Heart-vector and leads

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The investigation of the electrical action of the heart without serious intervention in the life processes must in practice be based on measurements of potential on the body surface. The development of research has followed two entirely different paths. The first one is the collection of empirical data concerning the relation between heart disease and the electrocardiograms taken from the periphery, and is the method of conventional electrocardiography, the importance of which I need not emphasize. Neither do I need to stress the great merit of Einthoven in this connection. But Einthoven led the way to another approach to this problem in originating the notion of what is now called the heart-vector. He drew attention to an interpretation of the ECG as a consequence of a series of events beginning with an electrical action inside the heart muscle. This electrical action sets up a field of current in the trunk, and this in its turn generates a distribution of potential over the body surface (Fig. 1). This connection of inside action and outside effect represents a physical problem and this may explain why a physicist has the honor of speaking to you on this occasion.

It is noteworthy that Einthoven tackled the subject geometrically. His triangle (Fig. 2) is too well known to make it necessary to explain it here in detail. But it is worth while to remark that this method is not only geometrical but also intuitive, and naturally so. The physical laws governing the field of current in a three-dimensional conductor, such as the human trunk, have an analytical form; they are formulas. And although they are partly expressed in the symbols of differential geometry, the only possibility of drawing conclusions from them in a rational way is to solve a partial differential equation with boundary conditions.

It must be said that the work of so many investigators after Einthoven has created a difficult situation. Each of them has given his own idea concerning the relation between heart-vector and leads, and almost all of these systems are both geometrical and intuitive, and, therefore, irrational. I shall not mention names but it is my conviction that this variety of systems of vectorcardiography has hampered the development of vectorcardiography, and that not only, and not even mainly, because they are not exact or not correct. They give results that are appreciably different, and, therefore, one investigator cannot interpret the results, the patterns, obtained according to the method of another. Standardization is urgently needed, and I think in this respect everybody agrees, provided that the system he uses should be accepted as a standard. To my mind, there is only one way out of the present chaos, and that is a rigorous study of the inside-outside relation already mentioned. It goes without saying that physics has to

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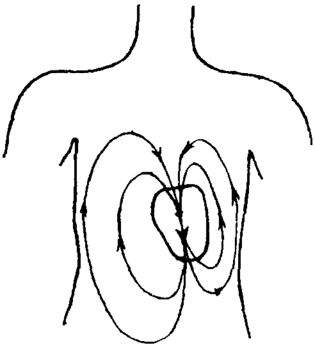

Fig. *1*. Field of current in the human trunk, caused by the electrical action of the heart.

contribute to this program, and that the basis of the theoretical treatment must be analytical.

Several properties of the object of study, the human heart located inside the trunk, have to be considered. These are properties of the heart and of the trunk both. The principal ones are the following: (a) the nature of the electrical sources in the heart muscle; (b) the distribution of these sources over the heart; (c) the shape of the boundaries, in the first place, of the thorax, and the position of the heart relative to it; (d) the electrical properties of the conducting tissues, especially those outside the heart. Heterogeneity and also anisotropy should be taken into consideration.

The first point, a, was discussed by Dr. Weidmann and Dr. Durrer this morning, and I may use their conclusions. The sources are essentially of dipole character, and each elementary source, generated by one muscle fiber, is so small that we need not consider their dimensions and distances in our macroscopic treatment.

Concerning all further points, b, c, d, the solution of the problem, the relation of heart-vector and leads, as given by Einthoven, is a simplified assumption. (b) The dipole is a point-shaped source and located in a fixed point. (c) The thorax is spherical and the source is in its center. Only the phenomena in the frontal plane are discussed. (d) The material in the trunk is homogeneous and isotropic.

As a first approximation this conception is certainly valuable and has been useful in many clinical discussions. But some of Einthoven's followers have seen in it an exact description of the true events, and this is much more than Einthoven ever pretended.

The view of the physicist is different from that of the physician or physiologist, as I mentioned before. May I outline the main ideas developed in the last fifteen years or so. I hope you will not object too much when, in doing so, I give you a more or less one-sided view.

Returning to the points a, b, c, d, it may be stated that b is the most essential one in a certain aspect. So we need not assume that c and d hold. If only the dipole is point-shaped and stationary, the trunk may be built in any way in regard to its shape, the position of the heart, and the material. In this case, all equations relating dipole and leads are linear, i.e., they contain only sums (or differences) of the variables. Then, leaving undecided and undiscussed all that is in between dipole (or heart-vector) and lead, we must conclude that every lead has a linear relation to the dipole. As we must and shall use an analytical description, this dipole must be defined and handled as a set of components, most easily in an orthogonal coordinate system. Let the orthogonal components of the heart-vector be X, Y, Z, and V be an arbitrary lead; then the linearity just mentioned has as a consequence a linear relation between V, on the one side, and X, Y, Z, on the other, so:

$$V = aX + bY + cZ \qquad (1)$$

In this formula, X, Y, Z are functions of time; they vary during the heart beat and are repeated almost periodically. The

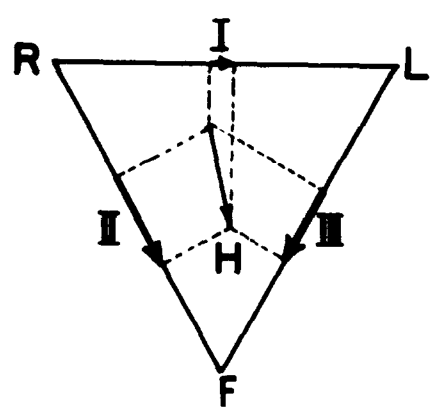

Fig. *2*. Heart-vector projected on the sides of the Einthoven triangle.

coefficients *abc*, on the other hand, are constant, i.e., independent of time. It is by this equation that we express the linear relation of inside "cause," *XYZ*, and outside "result," *V*.

I shall remind you very briefly of how we can make practical use of this equation as the basis of a lead system of VCG. From three equations of the type of the equation mentioned, the three unknowns can be solved by elementary algebra. To find the solution numerically the 3×3 coefficients must be known. They can be determined by model experiments, and it is here that points c and d of our list of conditions come in. The shape of the body does not give serious difficulties and has seldom been the subject of discussion. But d is a more important point. Anisotropy has been neglected by all, but I have reasons to doubt the justifiability of this neglect. The opinion about heterogeneity seems to depend on nationality. Whereas in this country we have reckoned with an appreciable heterogeneity, the investigators in the United States have worked with a homogeneous model. I suppose that the reality is intermediary, and I hope that they believe so too.

The numerical solution of the three equations gives the orthogonal components *XYZ* of the heart-vector as a linear function of three independent leads. By electronic means a display can be realized giving the heart-vector and the vectorcardiogram in any projection. These technical details do not belong to the subjects of this day.

So far this analytical procedure does not need any geometrical means. But if desired, these can be deduced from our equation. The latter can be interpreted as a relation between the scalar quantity *V*, a voltage, and two vectors, the heart-vector with orthogonal components *XYZ* and the so-called lead-vector with components *a*, *b*, *c*. *V* is the so-called scalar product of the two vectors *XYZ* and *abc*. It is equal to the product of the magnitude of one of them and the projection of the other on this one. This interpretation is secondary but popular among physicians. It can be generalized by the conception of the image space in which every point of the body surface has its image.

But let us leave this imaginary world to return to reality. How can we check whether the assumptions with respect to b, c, and d are correct, i.e., near enough to the truth to be the foundation of a clinical method? Of these assumptions, b, the dipole hypothesis, is certainly the most essential one. Is it a good approximation to assume that the dipole action is confined to a region the dimensions of which are small with respect to the corresponding dimensions of the thorax? There are two ways to answer this question.

1. The first one in its most simple and at the same time most general form is a method indicated by the late Dr. Becking. It can be derived from the linear equation (1). From three equations of this type, giving the voltage in three leads, each expressed in the time-functions *XYZ*, the latter ones can be solved and expressed as linear functions of the three *V*'s, which are also time-functions (electrocardiograms). Now these three linear functions of three *V*'s can be substituted in a fourth equation of the same type, valid for a fourth independent *V*. In this way this fourth lead is expressed linearly in three other leads. This must be true for any body independent of the position of the dipole, if only it is point-shaped (or at least very small) and stationary. It is easy to test such a linear relation of four leads by electronic means, but I will not explain to you here how it is done. The result is that there are deviations from the ideal case great enough to be of practical importance. It must be emphasized that these are measurements on human bodies. They have nothing to do with model experiments or assumed coefficients. They show in the most direct way that the dipole hypothesis, although it has some meaning, is a too fargoing simplification.

Older than the Becking method but intimately related to it is the test of the dipole hypothesis that is known as the mirror-image method or the cancellation method. It is so well known that I shall not explain it here. As to the result, the opinions are not entirely unanimous. Some investigators have stated their belief that according to this method it can be proved that the dipole is point-shaped and stationary. But I cannot help supposing that in

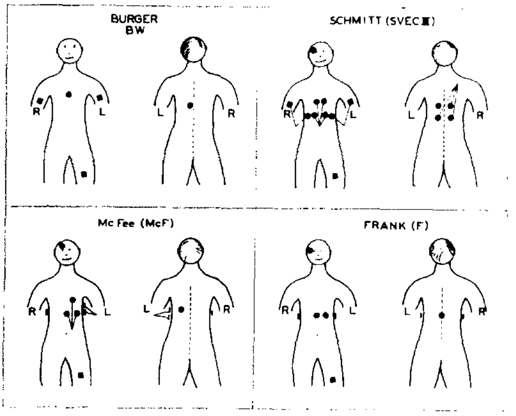

Fig. 3. Situation of the electrodes in the lead systems of Frank (F), Schmitt (S), McFee (M), and Burger (B).

some cases this is wishful thinking. In many cases, according to my own experience and that of others, the deviation from the pure dipole action is too great to be neglected. This is the more urgent since it is emphasized that a good cancellation may be arrived at with dipoles distributed over a volume that is not at all small with respect to the thorax.

2. A quite different test of the dipole hypothesis is a practical one, the comparison of loops obtained by different lead systems of VCG. By looking at the loops a subjective judgment of the correspondence is obtained, which has all the drawbacks of subjectivity, but at the same time all the advantages. But yet the comparison of loops obtained by different lead systems must be expressed in a quantitative way. Therefore, we have awarded marks to the agreement, calling 10 the best agreement that can be expected, such as is shown by successive heartbeats in one and the same system. The correspondence of loops which show no relation at all is called zero. An advantage of these scores is that we can weigh the criteria according to their clinical significance, such as left or right preponderance and clockwise or counterclockwise rotation.

Long ago, when applying this method in comparing two systems of our own and a system without physical foundation, we found that the correspondence of those two was better than that of each of them with the third. But even when two systems based on model measurements are compared, the agreement in some cases is sometimes far from ideal. This cannot be ascribed to wrong coefficients alone. If this were so, the noncorrespondence should be of a simple kind, to be expressed by a linear transformation. This relation I hope to explain later. For the moment it may suffice to say that several investigators agree in the explanation of insufficient agreement in the majority of cases: the heart is not acting as a point-shaped dipole but as a distribution of dipoles over the heart muscle. Since the latter is not small with respect to the dimensions of the trunk, the approximation of the dipole hypothesis is insufficient, especially for the sagittal component, i.e., the component in the direction of the smallest dimension of the human thorax.

Several investigators, and these are all physicists, have tried to take this circumstance into account. This problem could only be solved by applying an infinitely great number of electrodes, as was proved by Gabor and Nelson. But for practical reasons the number has to be restricted, and these are the arguments that count heavily for every physician applying vectorcardiography.

The correct way to investigate the influence of the dipole distribution over the heart, i.e., in a part of the thorax that is not at all small, is to use a model and move the artificial dipole in it. By experiments of this kind it is possible to study the effect of dipole position. Then an attempt can be made to design a system, the leads of which will not depend too much on the dipole position, so that they can be used to find the total dipole, irrespective of the distribution of its local constituents. This was carried out by some American investigators in a very elegant way. In our system we did it less sophisticatedly.

The old method of comparison, the award of scores, was the first one we applied to get an idea of the effectiveness of the use of more than the essential minimum number of electrodes, namely, four.

Lately, we have been comparing four systems, all with a sound physical foundation and corrected for dipole location. Three of them, all of American origin, are based on a homogeneous model. They are the systems of Frank, Schmitt (SVEC

III), and McFee. The McFee system was communicated to us by the author, but has not yet been published as far as I know. The positions of the electrodes in the four systems are indicated in Fig. 3. The weights attached to the contributions of each electrode are effected by resistances as described in the publications of Frank and Schmitt. In McFee's system the two electrodes at the left side have the same weight, just as is the case with the three precordial electrodes.

The fourth system is one of our own, in which the quantitative relations were deduced from a heterogeneous model in which the specific resistance of the air-filled lungs is taken to be four times that of average human tissue.

The number of electrodes of the systems compares as follows: homogeneous model—F, 7 electrodes, S, 14 electrodes, M, 9 electrodes; heterogeneous model—B, 5 electrodes.

This number is important for the decision of which system to use clinically, just as is the electrode location, especially that of the dorsal electrode or electrodes.

The result of the comparison is shown in Fig. 4. It has been deduced from some 150 to 200 comparisons, mainly cases of heart disease. The score is given for the agreement of the frontal and of the horizontal projections, respectively. All combinations of the four systems figure in this diagram. The following conclusions can be drawn from it.

1. The agreement is better for the frontal than for the horizontal projection. This is a consequence of the uncertainty in the sagittal component of the heart-vector, caused by the small dimension of the human trunk in sagittal direction.

2. The agreement of the "American" lead systems F, S, and M *inter se* is better than that of B with each of these three. This may be caused by two circumstances, the small number of electrodes in B (5) that makes it more difficult to reduce the influence of dipole location, and the assumption of heterogeneity of the thorax in the B system.

3. The agreement between the S and M systems is so satisfactory that for practical purposes one of the two can be omitted. Since S has more electrodes than M, which is a complication in clinical use, we think that system S can be abandoned and M chosen in its place.

Only in a fraction of all cases does real discrepancy exist between any two systems, i.e., a difference so pronounced that it would lead to a different diagnosis. Anyhow, this fraction, of the order of 20 per cent for the worst combination of lead systems, is too great to be accepted.

In the last few months we have applied quite a different method of comparing lead systems. This procedure was tried tentatively some years ago, but now we have used it more rigorously. We arrived at it by the following line of thought. If indeed the dipole hypothesis were true, then two arbitrary lead systems, each of them with any number of electrodes, should have a simple relation. From our fundamental equation

$$V = aX + bY + cZ,$$

it can be deduced that each coordinate of a point of a loop in one of two arbitrary lead systems is a linear function of the coordinates in the other system. This is true whatever be the values of the coefficients chosen for the two systems; they may be correct or entirely wrong. The mathematical relation between two such lead systems (let us call them C and D) can be expressed by the following set of formulas:

$$\left.\begin{aligned} X_D &= p_1X_c + q_1Y_c + r_1Z_c \\ Y_D &= p_2X_c + q_2Y_c + r_2Z_c \\ Z_D &= p_3X_c + q_3Y_c + r_3Z_c \end{aligned}\right\} \quad (2)$$

I regret that I cannot describe this relation

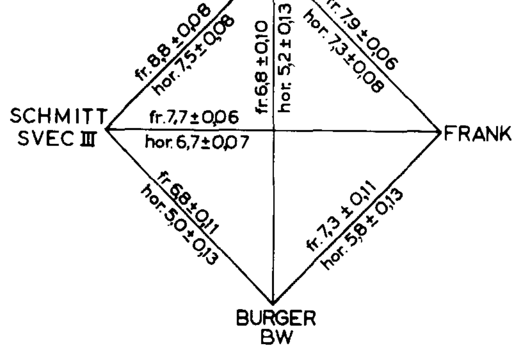

Fig. 4. Marks awarded to the agreement of vectorcardiograms. Averages and standard errors.

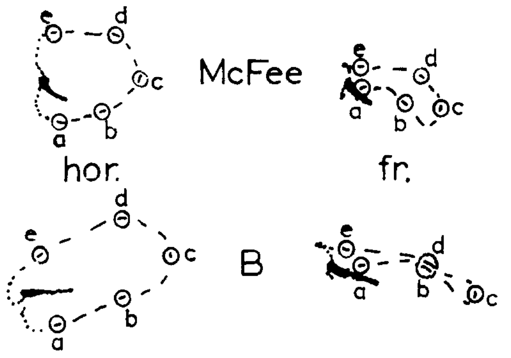

Fig. 5. Five synchronous points, *a*, *b*, *c*, *d*, *e*, on frontal and horizontal projections of the vectorcardiogram in two lead systems.

adequately without algebra, but here again we have an example of the fact mentioned before that the algebraic form is primary. Yet it is possible to mention examples of linear relations or transformations that are expressed by a special form of this set of three linear equations and may be interpreted geometrically in a simple way. I refer to a rotation and a one-sided or all-sided dilatation or compression. Another transformation of this kind, less known in daily life, but important in our problem is a so-called shear. In a special case it can be described geometrically as a horizontal displacement of all points to an extent proportional to the vertical coordinate. It is precisely this transformation that plays an important part when VCG systems are compared. This was evident from clinical discussions before it was demonstrated exactly by mathematical treatment.

I have hesitated a good deal before deciding to say more than a single word about this more exact mathematical treatment. I determined to do so because I prefer to be considered by you as a bore rather than as a mathematical witch doctor.

We can be certain a priori that the set of equations (2) does not hold generally because the dipole hypothesis is not generally true. So we have to reckon with the fact that (2) is a rough approximation only. It may be that in a single individual it describes tolerably well the relation of the loops in one lead system to those in another. But in another subject the nine coefficients, p, q, r, will have other values. Now this is a practically worthless result. We are far from the ideal to adapt the lead system to the individual. What we need is a set of coefficients which are independent of the subject or patient. Therefore, we must abandon the idea to allow for the accidental peculiarities of body build, inside and outside, and lay all subjects and patients in one and the same vectorcardiographic Procrustean bed. Apart from the individual and accidental varieties, we may hope to find a systematic relation, according to (2), between two lead systems when we compare the vectorcardiograms of a sufficient number of human bodies.

We never can find a set of nine coefficients (p, q, r) that satisfies the equations (2) for all points of the loops of all our subjects. But we must deduce the coefficients that are the best we can obtain. The practical solution is the following: On one pair of loops, frontal and horizontal, in one system for a certain individual we choose a number of corresponding points. Then we try to find the synchronous points on the frontal and horizontal projections of another system (Fig. 5). Each point, say a, has three coordinates that can be measured from the pair of projections in one system, say C, and likewise in the other, D. These 2×3 coordinates, substituted in the equations (2) give three equations, with the nine unknowns, p, q, r. On each QRS loop we have chosen five points, so that they determine its shape approximately. Since each pair of corresponding points gives three equations (2) for the nine unknowns, these five points give $5 \times 3 = 15$ equations. So the number of equations (15) is more than the number of the unknowns (9); the problem is overdetermined. This is still the more true when we consider that there is no reason to restrict the calculation to one individual.

Therefore, we have measured the coordinates of corresponding points on the loops of 150 or more subjects and solved these 150×15 equations with 9 unknowns. It is obvious that this is impossible in the ordinary algebraic sense. In such cases we try to make the best of it. We know that it is impossible to find nine coefficients, p, q, r, which satisfy these more than two thousand equations, but we are content with the nine values, p, q, r, that give the best, or the least bad, solution, a kind of average over all subjects. What this means exactly may be left unexplained here. May it suffice to say that the classic method of least squares gives a scheme for the calculation, which is easy but tedious to perform. As an example, the average transformation of the Burger into the McFee system is given here:

$$\left.\begin{aligned} X_M &= 0.70\ X_B + 0.22\ Y_B + 0.23\ Z_B \\ Y_M &= 0.04\ X_B + 0.91\ Y_B - 0.16\ Z_B \\ Z_M &= -0.44\ X_B + 0.68\ Y_B + 1.11\ Z_B \end{aligned}\right\} \quad (3)$$

Such calculations make sense only when we draw conclusions from them, and when these conclusions have any effect on our further behavior. The most important conclusion is that in addition to the systematic effect, as found in the way described above, there is a random effect caused by individual differences. In some individuals the average transformation fits quite well so that, for example, after it is applied to a B-loop it gives a loop that gives an excellent agreement with the M-loop. But in other subjects the agreement after transformation is unsatisfactory. Yet the transformation is worth while, since it reveals that the systematic discord expressed by it is of the same order as the random effects.

A second conclusion is that of all transformations that of S in M (or the reverse) is nearest to identity, thus confirming our subjective scores.

It would be well if the transformations could be expressed in a simple geometrical form. This cannot be done exactly; but as a first approximation, B can be obtained from the other systems by a shear. In the American system the downward part of the QRS loop is directed more to the back than in the B system.

We now have added a system that results from the B after transforming it to M. If there were no random individual effects and the dipole were point-shaped, this new system would give results identical to those of the M system. In reality it does not agree so well, but yet the result of the transformation is not so bad. It gives a new B system—we call it B_M—which in the average agrees better with M than does the original B. The scores for the correspondence between B_M and M, as far as we have them now, are almost as good as those for the American systems mutually. Now, when we recognize that in B and B_M only five electrodes are used, this result is remarkably favorable.

What may be the cause of the systematic difference between B and the American systems? It is probable that, for a part at least, it is the assumed heterogeneity in the first system and the assumed homogeneity in the others. Model experiments with different amounts of heterogeneity and numbers of electrode positions in the four systems might contribute to the answer to this question.

The future of vectorcardiography depends on the degree of correspondence and noncorrespondence between different systems. What can we do about it? Can we standardize at this moment? I think one thing is certain: all systems without rational physical foundation must be abandoned. The correspondence among the remaining systems is not bad, even so that some cardiologists say that each of them can be used in clinical practice without serious discrepancies. I fear this is a little bit too optimistic. But in the transformation I described a way is shown for standardization among others by application of a transformation which provides a kind of average.

Let us be optimistic and suppose that in a few years a common opinion has been reached. What then? Is this the end of the task of the physicist in the development of vectorcardiography? I think not. All this was only hunting for the cardiac dipole. But then a much more elusive prey is left, the quadripole and further multipoles. And all of these must be seen as effects caused by the essential electrical processes of which Dr. Weidmann and Dr. Durrer have spoken. So I see a future of intimate collaboration of physicians or biologists with physicists in a time when there will be no longer a sharp boundary between these two groups of scientists.