

THE SIGNIFICANCE OF ELECTRICAL IMPEDANCE MEASUREMENTS ON THE HUMAN BODY

J. W. HORTON AND SAUL HERTZ

From the Department of Electrical Engineering, Massachusetts Institute of
Technology and the Department of Medicine, Harvard Medical

School and Massachusetts General Hospital

BOSTON, MASSACHUSETTS

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 verifica-

tion 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,

8

between the technique used by Brazier and that developed by us is in the
The Selection of the Sample for Measurement. The essential difference
 terms mean exactly the same thing.

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 \tilde{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 con-
 venient symbol to stand in the place of the expressions $\tan \phi$ or X/R . The 3

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 en-
 gineers. The accepted symbol for this quantity is \tilde{Q} and the expressions \tilde{Q} , $\tan \phi$,
 and X/R are well understood to be equivalent. We feel strongly that the nomen-
 clature suggested by Brazier, in which values of the tangent are referred to as angles,
 is without justification.

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 3 of the above mentioned quantities, namely, R , X , and Z . 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 appre-
 ciation, 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.

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.

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

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

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

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

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

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