THE ZERO OF POTENTIAL: A PERSISTENT ERROR

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THE word "potential" is found not only in papers on physics, but also in some papers on medical subjects. This is especially the case in subjects related to the electrical action of the heart, electrocardiography, and vectorcardiography. It might, therefore, be worthwhile to explain from a physical viewpoint an important property of the electrical potential. It must be emphasized that in the following pages it will be supposed that the notion potential, as occurring in medical literature, is the same as the physical one. It is only on this condition that a discussion on this subject between physician and physicist is possible.

Originally the potential is introduced in the theory of electricity as an auxiliary mathematical quantity. It was only after further development of experimental knowledge that it acquired a practical meaning. For a correct understanding it would be necessary to use some mathematics, but this can be avoided by making use of the notion "work". Then we have the definition: The potential difference between the points A and B is equal to the work necessary to bring the unit of positive charge from B to A, or more exactly, it is the quotient of this work for an arbitrary charge and the value of this charge. So work = charge × potential difference.

Such a work function can be calculated from a knowledge of the field along the path of the charge from B to A. If another path is chosen to go from B to A, the work is, according to the law of conservation of energy, the same as in the first case. So the potential difference depends only on the positions of the points A and B. It is this property of the electrical field that gives the thus-defined potential difference its importance.

The work must be computed as a sum of infinitely small contributions over the infinitely small elements of the path; it is an integral. In simple cases, this can be done mathematically and may lead to a simple formula. So if we have a point-shaped fixed charge + q, the field strength is found to be q/r^2 according to Coulomb's law and is directed along the radius r (Fig. 1). Then the result of the calculation is that the potential difference between A and B is:

$$V_A - V_B = q/r_A - q/r_B \qquad (1)$$

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But what is the reason that we call this quantity potential *difference* and write it as a difference of two quantities V_A and V_B? This can be seen from Equation (1), if we choose the beginning point B very far away from the charge q, to put it in mathematical terms, in infinity. Then the denominator r_B of the second term at the right side of Equation (1) is very large and the fraction q/r_B, therefore, very small. Then we can neglect q/r_B and find

$$V_A = q/r_A.$$

This is the work that has to be performed per unit of charge to go from infinity to A. It depends only on the position of A in the field.

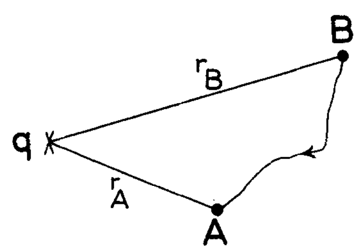

Fig. 1.—The work necessary to bring a unit charge from *B* to *A* depends on the position of the points *B* and *A*. *q* = point-shaped charge.

We see now that the potential difference between A and B can be taken as a difference of two quantities, each depending on the position of one point, A and B, respectively. But it must be borne in mind, that those two quantities V_A and V_B have only a mathematical meaning, and their difference, $V_A - V_B$, is the quantity that matters and can be defined directly, without bringing in infinity.

But the potential difference between two points has indeed the character of a difference. That is to say that if we know the potential difference $V_A - V_B$ between A and a third point C, and know also $V_B - V_C$, then we can find $V_A - V_B$ by subtraction:

$$V_A - V_B = (V_A - V_C) - (V_B - V_C).$$

Therefore, the desire remains to determine the potential of a point itself, without using the unattainable and fictive infinity. Instead of the potential of infinity we want to define a reference potential that has to be the same for all places and all times. The potential of the earth is chosen as such a zero-potential. This is an easy reference point, fulfilling all practical requirements, but it is not at all certain that it is identical with the potential in infinity, as defined mathematically. It is not even certain that the potential is the same all over the earth; it must show differences, indeed, as there are electrical currents inside the earth. But all this does not prevent us from using the earth's potential as a reference point in physics and techniques.

In electrocardiography a lead is a potential difference defined as above. It depends not only on time, but also on the positions of the two electrodes, just as the potential difference $V_A - V_B$ in the preceding simple example. It is not surprising that the question has arisen whether the potentials of each of the electrodes could be recorded. This could be done if there were a reference potential. Infinity cannot be considered practically but the earth can. Now it is certainly possible to record the potential of the left and the right arm for example, separately, with respect to the earth's potential, although this measurement needs some technical refinement to avoid an influence of the connection of the patient to the apparatus on both potentials. But what would be gained by this technique compared with the usual recording of Lead I?

To explain the situation it might be compared to the case of an accumulator. The potential difference between its two poles is 2 volts. This value is determined by the chemical character of the electrodes and of the electrolyte. The chemical reactions inside the accumulator maintain the potential difference of 2 volts, and the reverse, the value of this potential difference gives us some information of these reactions. The knowledge of the potential of either pole with respect to the earth's potential does not add anything to this information. It is determined, not only by the chemistry inside the accumulator, but also by the unessential leakages caused by imperfect insulation against ground. We can influence this situation purposely by connecting the plus pole to ground. It acquires the potential 0, while the other is -2 volts. If the reverse the minus pole is grounded, it has the potential 0 and the plus pole is $+2$ volts. In either case the potential difference is 2 volts. By grounding one pole or the other no information at all is gained as to the processes happening inside the accumulator.

The same is to be found in electrocardiography. We can connect the left or the right arm to ground and get the same electrocardiogram in both cases. It is still the same without any intentional grounding, but in this case the conditions must be such that interference is prohibited. The potential of each electrode with respect to ground could be measured, although with difficulty, but it depends on the uninteresting and accidental leakages of the different points of the body of the patient to grounding. Measurement of both potentials against grounding could not add any information as to the processes inside the patients' body. These processes determine the potential difference in the lead, the potentials themselves (against grounding) depend on the leakages mentioned.

From the preceding it will be clear that the assertion that Wilson's central terminal is on zero potential cannot be correct. The potential difference between all points in the body and on its surface as well as of combined electrodes as the central terminal are determined by the electrical action of the heart. The potential against grounding depends on intentional or accidental ground connections. The central terminal may be connected to ground purposely without influencing any electrocardiogram. If another electrode is grounded, the central terminal gives an electrocardiogram if connected to ground. This can be easily predicted from the extremity leads.

What could then be the meaning of the central terminal? If it is not, that its potential is zero, it could be that its potential is not influenced by the heart beat. This is often supposed but is not true either. It may be evident from the preceding that we can connect the central terminal to ground, without influencing any electrocardiogram. If it is not grounded purposely its potential with respect to grounding will show a fluctuation. This depends on accidental leakages and is not of any importance.

Perhaps the meaning of the central terminal is only that its potential is the average of the potentials of the extremities so that it is symmetrical with respect to these three. This is not so very important as the extremities themselves are arbitrary electrodes. But this may explain the role played by the central terminal in clinical electrocardiography.

In studying electrical phenomena, we always encounter differences of potential. The differential equation, obtaining for the electrical field, contains differential quotients of the potential, i.e., infinitely small differences; in Ohm's law not the potential itself but a difference of potential occurs. The same is the case in electrochemical phenomena, in cases of piezoelectricity, Stark effect, etc. We may search the literature of physics and chemistry but nowhere do we find a case where it is the potential itself that comes in. We may always add a constant to the potential, and still all laws and formulas hold good. When we sometimes find a formula, in which it looks as if the potential occurs, we always can transform it so that it is written as a relation between potential differences. For this reason a physicist will never try to find the absolute value of a potential or a point of zero potential. He grounds his apparatus, if necessary, at the proper point, without affecting the phenomena he studies.

But it still might be that this general argumentation is not so convincing for a physician as it is for a physicist.

It will be supplemented therefore by a few remarks. The potential V in a point, at a distance r from the dipole M, acting in an infinite homogeneous space, is given by the following formula:

$$V = \frac{M \cos \Theta}{r^2} \quad . \tag{2}$$

Θ is the angle between the directions of M and r.

This formula for V gives a value zero at infinity, but this is not essential, as we may add a constant C to Equation (2):

$$V = \frac{M \cos \Theta}{r^2} + C \quad . \tag{2a}$$

This expression obeys the differential equation for V just as well as Expression (2) and describes the observable phenomena in the same way. So the potential of a dipole in infinity is not necessarily zero.

When we enclose the dipole by a conducting envelope, the Formula (2) or more generally Formula (2a) must be changed. This change is relatively significant in the neighborhood of the dipole, but far away from it Expression (2a) must be changed appreciably. At the envelope, V must assume a constant value, which can be chosen at will. For example it can be zero, i.e., the earth's potential. But the envelope may also have a very high potential. This has, however, no influence whatever on the observable phenomena inside the envelope. These only depend on potential differences, generated by the dipole. This is not only true in this special case of a dipole but holds for all electrical phenomena taking place inside the envelope. Within the large conductors of high voltage generators, human beings can stay without perceiving any effect of the potential, even if this is some million volts above the earth's potential. The electrical effect of their heart beat under these conditions is quite normal, and their electrocardiogram could be recorded without any interference or abnormality.

These circumstances may be compared with those in the gravitational field where there is a potential energy of the bodies analogous to the potential energy (= potential × charge) of an electrical charge in an electric field. If we study the mechanical events of bodies subject to gravitation, e.g., their trajectories, it does not matter if we are at ground level or high up in the mountains. In studying their motion we cannot find the zero level, say the height of the sea level. The latter is an arbitrary zero point, just as the earth's potential. It does not enter essentially in the equations of motion. Here it is only differences of height that matter, just as it is only differences of potential that matter in the electrical phenomena.

From the preceding it may be clear that a so-called unipolar lead has not the simple meaning commonly attributed to it. It cannot be defined as the potential difference of a point of the human body and a point of zero potential, as the latter does not exist. So it can only have a practical meaning. It may be the potential difference between two points, the position of one of which is an essential variable under study, while the position of the other point is always the same. As such, may be chosen Wilson's central terminal, the left leg, or another point which is agreed on.

CONCLUSION

The previously given considerations are of a purely physical nature. They have a bearing on cardiology by the fact that some cardiologists have given their time in trying to find the zero potential. These investigations bear witness to the experimental or theoretical skill of the authors. It is often difficult to find the error in their argumentation, but yet every physicist is convinced that it must be wrong. They spend a good deal of time and interest in their efforts to arrive at a purpose which does not exist. It is superfluous to cite papers here, as it is not the aim of this paper to oppose any authors but to warn seriously all cardiologists interested in potential problems not to waste their time that they can spend so much better. Should there yet be a real problem in looking for a practically predilected reference potential, then this problem must be solved in collaboration with those who have had the schooling and training to treat it in the proper way.

SUMMARY

Any point of an inanimate system or of a human body can be connected to earth to obtain zero potential. The processes inside the system are independent of this connection. It is only the potential differences which matter. An absolute value of the potential does not enter in the physical laws and, therefore, can never be determined. An essential zero-potential does not exist.

SUMMARIO E CONCLUSIONES IN INTERLINGUA

Omne puncto del corpore human—exactemente como omne puncto de non importa qual systema inanimate—pote esser connectite al terra con le resultato de un potential zero. Le processos intra le systema es independente de iste connexion. Lo que importa es exclusivemente le differentia del potential. Un valor absolute del potential non figura in le leges del physica e per consequente non pote esser determinate. Il existe nulle potential zero essential. Nonobstante, certe cardiologos se ha effortiate a trovar lo. Le objectivo de iste articulo es prevenir omne cardiologos que illes non deberea guastar lor tempore in tal vanitates. Investigationes de iste typo non contribuera unquam a nostre cognoscentias del processos electric que es generage per le activitate del corde.