Reprinted from ENDOCRINOLOGY:
The Bulletin of the Association for the Study of Internal Secretions,
Vol. 20, No. 6, November, 1936, Pages 831 to 838.

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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, 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 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 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, 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 resonable 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 (5). Further support for the supposition that branches S_{LT} and S_{RT} (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 potentiometer 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 and of those which Brazier has used in her comparative study.

In our work no measurement is regarded as acceptable unless the reactance value is believed to be good to at least 2 per cent. By the conditions required for balance, resistance values, although about 10 times as great as the associated reactances, are known to the same numerical accuracy. They have, then, one tenth the percentage error. The accuracy with which Q is known is thus determined almost wholly by the error in the reactance component and is, in consequence, likewise good to 2 per cent.

Such accuracy is necessary in studying certain interesting changes in impedance with fatigue, with position of the body, with portion of the body

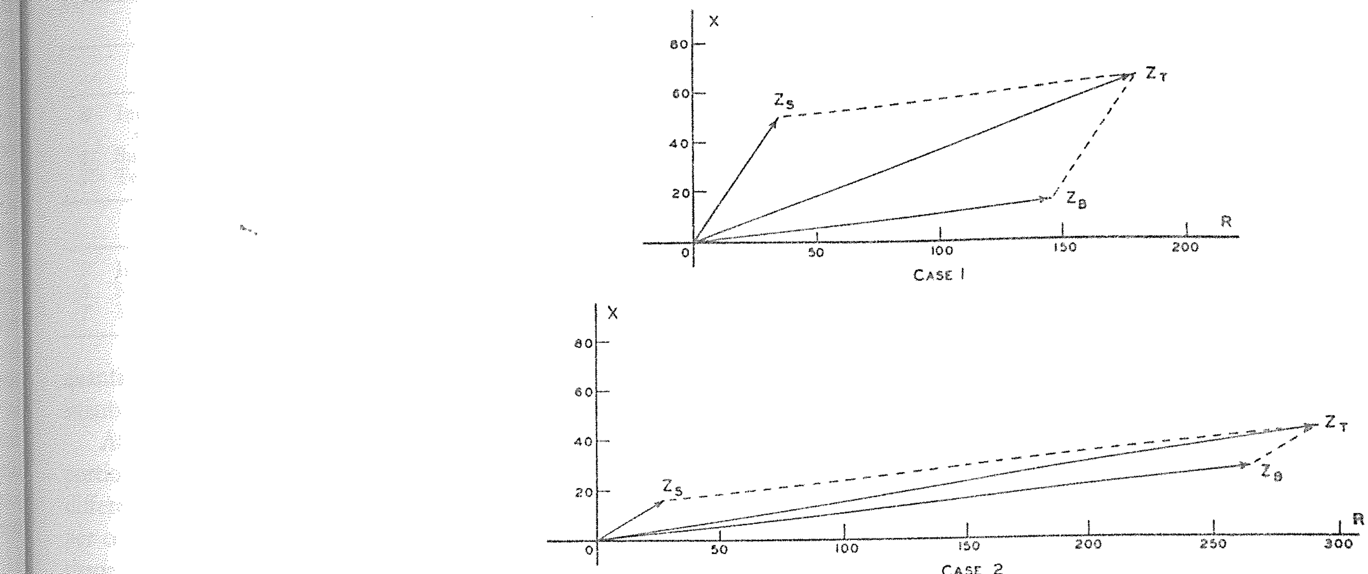

Fig. 1. Vector diagrams of the impedances of the constituent and total samples taken with band electrodes on the upper arms (case 1) and by the immersion method (case 2). Scale units are ohms. Vector angle is measured from R-axis. Significance of subscripts and numerical values are given in table 1.

measured, and with similar variables. To obtain this accuracy it is imperative that the body be reclining and completely at rest. Under these conditions the accuracy with which impedance measurements may be made is limited by variations in impedance accompanying respiration and pulsations in blood flow. These variations restrict the accuracy of measurement, with our present apparatus, to about 0.05 ohm.

In a previous paper (2, table 1) are shown the formulae by which the several constituent impedances of the human body may be computed in terms of the impedances measured between each of the terminal pairs of our 4-electrode arrangement. For the reason pointed out in the preceding section there are 2 formulae for each quantity. In other words, each quantity may be evaluated by either of two sets of data taken from the 6 observed values. By means of the comparisons thus afforded it is possible to obtain a numerical estimate of the accuracy of the data presented by Brazier in her recent paper (1). Having computed from this data the impedances of each of the 3 branches, S_{LT}, S_{RT} and B, for each of the 12 subjects, it appears that, on the average, resistance values do not agree within 2 ohms and reactance values do not agree within 1 ohm. In some cases the agreement is perfect; in others the discrepancies are so great that computed values of Q for the internal tissues, which should be the same, differ by 10 per cent. It is our feeling that no significance can be attached to data in which the maximum error is as great as one-fifth this amount.

Results of Separate Measurements of Branch Impedances. To aid in a clear understanding of the relations between the several impedance quantities for the various body samples under consideration the vector diagrams of figure 1 have been prepared. The data are from the same subject as that for figure 4 (2). In the upper diagram are drawn to scale the vector quantities representing the impedances between band electrodes placed on the upper arms. The values for the lower diagram are those involved in the immersion method. To facilitate analysis of these impedances the numerical values of the individual

TABLE 1. VALUES OF THE SEVERAL IMPEDANCE QUANTITIES FOR CONSTITUENT AND TOTAL SAMPLES TAKEN WITH BAND ELECTRODES ON THE UPPER ARMS AND BY THE IMMERSION METHOD. DIAGRAMMATIC REPRESENTATION IS GIVEN IN FIGURE 1.

	Sample	R	X	Z	Q
	Case 1				
B	Internal tissues between band electrodes on upper arms	145.7	16.1	146.5	0.110
S	Sum of external tissues under band electrodes	34.6	49.8	60.6	1.44
T	Total sample between band electrodes	180.3	65.9	191.8	0.365
	Case 2				
B	Internal tissues between elbows	265.3	28.7	266.8	0.108
S	Sum of immersed arms	27.0	16.0	31.4	0.592
T	Total sample taken by immersion method	292.3	44.7	295.6	0.153

quantities, R, X, Z and Q, for each sample, are given in table 1. Particular attention is called to the following points.

Although the internal tissues included in the two cases are for different portions of the body and the magnitudes of their impedances are markedly different, the tangents of their vector angles, Q_{B_1} and Q_{B_2}, differ by only 2 per cent. This illustrates our claim that, to a first approximation, the internal tissues are homogeneous with respect to the quantity Q. The argument in favor of Q as an indicator of the quality of the sample has already been presented. The validity of this argument rests upon the assumption that the sample is homogeneous. It is therefore enhanced when the sample is composed solely of internal tissues. It was found early in our work, as already reported, that similar homogeneity was not present in surface tissue.

The resistance of the total sample, in case 1, is due largely to the resistance of the internal tissues. It is, therefore, greatly influenced by the location of the band electrodes. The reactance of the total sample is due largely to the reactance of the surface tissues. It, then, is greatly influenced by the size of the band electrodes. The value of Q for the total sample, being the ratio of these quantities, is thus dependent upon both the size and the location of the electrodes. It does not measure an inherent property of the body.

It is evident from an examination of the values of the impedance quantities shown in the table that the only one which is the same in the two cases is the quantity *Q* for the internal tissues. It is also true that, of all the quantities listed for each case, this one only is almost wholly independent of factors subject to the discretion of the observer and is determined solely by the properties of the tissues.

This exhibit demonstrates the interrelations between the several impedance quantities of both constituent and total samples for two different body connections. Brazier's statement that the quantities appearing in our method bear no relation whatever to those appearing in hers is obviously a denial of the laws of mathematics and of electrical technology. The relation is that of the parts to the whole.

The two cases illustrated above were selected because they are those for which Brazier claims significant relations between the impedance of the total sample and thyroid condition. She also claims that the impedance of the internal tissues shows no such relation. These conclusions are not consistent when viewed in the light of established facts. The internal tissues have been shown to contribute a major portion of the impedance of each of the total samples. The contribution of the surface tissues has been shown to be dependent upon the details of the electrical connections. The two contributions are certainly independent of each other, as the two types of tissue may be combined in any arbitrary manner. It must follow, therefore, if the impedance of the internal tissues bears no relation to a given condition, that the impedance of any sample of which these tissues are a major constituent must also be unrelated to that condition.

INTERPRETATION OF RESULTS

In this section it is particularly important to distinguish clearly between verifiable facts, statistical evidence, and conclusions based on statistical evidence. The statistical evidence underlying our conclusions as to the relation between electrical impedance and thyroid condition may be summarized as follows:

A) The quantity *Q* shows a tendency to have lower values for hyperthyroids and higher values for hypothyroids than for normal subjects of the same sex. This is reported by several investigators who have used the Brazier technique. We have shown that it is particularly true when the internal tissues are measured alone. In addition to the data which have already been published on this point may be shown the data plotted in figure 2.

B) The quantity *Q* for hyperthyroids shows no tendency to approach the normal range with iodine medication. This, again, has been established by a number of observers during studies based on the Brazier technique. As shown before (3, fig. 5), it is also found to be the case for the internal tissues alone.

C) The quantity *Q* for hypothyroids shows some tendency to vary toward the normal range as a result of treatment with thyroxin. This is clearly shown, for the internal tissues, in the previous paper (3, figure 4, chart E).

D) The quantity *Q* for the internal tissues of a considerable number of miscellaneous non-thyroid hospital cases has been found by us to have values outside, and particularly below, the normal range. This is well illustrated in figure 2. There is little evidence regarding similar cases measured by the Brazier method, except that recently reported by Robertson and Wilson (6). No obvious correlation was found for the commoner disorders present in medical and surgical wards. A single case of Addison's disease was examined and found to be below the normal range. An important point in connection with evidence pertaining to a situation of this character should not be overlooked;

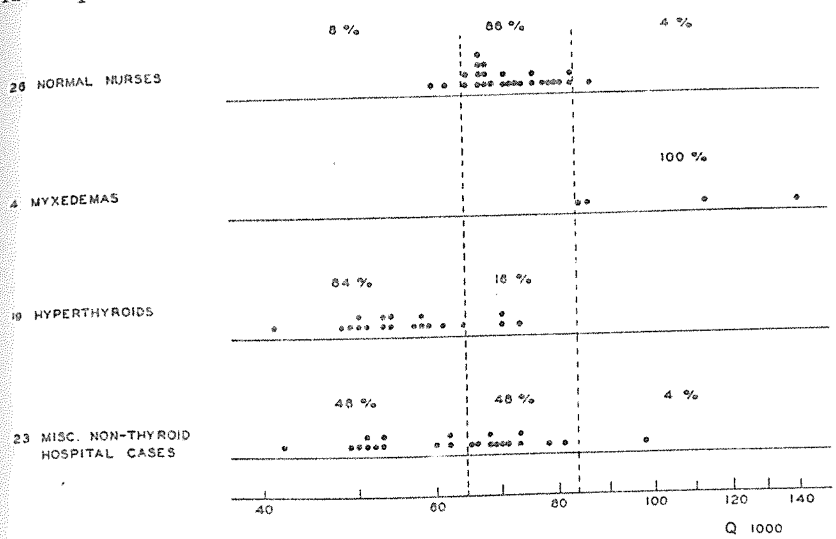

Fig. 2. Values of the quantity Q for the internal tissues, measured between band electrodes on the upper arms, at 10 kilocycles, for 72 women. Percentage distributions in three arbitrarily assigned ranges are shown.

more data are required to indicate that it does not exist than is sufficient to prove that it does.

E) Values of the quantity Q for the internal tissues are not indicative of the B.M.R. (3, fig. 6, 7). It is also true for non-thyroid patients.

F) There is some slight evidence that the value of the quantity Q for the internal tissues, in hyperthyroids, rises following thyroidectomy. This has been found in cases showing no change in B.M.R.

There appears to be general agreement regarding the first three of the above statements in so far as they apply to data taken by the immersion method. The only data other than our own on the internal tissues is that covering the 12 cases reported by Brazier (1). This appears not to confirm our findings. We believe, however, that the number of cases covered by our investigations, together with the accuracy which we know to hold for our measurements, entitles our data to consideration. If the validity of our data is admitted it will be found to support our conclusion that the statistical evidence as to the relations between impedance and thyroid condition found in data taken by the Brazier method appears even more clearly in data taken on the internal tissues alone.

Our conclusions, reached after a careful study of the evidence summarized above, are as follows. *A*) Determinations of the quantity *Q* cannot be used in place of determinations of B.M.R. because of lack of concurrence between them. *B*) The quantity *Q* is not a specific indicator for thyroid condition because other pathological causes have been found which give the same deviations from normal.

Brazier's argument in favor of using impedance data in place of the B.M.R. is obviously based on her belief that it yields more pertinent information regarding thyroid condition. Assuming this to be true it must be conceded that it does not yield the same information. In consequence we feel that, while one measurement may supplement the other, it cannot replace it.

The second point where Brazier's conclusions and ours differ involves the clinical utility which may be ascribed to impedance data. Although the existence of a relation between the quantity *Q* and thyroid activity has been clearly demonstrated we are not yet willing to recommend the introduction of impedance measurements into general diagnostic practice.

An examination of Brazier's criticism of our work discloses that it is based, not on any fallacy in our fundamental technique, nor on any error in our measurements, but on our conclusions. The obvious primary basis for her objections is found in the following statements (1). "With such widely differing techniques there is little reason to expect any close concordance in the results obtained, nor have Horton, Van Ravenswaay, Hertz and Thorn (10) demonstrated any such concordance, yet they assume that their results may be used to dispute conclusions arrived at by other workers who have been concerned with the impedance angle of the body measured by the Brazier technique." And again: "Since in spite of their obvious recognition of the wide difference between the methods they still make the tacit assumption that their failure to obtain significant results entitles them to dispute the properties of the impedance angle as established by workers using the Brazier technique."

We believe that concordance between the results has been fully demonstrated, both factually and statistically. Our conclusions as to the clinical value of the Brazier method are based on data taken by that method. We believe that significant results have been obtained by measurements on internal tissues alone. We do not dispute the properties of the impedance angle, only the conclusions as to the present utility of these properties in indicating thyroid condition.

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