were also calculated cumulatively in increments of ten trials. For each field intensity and orientation, learning curves of mean t values against the number of trials were then plotted for fish significantly conditioned and for nonsignificant fish.

Nearly all eels exhibited a conditioned response to perpendicular fields as low as 0.167×10^{-2} μamp/cm^2 in fresh water (Table 1). Fewer responses were observed at 0.167×10^{-3} μamp/cm^2 and none were observed at 0.167×10^{-4} μamp/cm^2. At 0.167×10^{-2} μamp/cm^2 in water of resistivity 400 ohm-cm (0.67 μv/cm) all eels responded (Table 2), and in water of resistivity 40 ohm-cm (0.067 μv/cm) (approximately 17 per mil salinity) about half responded. The response was absent at 0.167×10^{-3} μamp/cm^2 and resistivity 400 ohm-cm. No eels responded to fields applied parallel to their bodies (Table 1).

The learning curves substantiated these findings. In all cases of parallel fields and at the lowest perpendicular field intensity at each water resistivity the nonsignificant groups gave no indication that any learning had occurred. At 0.167×10^{-2} and 0.167×10^{-3} μamp/cm^2 in fresh water the nonsignificant groups had learning curves which suggested that some learning occurred; however, our criterion of significance was not reached.

The eel's sensitivity is well within the range of naturally occurring oceanic electric fields. For example, in certain study sections of the Gulf Stream we have predicted values of up to 0.016 μamp/cm^2 (0.46 μv/cm) (*10*). Electric fields are at a maximum in the Gulf Stream, but surface potential gradients of at least 0.10 μv/cm also occur, for example, in the Labrador, West Greenland, North Atlantic, Irminger, and Antilles currents (*11*). All of these are almost certainly involved in migration routes of American and European eels.

While demonstration of a sensitivity does not prove its use in orientation, the fact that the eel is sensitive to perpendicular fields, but not parallel fields, provides a mechanism by which water current direction can be determined. Interaction of moving water with the vertical component of the geomagnetic field would generate a potential gradient perpendicular to the body axis, if the eel were oriented upstream or downstream. The potential gradient would be parallel to the body, if the eel were oriented across the water current. By simply aligning the body to sense the electric current the eel could remain oriented to the water current. If it can also sense polarity, it could discriminate upstream from downstream. The horizontal component of the geomagnetic field interacting with moving water produces vertical fields, which would provide no directional information to the fish. However, most migratory fish, such as salmon and eels, have routes distinctly north of the equatorial region, where the vertical component is the major portion of the total geomagnetic field.

This method does not distinguish between conditioning to the d-c field itself and conditioning to the change in electric field at the onset of the CS. However, since it is sensitive perpendicular but not parallel to its body, an eel in a natural water current system would experience a rapid change in electric field when it turned its body from side to side as in its swimming movements.

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Ultrasonic Doppler Technique for Imaging Blood Vessels

Abstract. *Present ultrasonic Doppler flow detectors that use the Doppler effect on waves scattered from moving blood have provided useful information when directed by hand to trace the circulation of animals and man. By scanning with a highly directive flow detector, the areas of flow can be localized. Images can be formed of the interior of blood vessels. These images have the appearance of arteriograms and venograms made by dye contrast radiography, but have none of its hazards. The resolution appears adequate for useful images.*

We have found that the scanning techniques can be used with a continuous-wave ultrasonic Doppler flow detector (*1*) to produce images of blood flow within vessels. This technique appears to extend the usefulness of these very sensitive devices by adding spatial information. Similar additions have been found invaluable in other fields. For example, ultrasonic diagnostic apparatus was not widely used until scanning techniques had been demonstrated (*2*).

It is necessary to scan the Doppler transducer over the surface of the patient or animal to be examined. The detector must have a narrow sensitive area so that areas of flow can be accurately localized. Figure 1 illustrates the principle and suggests how a film might be exposed directly by a bulb mounted on the transducer in the man-

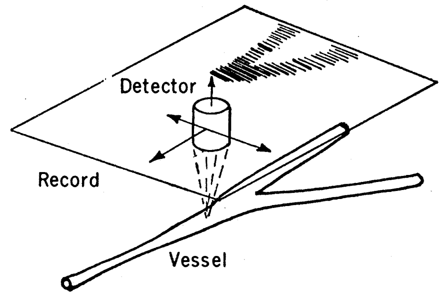

Fig. 1. Representation of the use of a focused Doppler detector to image flow within a blood vessel. The acoustic transducer was coupled to the test object or subject by immersion in a shallow water bath with sound transparent bottom. Display of the images is made electronically on an oscilloscope for convenience.

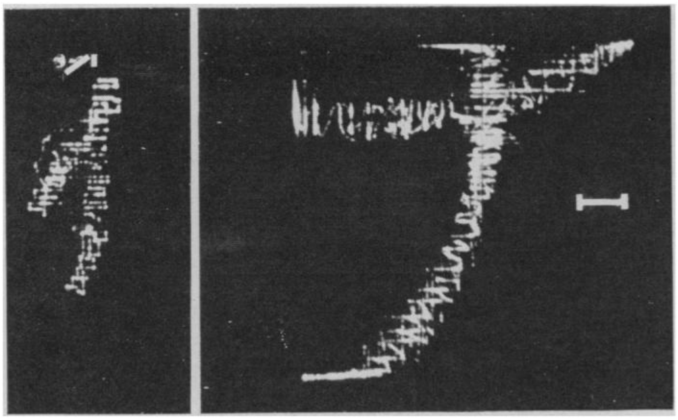

Fig. 2. (Left) Image of the intersection of the tubing formed into a loop. The scale (1 cm) was obtained by measurement and calculation from the dimensions of the apparatus and is accurate to within 3 percent throughout the depth of field of the scanner. The inside diameter of the tubing is 0.6 cm. (Right) Image of the flow in the left carotid artery and its bifurcation in the neck of a human volunteer. Both internal and external carotid artery branches can be seen above the bifurcation. Irregularity of the scanning pattern is caused by the manual operation of this simple apparatus. Scale is 1 cm.

ner of some of the early nuclear scanners.

In our initial study, we used an available Doppler transducer and a focusing plastic lens. The transducer had a lead-zirconate-titanate element, 1 cm in diameter, with the electrodes divided to provide separate sending and receiving areas. The spherical concave lens focused the sound at a nominal 3 cm from the transducer and provided a field 1 mm wide, extending from 2 to 4 cm in range. The transducer was swung across the vessels of interest while suspended at the end of an arm. The X and Y coordinates of the transducer were made to deflect the spot on the cathode-ray tube by wires connected from the ends of the arm to spot-positioning potentiometers. The Z coordinate was provided by intensity modulation with the amplitude of the Doppler shift frequency. The scanning pattern was determined manually by the operator. Since the operator could see the image being formed he was able to shorten the scanning time somewhat by confining the scan to the immediate area of the vessel. A 5-Mhz carrier frequency for the Doppler detector was best for recording flow from vessels located behind several centimeters of muscle.

The audio frequency Doppler signals from the detector were amplified sufficiently to provide a 30- to 40-volt signal for intensity-modulating the cathode-ray tube. Frequencies below 300 cycles were removed by three sections of resistance capacitor (RC) filtering at different points in this amplifier. The amplifier output was rectified, and the noise peaks were removed by an RC low-pass filter. The resulting wave was chopped by a contact modulator at 500 hz to convert it to an alternating voltage at a frequency that would appear on the oscilloscope. A memory oscilloscope is convenient to use, although control of the intensity is necessary to prevent overdriving by strong signals. The photographs shown in Fig. 2 were recorded by a time exposure in a camera attached to a second oscilloscope.

Figure 2 (left) shows the result of a test to investigate the resolution of the system. A piece of vinyl tubing (0.6 cm inside diameter) was formed into a loop and placed in the bottom of a water bath, and water containing scatterers was pumped through the tubing. The scanner was swung back and forth over the tubing to record flow in the area near the crossing of the two tubes. Both tubes at this crossing appear to be approximately the same size even though one is passing over the other. Reference to the centimeter-calibration mark on the figure shows that the inside diameter of the tube is well represented.

After this test, human volunteers were used to record the flow within the bifurcations of their carotid arteries. Figure 2 (right) is representative of the images of the bifurcation of the left carotid artery. To make pictures from volunteers it was necessary to reject Doppler signals of less than 300 cycles to avoid imaging the jugular vein. Rejection of the low frequency signals causes two problems. The first is that the low velocity flow at the edges of the artery is not recorded and thus the artery would tend to look too small. This effect is apparently compensated by the increased size of the artery caused by the width of the sound beam.

The second problem is that the flow is recorded only during the peak of systole, so that each pulse produces only a dot or short streak on the film, thus slowing the scanning rate. A better solution would be the use of wide-band phase-shift networks, such as those used in single side-band telephony, to obtain separate outputs for flow away from and toward the transducer.

Even if the accuracy of the pictures is not adequate to allow accurate measurement of the vessel lumen, the technique still offers promise in the study of flow in animals and man. The scanning technique permits positive identification of the vessels from which flow recordings of velocity can be made by conventional Doppler recording techniques. A promising medical use is in screening patients for the much more traumatic radiographic contrast-medium visualization procedures. A considerable advantage of these images is that they look like present-day arteriograms and venograms. Since the pictures have the same anatomical configuration that is revealed by x-ray arteriography there is little new technique that need be learned to interpret them. They are somewhat easier to interpret since bone shadows do not appear. The name ultrasonic arteriography in fact was suggested for similar pictures made with much more complex pulsed-Doppler apparatus (*3*). Our technique has the advantage of using available and more economical apparatus and the very sensitive and narrow-band continuous-wave Doppler detector.

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