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An Electromagnetic Catheter Blood Flow Meter of Minimal Lateral Dimensions*

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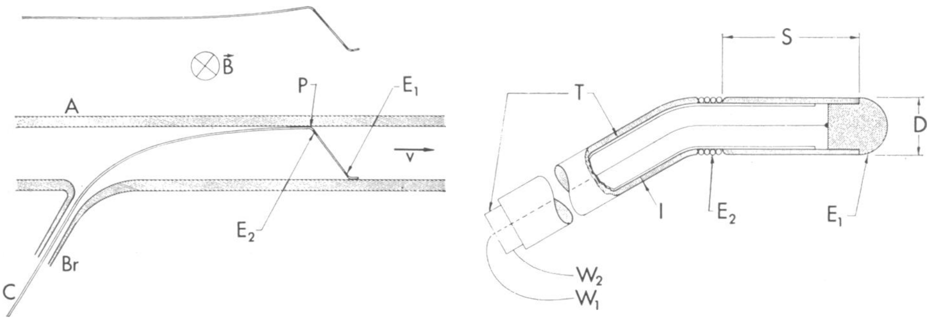
Abstract. A method is described to reduce the lateral dimensions of an electromagnetic catheter blood flow meter to the maximum possible extent. To achieve this, the magnetic field is generated by a magnet placed outside the subject. Thus, only the electrodes and a minimal supporting structure have to be introduced into the blood vessel to pick up the electromotive force induced in the blood streaming at right angles to the magnetic field. To suppress induction of a transformer electromotive force in the electrode leads, the latter form a co-axial lead system of small gauge. One electrode is at the tip of the insulated external tube of this lead system (a gauge no. 28 hypodermic tube) and is insulated from it. The other electrode is a bare section of the external tube about 2 cm from its tip. The tube is bent at an angle of about 30° just below the second electrode. Thus, this bent section places the two electrodes near two diametrically opposite wall sections of the blood vessels after insertion of the fine catheter via a hollow catheter through a branch blood vessel into the main vessel. The catheter is rotated until the plane containing the bent section is perpendicular to the magnetic field. The potential difference between the two electrodes measures the volume rate of flow through the blood vessel. This principle can be used to monitor the flow in the major blood vessels as well as in their branches. Catheter flow meters down to about 0.5 mm in external diameter have thus been made and much smaller ones can be made without excessive difficulty.

Introduction. The original form of the electromagnetic blood flow meter requires surgical exposure of the blood vessel to which the flow transducer is to be applied.[1] To minimize the extent of surgical intervention, electromagnetic catheter flow meters have been devised[2-5] which incorporate transducers near the tip of a flexible tube (catheter) which can be introduced through a branch blood vessel into the main blood vessel. Until now all such devices required exposure of and incision into the blood vessel for their introduction because of their large lateral dimension (about 3-mm diameter). If such measuring devices are to be applied to human subjects in clinical tests, their lateral dimensions must be greatly reduced to permit their introduction by a safe and simple puncture. A reduction of the catheter diameter by a factor of 10 would reduce the area of the puncture in the artery by a factor of 100, thereby making the penetration of the blood vessel very much safer. A sufficiently narrow catheter can be introduced into an artery by the percutaneous technique in which a hypodermic needle is passed through the skin and muscle tissues into the artery. A hollow catheter can now be inserted through the needle into the blood vessel with the aid of a guide wire. A narrower catheter harboring a measuring device such as a flow meter[6] can now be inserted into the blood stream. In a previous paper it was shown how the lateral dimensions of a flow sensor can be greatly reduced by relying on an external magnet to generate a magnetic field penetrating a subject. Electrodes affixed to a thin insulated loop which could collapse to pass through a narrow tube were introduced into the aorta via a branch artery at the tip of a catheter of far smaller dimensions than any used so far for this purpose. The present paper describes a much simpler configuration for sensing the electrical flow signal which, in addition to great simplicity, also achieves the ultimate degree of miniaturization of the electromagnetic flow meter. Catheter flow sensors as small as about 0.5 mm in diameter have been made without difficulty and much smaller ones can be made without serious difficulties.

The tubular flow sensor: The basic problem to be solved is as follows: If we establish a magnetic field at right angles to the bloodstream, the electromotive force induced in the moving blood carries information about the instantaneous rate of blood flow. By monitoring the potential difference between the ends of an artery diameter at right angles to the magnetic field, we can measure the average volume rate of blood flow through the artery. The key insight which leads to the idea of the present catheter flow sensor is as follows: The two electrodes do not have to be located at the ends of a tube diameter if the magnetic field extends over a tube length large as compared to its diameter. We can, for instance, displace the top electrode several centimeters upstream without a change in the flow signal. This possibility suggests the configuration shown in Figure 1*A*. The thin flexible catheter *C* is introduced via branch *Br* into the artery *A*. A bend in the catheter near point *P* places its end section diagonally across the tube. The magnetic field established by an external magnet is per-



(*A*) (*B*)

FIG. 1.—(*A*) *Top:* The catheter flow sensor prior to insertion into conduit. The section preceding the bend is slightly arched downward. $\vec{B}$: magnetic field vector perpendicular to the page.

Bottom: The catheter *C* is inserted through the branch Br into the artery *A*. E_1, E_2: electrodes. *P:* point at which the catheter is bent. $\vec{v}$: fluid velocity.

(*B*) *T:* hypodermic tubing. *I:* insulating cover. E_1, E_2: electrodes. *S:* separation between the electrodes. *D:* diameter of catheter. W_1, W_2: lead wires.

pendicular to the page. The electrodes E_1 and E_2 are now properly located to pick up the electrical flow signal induced in the blood flowing with velocity $\vec{v}$ across the magnetic field. The same considerations can now be applied to the evaluation of this flow signal as have been used in connection with the loop flow sensor.[6]

Figure 1*B* shows the simplest scheme for such a flow sensor. A no. 28 gauge hypodermic tube *T* (about 0.36 mm outside diameter) is bent as shown and insulated by a suitable dielectric coating *I* or by Teflon or silicone rubber tubing pulled over it. This insulation is interrupted in a zone where a thin platinum or silver wire is wound over it to form electrode E_2. The electrode wire ends are soldered to tube *T*. The wire W_1 actually nearly fills the lumen of the coaxial tube *T* and electrode E_1 which forms the end point of the catheter and is about 2 mm removed from the tube *T* and insulated from it and fixed to it by epoxy cement (Epoxylite Corp., South El Monte, Calif.).[†] The electrode E_1 is preferably made of Pt and it is recommended to platinize both electrodes.[7] The tube *T* acts as a second electrode lead from E_2 and is connected to wire W_2. Wires W_1 and W_2 are twisted and connected to a methyl methacrylate plug, which is cast over the end point of the catheter.

The bent section of the catheter straightens out easily to pass through a narrow tube and resumes the shape shown in Figure 1*A* in a wider tube. For measurement of branch flow, a smaller distance *S* between E_1 and E_2 should be used. The catheter must be maneuvered from the aorta into an artery branch where the section *S* assumes a similar position relative to the artery axis and magnetic field as indicated in Figure 1*A*. Because of the coaxial structure and close fit of the Teflon or nylon insulated wire W_1, the transformer electromotive force is very effectively suppressed. This flow sensor achieves the greatest conceivable simplicity of construction and compactness and can be reduced in lateral dimensions more easily than any other configuration previously used.

Performance of measurements: The most advantageous means of generating the magnetic field would be by a pair of Helmholtz coils which yield a field of great uniformity between them. It is, however, not convenient to have the animal between two coils. Hence, a single coil yielding a known magnetic field distribution has been placed under the animal in our experiments. The same coil and electronic apparatus and calibration procedure as described in connection with the loop flow sensor have been used.[6] Since there is no loop available in this case to measure electrically the product of the artery diameter and the effective component of the magnetic field, they must be determined by separate observations in the present approach. The magnetic field at the site of the artery is determined for the given location from the plot of the magnetic field intensity distribution. The catheter is rotated until a maximum flow signal is obtained in the vertical magnetic field. The plane in which the sensor is bent is then perpendicular to the magnetic field, and an X-ray radiogram of the catheter flow sensor reveals the internal diameter of the artery which constrains it. The information about the artery lumen and magnetic field intensity under the experimental conditions determines the sensitivity drop of the instrument as compared to the sensitivity at standard conditions under which it was calibrated.

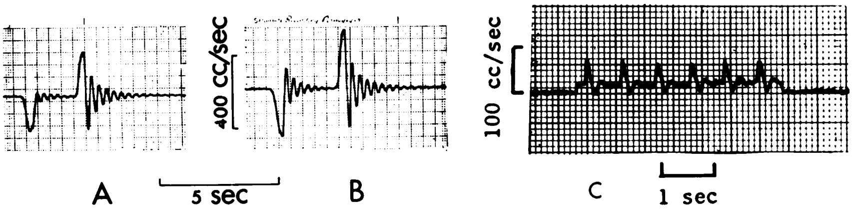


Fig. 2.—Oscillations in a fluid column recorded under similar conditions (*A*) with the present catheter flow sensor, and (*B*) with the loop flow sensor. (*C*) Blood flow tracing in a dog's abdominal aorta taken with the tubular catheter flow probe.

Figure 2 shows a comparison between the performance of the present flow sensor (Fig. 2*A*) with the performance of the more complex loop flow sensor[6] (Fig. 2*B*). The performance is identical except for a somewhat smaller sensitivity of the tubular sensor. This difference is due to the fact that the electrodes in the tubular sensor were placed some distance away from the tube wall whereas in the loop sensor they were in contact with the tube wall, thus spanning the entire tube diameter. By placing the electrodes of the tubular sensor close to the wall, the same sensitivity as for the loop sensor can be achieved. Figure 2*C* shows a blood flow tracing taken in the abdominal aorta of a dog.

The present approach appears to have reached the ultimate conceivable miniaturization of an electromagnetic catheter flow sensor. This scheme can be used to build flow sensors of much smaller dimensions than described in this paper. This reduction in dimensions is of decisive importance in the development of a blood flow measuring device for percutaneous introduction into human subjects for clinical determination of blood flow in the major blood vessels and their branches. Various modifications of the present scheme and its detailed evaluation will be published elsewhere.

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[†] It is easier to make E_1 similarly to E_2 by winding a platinum wire over the insulation near the tip, connecting it to W_1, and sealing the open catheter tip with a bead of Epoxy.

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