

THE SIGNIFICANCE OF ELECTRICAL IMPEDANCE MEASUREMENTS ON THE HUMAN BODY

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In a recent paper, "The Impedance Angle and Thyroid Disease," Dr. M. A. B. Brazier (1) has severely criticized work along related lines which has been carried out jointly by the Department of Electrical Engineering of the Massachusetts Institute of Technology and the Metabolism Clinic of the Massachusetts General Hospital. This work has been reported in two earlier papers (2, 3). Brazier's comments are of a nature which seems likely to cause unwarranted confusion and misunderstanding regarding the true significance of our study. It appears desirable, therefore, to restate certain facts regarding this study, with particular emphasis on those points which have been brought into question. This is done in the hope of preserving that clarity of outlook without which the real value of any investigation must inevitably be obscured. There are two major questions involved in the objections which Brazier has raised regarding the studies reported by us. One is concerned with the measuring technique; the other with the pathological significance of the quantities measured. The first involves facts. These are subject to exact verification and may be analyzed with mathematical rigor. Here both Brazier's results and ours may be appraised in terms of the numerical accuracy with which the quantities measured are determined. The second question involves judgment. Here it would seem that the more complete and reliable the data at our disposal the more dependable should be the conclusions. In this latter respect we have looked upon our work as a logical sequel to that reported some time ago by Brazier (4).

The Quantity Measured. In both Brazier's work and in our own the property measured is an electrical impedance. Electrical impedance is a physical property of matter and exists as such, quite independently of any method used for its evaluation. Brazier's statement that our technique measures a different property from hers is misleading.

Impedance is the property of an electrical circuit which determines the alternating current flowing in it under any given impressed alternating voltage. It is, by definition, the ratio of the applied voltage to the resulting current. In general, impedance represents the combined effects of two other properties, resistance and reactance. Like impedance, each of these simpler properties is defined as the ratio of a voltage to the accompanying current. They are distinguished by the fact that energy associated with current flowing in a resistance is entirely dissipated as heat,

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whereas no energy loss results from the flow of current through a reactance. Resistance and reactance combine to give the magnitude of the resultant impedance in accordance with the following formula:

$$Z = \sqrt{R^2 + X^2}$$

where Z = total impedance, R = resistance component, X = reactance component.

The relations between these quantities may be shown graphically by diagrams in which resistance values are plotted horizontally and reactance values are plotted vertically (see fig. 1). The resultant impedance is thus represented by a line of definite length, Z , making a definite angle, ϕ with the horizontal. This line is known as a vector and the angle as a vector angle. The magnitude of this vector angle is obviously fixed by the relative magnitudes of the resistive and reactive components. Its value is given by the expression

$$\tan \phi = \frac{X}{R}$$

Resistance, reactance and impedance magnitudes are each expressed in terms of the same electrical unit, the ohm. Impedances are added by adding their resistive and reactive components separately.

A point of great importance to the investigations in question appears here. Numerical values of the resistance, R , and of the reactance, X , depend upon the nature of the conducting material, upon its length and upon its area of cross-section. It is evident, then, given a homogeneous material, that a change in size or in shape of the sample measured will result in proportional changes in R and X . It is also clear that these changes, being proportional, will not affect the vector angle, ϕ . For a homogeneous sample, therefore, this angle is a function of the nature of the material only and is independent of its size or shape. The appreciation, by Brazier, of the clinical convenience of this qualitative property of the vector angle must be considered a noteworthy contribution to the study of the pathological significance of electrical impedance.

Both in Brazier's work and in our own it has been found convenient to express numerical results in terms of the tangent of the vector angle rather than in terms of the angle itself. The use of this quantity is, of course, entirely permissible as the angle and its tangent are explicit functions of each other. Since our numerical values were those of the tangent we felt it desirable to so specify them and hence adopted the symbol which has for many years been used for this purpose by electrical engineers. The accepted symbol for this quantity is Q and the expressions Q , $\tan \phi$, and X/R are well understood to be equivalent. We feel strongly that the nomenclature suggested by Brazier, in which values of the tangent are referred to as angles, is without justification.

Brazier has suggested that we have called the result of our computation the 'internal impedance' with a new symbol, \tilde{Q} . This is not the case. The symbol Q is not new, does not stand for the impedance, and is not restricted to the internal tissues. It is well established in electrical technology as a convenient symbol to stand in the place of the expressions $\tan \phi$ or X/R . The 3 terms mean exactly the same thing. *The Selection of the Sample for Measurement*. The essential difference between the technique used by Brazier and that developed by us is in the

selection of the portion of the body the impedance of which is to be determined. In her first paper (4) Brazier discussed the distinction between internal and surface tissues and reported on a series of measurements directed toward a determination of their respective contributions to the impedance of the total sample as measured by the immersion method. Brazier's results, together with our own initial investigations, suggested the desirability of a more direct evaluation of the impedances of these two constituents of the total sample. To this end we developed the 4-electrode method (2).

By placing 4 electrodes on the body and measuring the impedance between each of the 6 possible terminal pairs, data are obtained from which may be computed an electrical network exactly equivalent to the body. This equivalence is restricted to the frequency and amplitude of the current used in the original measurements. In general such an equivalent network would require 6 branches. In every measurement which we have made, however, we have found that the 6 observed impedances are not mutually independent, but that any 5 are sufficient to completely specify the network. The equivalent network, therefore, has 5 branches, (2, fig. 1, p. 561). The impedance of each branch may be exactly stated in terms of the impedances measured between the several terminal pairs. Should an actual network be set up having the arrangement shown and with the impedances computed by the formulae given (2, p. 561), it would be impossible, at the frequency and amplitude of current in question, to distinguish between the network and the body by any electrical measurements which might be made at the terminals. There exists such an equivalent network for each frequency at which measurements may be made. The constituent impedances evaluated by our 4-electrode method may be defined rigorously only in terms of these equivalent networks.

The data previously presented (2, fig. 2 and 3, p. 563) show that the several network branches have distinctive frequency-impedance characteristics. It is a reasonable hypothesis to associate them with distinctive types of tissue. That our so-called surface sheath is, in fact, the skin is supported by the close correspondence between our results and those of bio-physicists who have made direct measurements on human skin and on frog skin (3). Further support for the supposition that branches S_{27} and S_{37} (2, fig. 1) are due to the surface sheath and branch B to the internal tissues, is found in the fact that the impedance of the immersed arm, computed on this assumption, agrees closely with values obtained by direct measurement (2).

As a result of the separate evaluation of the impedances of these two distinct types of branch it is now possible to study directly the contribution of each to any correlation between the electrical impedance of the body and its physiological condition. It certainly is not necessary to approach the conclusion that either the skin or the internal tissues may or may not be involved in such correlation through any process of deduction based on indirect evidence similar to that used by Brazier in her criticism of our work. Accurate numerical values may be established for each branch; these may be examined as such in conjunction with clinical classifications.

Reliability of Measurements. Brazier has referred to our use of a potentialometer as an essential difference between her technique and ours. It should be unnecessary to point out that the measuring instrument never alters a fact; it merely limits the accuracy with which the fact may be known. In this connection it seems in order to examine the relative accuracy of our measurements