Graphic Representation of Electrocardiographic Leads by Means of Fluid Mappers

By Richard McFee, M.S., Robert M. Stow, M.D., and Franklin D. Johnston, M.D.

A new method for the study of electrocardiographic leads is described. It makes use of plaster models having the same shape as the body in the frontal (or other) planes through which water flows in sheets. The flow of water is approximately analogous to the flow of electric currents through the body, and the flow lines are made visible by small crystals of soluble dye. If fluid passes in and out of the flow space from points that correspond to the location of electrodes of the electrocardiographic leads, the flow lines may be used to study the effects that electromotive forces arising in the heart have on these leads. With these models it is possible to study many different kinds of leads and the effects of variations of body shape, position of the heart, and electric conductivity of the tissues on them. Preliminary observations largely concerned with standard, unipolar extremity and chest leads are reported.

The study of electrocardiographic leads is not easy, because the body is a very complex conductor and the electric field within it is difficult to predict and visualize. The more or less mathematical approaches which have been made to the problem in the past have not been well understood by most cardiologists because of the mathematics, and not acceptable to others because of the relatively gross assumptions upon which the theories are based. In this paper we present a new method for investigation of electrocardiographic leads which makes use of simple laboratory instruments called fluid mappers. These are hydraulic models made with the same shape as the body and are arranged so that the resistance to the flow of fluid in them is analogous to electric resistance to current flow within the body. Fluid mappers require no mathematical background to build or operate, and for this reason we feel that this paper will be of interest to many cardiologists.

We believe studies with fluid mappers are important because they provide a simple method of obtaining graphic representations of various types of electrocardiographic leads and of visualizing the relations between the voltages recorded in them and the electromotive forces generated in different parts of the heart. The flow patterns seen in the mappers not only give a great deal of insight into the meaning of the leads, but also make it possible to estimate in a simple manner the errors involved in various electrocardiographic hypotheses including those upon which the Einthoven triangle and the central terminal for obtaining unipolar leads are founded.

Method

The first fluid mappers were constructed by Hele-Shaw and Hay in 1904 and were used to study electric and magnetic fields, having a two dimensional character. Their work was based on mathematical studies which indicated that there is a close analogy between such fields and the flow of fluids in plane sheets. The experiments of Hele-Shaw and Hay verified the accuracy of this theory, but their technic was so complicated that the method never came into widespread use. Moore in
1949 revised and greatly simplified the procedure with the introduction of his plaster of Paris fluid mappers. He showed how these simple and easily constructed devices may be used to study problems not only in connection with electric and magnetic fields, but also in relation to chemical diffusion and heat flow. Fortunately, we went to Professor Moore for advice, and it was in our conversations with him that the possibility of using fluid mappers to study electrocardiographic problems arose. In our use of fluid mappers, the flow of fluid simulates the flow of electric current in the body.

A fluid mapper consists of a plaster slab about 8 inches wide, 11 inches long, and \( \frac{1}{2} \) of an inch thick, with plaster barriers an inch or more wide and \( \frac{1}{4} \) of an inch thick along the edges. These barriers are made so that the region inside of them (the flow space) is of any desired outline, for example, that of the human body in the frontal or any other plane. A glass plate rests snugly on the barriers, and when the mapper is in use, water flows between the glass and the slab from sources to sinks (points of exit) that are located at points that correspond to sites of electrodes used to take electrocardiographic leads. The paths of the flow of water are made visible by crystals of potassium permanganate or methylene blue sprinkled on the plaster surface or glued to the under surface of the glass plate. The resistance to the flow of fluid (and this is analogous to the electric resistance of the tissues within the body) may be increased or decreased in any desired part of the model by raising or lowering appropriate areas of the plaster surface. Several views of a fluid mapper are shown in figure 1. The details of construction and operation are described in two very lucid, non-mathematical papers by Moore\textsuperscript{2,3} and will not be repeated here.*

**The Relationship between Flow Lines Seen in Fluid Mappers and Electrocardiographic Leads**

Before the results of our studies with fluid mappers are presented, a few words to explain why these devices are so useful in the study of electrocardiographic leads are in order. The flow lines made visible by crystals of dye in the mappers are approximate representations of lines of current flow in the body that would exist if a battery were connected either directly or indirectly through equal resistances to electrodes at points on the body that correspond to the sources and sinks (points of exit) of fluid in the mappers. At this point the critical reader may object, since he has observed that the sources for flow lines (either fluid or electric) are located at points that correspond to the sites for electrodes of electrocardiographic leads, and are not within the heart. In other words, the situation actually existing in the human body has been reversed. Therein lies much of the value of the method, and its use may be completely justified by the reciprocity theorem of Helmholtz. In its simplest form this theorem states that in any passive electric network made up of resistances connected to a battery and an ammeter, the current recorded by the latter will remain the same when positions of the battery and the ammeter are

* Mimeographed instructions describing in detail the procedure we have used in the construction and operation of the mappers will be sent on request.
interchanged. In the case of the system formed by an electrocardiographic lead and the body, this theorem implies that when the electromotive forces within the heart are directed perpendicularly to the flow lines, they will produce no voltage in the lead, and when they have the same direction as the flow lines they will produce a maximal effect.* To see how this simple principle is useful, consider the usual interpretation of lead I. This lead is supposed to be insensitive to electric forces within the heart, directed along the long axis of the body. If this is so, all flow lines resulting when lead I is connected to a source of current should pass through the heart horizontally, in the fashion shown in the upper right drawing in figure 5.

If all of the assumptions upon which the Einthoven triangle is based are assumed to be true, the flow patterns for the standard and unipolar extremity leads shown in the column on the right of figure 5 will be found. In the case of unipolar chest leads it can be shown that the flow lines within the heart should appear to radiate out from the exploring electrode on straight lines. The rigorous derivation of these ideal flow patterns and the principles used to interpret the flow lines will be given in another paper.

Results

Standard and Augmented Unipolar Leads

Three different models were used for studying these leads. The first corresponded to an electrically homogeneous body, and the second to a body in which the heart had about one-third the resistance of the other tissues. The third represented a body where the lungs and liver had nearly four times the resistance of the other tissues. In the second model the relative resistivities were approximately those found by Kaufman and Johnston, while the third was based on the same assumptions Burger and von Milaan used in their "Phantom." The shapes of the first two models were iden-

* More specifically, if a current is introduced into any lead, the resulting current density at any point in the heart will have the same direction and relative magnitude as the Burger "lead vector" for electromotive forces at that point.

Fig. 2. Flow lines that depict standard lead I, taken with a model that represents the body as a homogeneous conducting medium. Here water entered the flow space from the right arm and passed out from the left arm.

Flow space 50 per cent deeper in this region. This decreases the effective resistance of the heart to about \( \frac{1}{4} \) of that existing in other regions within the mapper.* Methylene blue crystals were glued to the under surface of the glass and water flowed in from the left leg and out through the left arm when the photograph reproduced in figure 3 was taken. Fig-

* The effective flow resistance in the mappers varies inversely with the cube of the depth of the flow space.
Inspection of figure 5 makes it clear that the flow lines through the heart found in various leads with the fluid mappers are similar but not identical to those obtained by use of the Einthoven triangle concept. We think that these results support the view that the Einthoven triangle theory is accurate enough for most clinical purposes. It is of considerable interest that, in the mappers made to reflect fairly closely the variations in electric resistance in the body, the flow lines passing through the heart are straighter than are those seen in models corresponding to a homogeneous conducting medium. This suggests that differences in tissue resistances may act to minimize, rather than increase, one type of error involved in the use of the Einthoven triangle.

*Chest Leads and the Central Terminal*

The interpretation of the standard and unipolar limb leads in terms of a manifest vector,
Fig. 5. Composite figure showing flow lines, in the region of the heart only, representing the three standard and unipolar extremity leads taken with three different mappers. Those in column A correspond to a body that is a homogeneous conducting medium, those in column B to a body with a heart of greater conductivity, and those in column C to a body with lungs and liver of lower conductivity (higher resistance) than other tissues. The drawings shown in column D illustrate the type of flow lines that would exist in the heart if all of the hypotheses, upon which the Einthoven triangle theory is based, were strictly true. It should be pointed out that, in these drawings, the flow lines outside of the heart need not be parallel and of the same direction as those within the heart. (See text.)
and of the unipolar chest leads in terms of a potential measured to an "indifferent" point, follow logically from the same set of assumptions. For this reason one would expect that studies which deal with the limb leads would also have bearing on the chest leads, and vice versa. Although this is doubtless the case, different combinations of electrodes are employed when the limb and chest leads are taken, and experiments designed to depict the

![Flow lines](image)

**Fig. 6. A.** Flow lines that represent a mid-precordial lead taken with the central terminal as the indifferent electrode. Here fluid passed into the flow space in equal amounts from the right arm, left arm and left leg and out through the orifice in the heart. The model used corresponds to a body with a heart of greater conductivity than the other tissues. **B.** Lines drawn from heart of model to represent idealized perfect unipolar lead. Note great similarity between **A** and **B**.

latter, as well as the former, are clearly desirable.

It was pointed out previously that if the central terminal is a truly "indifferent" point, then a source of current connected to an exploring electrode and to the central terminal should produce flow lines within the heart which radiate from the exploring electrode in a symmetric radial fashion. Figure 6 shows the flow lines produced when an experiment testing this was done. Here water flowed in at equal rates from the three limbs and out from the center of the heart. The mapper used here was one with a deeper flow-space over the region of the heart, corresponding to a heart with greater conductivity than the other tissues. The radial spread in the region of the heart shown by this figure closely approximates the pattern which would exist if all of Einthoven's assumptions were true, thus supporting the use of the central terminal as an indifferent electrode. Figure 6 should be compared with figure 7, which illustrates the asymmetric and curved flow-lines seen in the same model when it is arranged to simulate the CF lead. Here, of course, fluid passes only from the left leg to the heart.

Several other models of different kinds, including some representing flow lines in a sagittal plane, have been used to study chest leads. These also show that when the central terminal is used the flow patterns within the heart correspond fairly well to the theoretic pattern for an "indifferent" electrode, and that this is
not the case when other points are chosen as reference electrodes. It was found with these models that the radial spread of the flow lines within the heart was not appreciably changed when the latter was given a lower resistance than the rest of the body, although the field outside the heart was altered considerably. In addition, these studies indicate that even a thick layer of subcutaneous fat (offering high resistance to current flow) does not alter the flow lines through the heart greatly, thus suggesting that the interpretation of precordial leads is not influenced a great deal by the character of the subcutaneous tissues. Figure 8 illustrates the situation just mentioned. The lines are refracted as they pass through the portion of the model representing the subcutaneous fat pad, but the pattern of flow through the heart itself is not significantly changed.

It should be pointed out that the radial spread of the flow lines found in all of these models indicates that chest leads are most sensitive to electromotive forces in parts of the heart close to the exploring electrode. This means that the potentials measured by these leads will not, in general, be the same as they would be if all the electromotive forces in the heart were located at its center, or in other words will not be strictly proportional to the component of the mean cardiac vector in the direction of the electrode.

**Discussion**

The graphic representations of the various leads shown in our figures illustrate a number

![Flow lines that represent a mid-precordial lead with the left leg as the indifferent electrode. The same model was used as in the experiment illustrated in figure 6. To obtain this CF lead fluid entered from the left leg and passed out through the orifice in the heart.](image1)

![This figure shows flow lines in a model built to represent the body in a sagittal plane, with a raised barrier analogous to a thick subcutaneous fat pad under the exploring electrode. Refraction of flow lines in this region is evident, but the course of the lines passing through the heart is nearly the same as it would be if the fat pad were absent. Fluid entered the flow space here from a semicircular channel, corresponding to an indifferent electrode at infinity, and passed out through the orifice that represents the exploring electrode.](image2)
of important principles of electrocardiography. It will be noted that the current lines converge or diverge strongly near the regions of entrance or exit but are more nearly straight and parallel midway in their course. For this reason, when the heart is far from both lead electrodes the deflections produced by electromagnetic forces arising in different parts of the heart but having the same magnitude and direction will be nearly the same. On the other hand, when the heart is far from one electrode and close to the other, the lines will tend to crowd into the part of the heart close to the latter. This, of course, will make the lead more sensitive to electromagnetic forces in the portion of the heart closest to the nearby electrode.

Careful study of the figures shows that refraction of the flow lines always occurs with a change in the resistance of the medium through which they pass, in a fashion analogous to the refraction of light rays. This refraction is just one aspect of the over-all change in the flow pattern which results when the resistance of one part of the model is made different from the rest. Sometimes the end result is quite surprising, as it is in the model representing the heart of higher conductivity. Here the lines within the heart become more nearly parallel in spite of their sharp refraction at the boundaries of the heart.

If the conductivity of the heart is greater than that of its surroundings, the flow lines will crowd into it, and the deflection produced by a double layer electromagnetic force having a constant potential difference will usually be greater than it would be if the heart had the same conductivity as the tissues around it.

The use of fluid mappers in the solution of analogous electric problems in the human body is based on the assumption that the tissues of the body are resistive conductors. For high frequency alternating currents this would not be true, but studies of our own, as well as those of many other investigators, demonstrate that at the rather low frequencies involved in electrocardiograms these tissues may be considered to be pure resistances.

All of the studies which we have done thus far have indicated that the general character of the flow lines through the heart is not influenced appreciably by variations in the resistances of the tissues outside of it. It is possible, however, that changes of resistance within the heart may alter the lines therein but, in any case, mappers may be constructed for the study of this situation. Plateaus and depressions in appropriate parts of the heart would simulate variations in resistance from one region to another, and parallel grooves in the plaster would produce an effect similar to variations of electric resistance with change in the direction of current flow.

One cannot expect fluid mappers to give reliable information unless the plaster slabs are carefully and accurately made and the experiments using them performed with care. When we have followed these precautions, we have been able to reproduce closely flow lines representing certain leads with different mappers. Leakage across the barriers surrounding the flow space has been our most troublesome problem, and it can be prevented only by careful application of a thin layer of stopcock grease on the under side of the glass plate, where it rests on the barriers.

Two dimensional devices such as the fluid mapper cannot, of course, give direct solutions to three dimensional problems such as those encountered in the body. The chief value of the mappers lies in their ability to depict flow lines associated with different kinds of leads in a simple manner and in the quick and easy manner by which they give insight into difficult problems. We feel that they may be particularly useful in the qualitative study of the effects that changes in body contour, variations in resistance of the tissues, and shifts in the position of the heart may have on the various leads.

The studies reported here are only preliminary, and the effects of all the variables just mentioned have not been adequately investigated. Further studies with fluid mappers may make it possible to devise new leads with which the components of the heart vector in the various planes can be measured more accurately than is now possible. The need for improved technics of this kind, particularly in the field of spatial vectorcardiography, is clear.
SUMMARY

1. A simple new method for the experimental study of electrocardiographic leads is described. This involves the use of plaster slabs constructed so that water flows in a narrow space which has the outline of the body as seen in the frontal or other planes. The flow space is covered by a glass plate and the fluid enters and leaves from orifices which are located at points analogous to those of electrocardiographic electrodes. Fluid flow-lines through the heart or other parts of the model are made visible by crystals of potassium permanganate or methylene blue placed on the plaster surface or cemented to the undersurface of the glass plate. Variations in resistances of tissues within the body may be simulated by varying the depth of the space where the water flows within the mapper.

2. The flow lines shown by the fluid mappers have the same directions that electromotive forces at various points in the heart must have in order to produce a maximal voltage in the lead. Electric forces perpendicular to these lines will contribute nothing to the lead voltage.

3. The character of the flow lines in mappers representing standard and unipolar leads suggests that the Einthoven triangle concept is satisfactory for general clinical use and that the central terminal is a good indifferent electrode. Furthermore, it appears from these studies that a heart of lower, or lungs and liver of higher, resistance may act to increase the accuracy of these theoretic propositions rather than the reverse.

4. Fluid mappers provide a powerful new tool for the study of electrocardiographic leads and aid greatly in an understanding of their meaning. Further studies with these simple hydraulic models may lead to the development of new leads which are superior to those now available not only in the frontal but other planes as well.

ACKNOWLEDGEMENTS

The authors wish to express their indebtedness to Professor A. D. Moore. His industry and ingenuity have developed fluid mappers to the point where they are useful in many fields, and his suggestions have helped us greatly in the construction and operation of the mappers we have employed. Dr. Frank N. Wilson has encouraged us to carry out this work and has aided us a great deal in the preparation of the paper. We are deeply grateful for his unfailing support.

REFERENCES
