (18-28 kg). After anesthesia with pentobarbital sodium (30 mg/kg), we performed a femoral arteriotomy. After intravenous injection of
heparin (500 U.S.P. units/kg), we introduced the instrument into the femoral artery and advanced it into the abdominal aorta, with the spring, SP (Fig. 2), deactivated (i.e., no tension on wire, W). It proved possible to measure renal arterial flow without ancillary aids by searching for the ostium of the renal artery by adjusting the position of the catheter until the characteristic renal flow signal with its high ratio of diastolic to systolic flow was obtained. The catheter end was then arched as described above and further fine adjustments in its position were made to maximize the flow signal. Although, in favorable cases, correct placement of the instrument for renal flow measurement can be achieved in this way within 3 minutes of insertion into the femoral artery, the procedure is greatly facilitated by fluoroscopy (Fig. 3).

Renal arterial flow signals obtained from

**FIGURE 4**

Comparison between velocity pulses in the renal artery obtained by the electromagnetic catheter-flowmeter (bottom tracing) and a noncannulating iron-core electromagnetic transducer externally applied to the renal artery (middle trace). The top trace shows systemic arterial pressure. The slight differences in the wave forms recorded from the two transducers are ascribed to their separation by an elastic conduit (2 cm of the renal artery).

**FIGURE 5**

Zero flow reference obtained by withdrawing the transducer lumen from the ostium of the renal artery to press it against the aortic wall and thus stop the flow of blood in it. The end section of the catheter is kept arched during this operation. The record shows that the transducer can be returned to the flow-sensing position within 1 second.

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the catheter-flowmeter are shown in Figure 4 to be almost identical with those obtained from a 2.5-mm lumen split-pole noncannulating electromagnetic transducer (8) simultaneously recording from the same artery. The zero flow reference was obtained repeatedly by slightly withdrawing the catheter maintained in the arched position so as to press the lumen of the transducer against the aortic wall. This zero reference can be obtained and the probe returned to the flow-sensing position in less than 1 second (Fig. 5). The zero base line is remarkably stable and is identical to that obtained by occluding the renal artery (Fig. 6). The artery is occluded at B, yielding a pulsating base line in both flow records. At A, the crater of the catheter is pressed against the aortic wall and a smooth base line, shown at A, is obtained. The zero-flow base line can thus be obtained for this device by stopping flow through the sensor without interruption of blood flow through the aorta or renal artery.

Figure 7 illustrates the use of the catheter-flowmeter to determine the effect of intravenous norepinephrine on average renal blood flow.

Figure 8 illustrates measurement of blood flow in the superior mesenteric artery, a flow pattern different from that in the renal artery.

Calibration

In work with conventional electromagnetic flowmeters, one commonly considers as most reliable that method of calibration which is carried out under conditions closely approximating those of the physiological measurements. A calibration in vivo can be performed conveniently in animals by applying the catheter-flowmeter to the ostium of an artery through which the blood flow is recorded by means of a calibrated conventional noncannulating electromagnetic flow transducer. However, it is desirable to be able to calibrate flow in vitro. This requires a special device, which can be made of Lucite, to feed the flow
to the catheter flow transducer. We found the following scheme convenient. A tube approximately 3 cm i.d. and 6 cm long is closed at both ends by circular end plates about 1 mm thick. At the center of one end plate, a tube (about 5 mm i.d.) is cemented coaxially with the large tube. At the opposite end of the axis of the two tubes, a 3-mm hole is drilled centrally into the second end plate. A thick, soft, silicone rubber square perforated by an opening of the same diameter as the transducer lumen is cemented over the end-plate hole superposing the two openings. A Lucite plate carrying a similar perforated silicone rubber square over a hole 3 mm in diameter facing the opening in the end plate can be pressed by means of two screws against the perforated end plate so that the holes in the two silicone rubber squares are superimposed precisely. The Lucite plate and the tub end plate are then separated by loosening the screws. The flow transducer is sandwiched between them and aligned so that the perforated silicone rubber gaskets fit tightly around the transducer lumen after the screws are tightened. Blood or saline can then be fed into the nipple of the first end plate. The fluid fills the large tube and escapes through the opening in the terminal Lucite plate after passing through the lumen of the flow probe. The rate of flow against which the catheter transducer is to be calibrated can be measured by measuring the fluid escaping through the calibrating set-up or by a second flow probe placed in series with the input nipple of the calibrating device.

Table 1 illustrates the effectiveness of this calibration procedure. Fifteen rates of flow of physiological saline were selected: five values of constant flow, five of pulsating flow (approximately 1 cps frequency) recorded on the phasic flow setting of the electronic channel, and five of pulsating flow recorded on the average flow setting of the electronic channel (time constant 0.36 seconds). The average flow values for the pulsating flow curves were determined by planimetry. In all there was a concurrent volumetric determination of the average rate of flow. Figure 9 shows a plot of the points
TABLE 1
Catheter Calibration with Constant and Pulsating Flows on “Average” and “Phasic” Instrument Settings

<table>
<thead>
<tr>
<th>Volumetric flow determination (ml/min)</th>
<th>Constant flow, instrument deflection on “average” setting (time constant 0.36 sec) (mm)</th>
<th>Pulsating flow, average deflection (by integration) on “phasic” setting (mm)</th>
<th>Pulsating flow, average deflection (by integration) on “average” flow setting (time constant 0.36 sec) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>350 ± 5</td>
<td>33 ± 0.3</td>
<td>18.4 ± 0.3</td>
<td>17.1 ± 0.3</td>
</tr>
<tr>
<td>340 ± 5</td>
<td>31.5 ± 0.3</td>
<td>17.3 ± 0.3</td>
<td>17.1 ± 0.3</td>
</tr>
<tr>
<td>270 ± 5</td>
<td>25 ± 0.3</td>
<td>16.2 ± 0.3</td>
<td>15.5 ± 0.3</td>
</tr>
<tr>
<td>210 ± 5</td>
<td>20 ± 0.3</td>
<td>11.6 ± 0.3</td>
<td>10.4 ± 0.3</td>
</tr>
<tr>
<td>154 ± 2</td>
<td>14.5 ± 0.3</td>
<td>9.7 ± 0.3</td>
<td>9.0 ± 0.3</td>
</tr>
<tr>
<td>105 ± 5</td>
<td>18.4 ± 0.3</td>
<td>17.1 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>190 ± 5</td>
<td>17.3 ± 0.3</td>
<td>15.5 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>190 ± 5</td>
<td>15.5 ± 0.3</td>
<td>10.4 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>128 ± 2</td>
<td>11.6 ± 0.3</td>
<td>9.7 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>104 ± 1</td>
<td>9.7 ± 0.3</td>
<td>9.0 ± 0.3</td>
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</tr>
<tr>
<td>97 ± 1</td>
<td>9.0 ± 0.3</td>
<td></td>
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</tbody>
</table>

![Graph](image)

**FIGURE 9**
Calibration of the catheter-flowmeter with constant and pulsating flows. + = constant flow (instrument on “average” setting). O = pulsating flow (instrument on “phasic” setting). O = pulsating flow (instrument on “average” setting).

Obtained from Table 1. They lie on the same straight line as that expected for a typical electromagnetic flowmeter within the limits of experimental error (4%).

To ascertain to what extent the replacement of the blood vessel walls by the materials of the calibrating device could affect the calibration if the in-vitro technique were used.
instead of the in-vivo method, a comparison was made between two drastically different materials serving as walls of artificial models of the aorta with a side branch. One model was made of Lucite, whose conductivity is many orders of magnitude below that of the artery wall, and a second one of copper, whose conductivity surpasses that of the aorta by several orders of magnitude. The calibrations proved to be identical within the limits of experimental error (about 4%). Thus the material of the conduit does not perceptibly affect the calibration, and it can be carried out in vitro with adequate reliability.

When blood is used for calibration, changes in hematocrit do not affect the sensitivity. Blood plasma and whole blood yield the same calibration within the limits of experimental error (about 4%).

Discussion

The electromagnetic catheter-flowmeter has several advantages over the conventional electromagnetic transducer. It obviates the need for major surgical procedures to expose a deep-seated blood vessel. The hazard of stripping the arterial adventitia and possible interference with nerve supply is eliminated. Drugs are easily injected intra-arterially without puncturing the artery. Blood flow can be measured successively in several vascular beds using only one transducer; and, finally, the zero-flow reference level is very stable and can be readily and reliably obtained without interfering with the blood flow through the organ under investigation.2

At the moment, the method has limitations. Flow can be measured quantitatively only when the catheter is correctly positioned and no blood enters the artery ostium by flowing around the sides of the transducer. Furthermore, there are organs supplied by arteries which do not directly branch off the aorta, such as the hepatic, gastric, and splenic arteries. We believe, however, that some of these present limitations can be overcome by technical and methodological developments such as the use of a silicone rubber washer.

Our experience suggests that this device, sterilized by ethylene oxide, might be used with appropriate caution to provide continuous recording of instantaneous and average regional blood flow in conscious human beings. Such observations would probably be of value in the diagnosis and treatment of organic disease. As with all catheterizations of human subjects, there is a hazard of damaging the internal coat of the vessels through which the catheter passes. The presence of a rigid section with a slight protrusion may make the present catheter somewhat more hazardous than standard catheters. Also, the necessity of giving the patient heparin to increase clotting time would constitute an added risk.

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References

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