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SURVEY
OF
MICROWAVE ABSORPTION CHARACTERISTICS
OF BODY TISSUES

by H. Schwan, et al

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We will summarize absorption data pertaining to body tissues which, for the most part, were obtained in our laboratory during the past six years. Some of the data have been presented before;other data have been shown only before a small group; and finally, there are some important data of recent origin. We intend to demonstrate this material in toto for the following purposes :

First, it will show the variability of absorption characteristics among various types of tissues.

Secondly, we will show the variability of absorption values from sample to sample in a given type of tissue and determine the reasons for this variability.

Thirdly, because from the total knowledge of absorption characteristics now available for all major types of tissues, we can reconfirm our earlier statement that frequencies above 10,000 Mc are not so dangerous as frequencies below 1,000 Mc which, by comparison, constitute a major hazard.

Fourthly, from the complex absorption characteristics we are able to state that, in principle, it would be impossible to develop any type of dose meter which could be carried on or near the human body and give sensible readings.

The first group of figures will relate to a survey of dielectric data; the second to a survey of absorption coefficients; and the third to reflectance and energy distribution patterns.

In Figure 1 we present data to illustrate drastic differences between the dielectric properties of tissues with high and low water content. The capacitance is plotted in terms of dielectric constants for muscular tissue and fat within the frequency range of about 40 to 10,000 Mc. The upper curve pertains to muscular tissue and is representative of most body organs. The lower curve relates to fat and subcutaneous fatty material and is also characteristic of other tissues of low water content. The variation from one sample of muscle tissue to another is within about 10 per cent, i.e. the dielectric constant of muscular tissue and body organs varies only slightly so that it is reasonably easy to reproduce these data. The specific resistance is plotted on the ordinate and the frequency on the abscissa within the frequency range of 40 to 10,000 Mc (Figure 2). The resistivity data for muscular tissue are reproducible over the entire frequency range while the fat data fluctuate considerably as indicated by the broad band extending nearly across the graph. This indicates that the resistivity of fatty material cannot be readily duplicated and that the variability from one sample of fatty material to another is considerable.

Figure 1 - Page 4 -

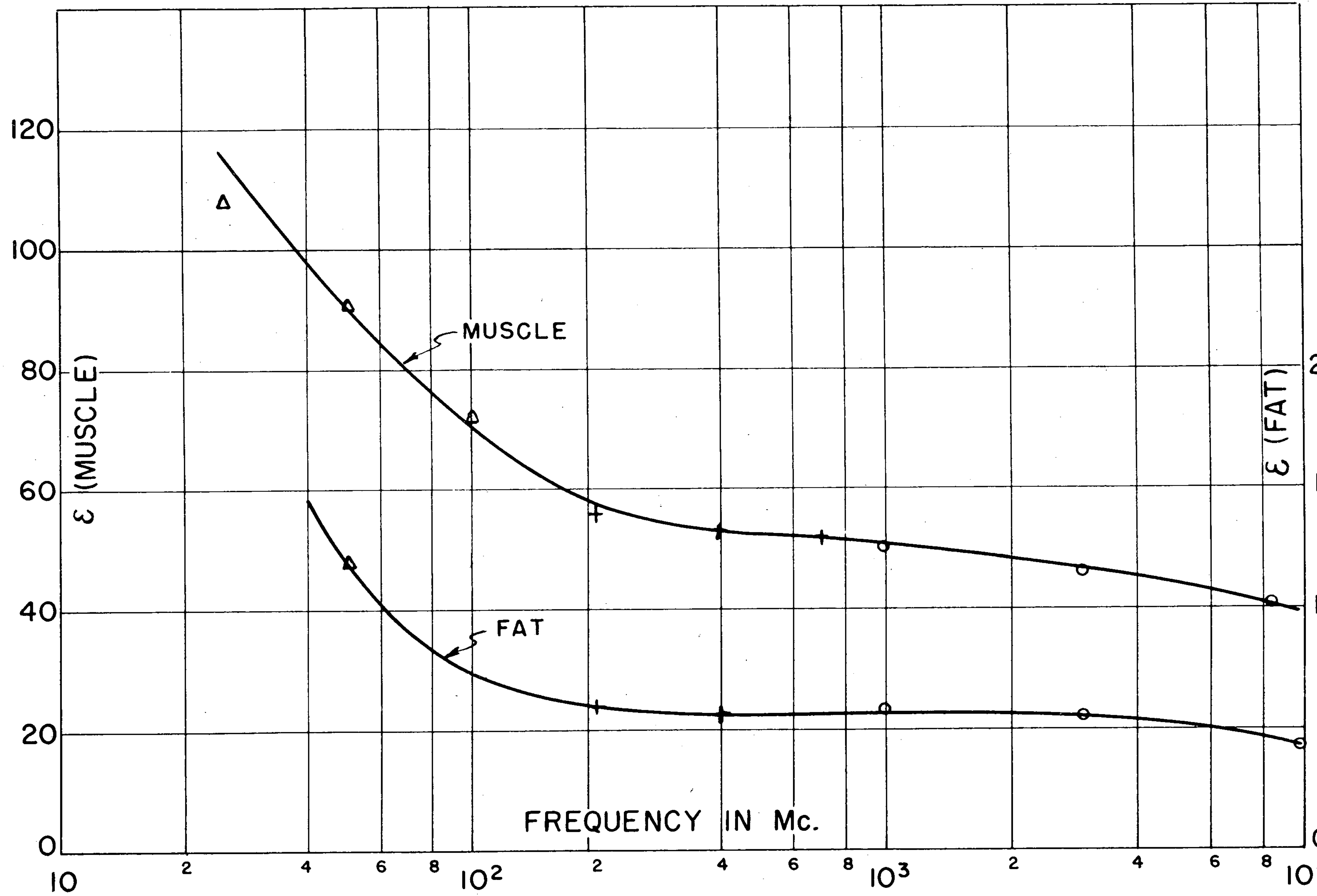
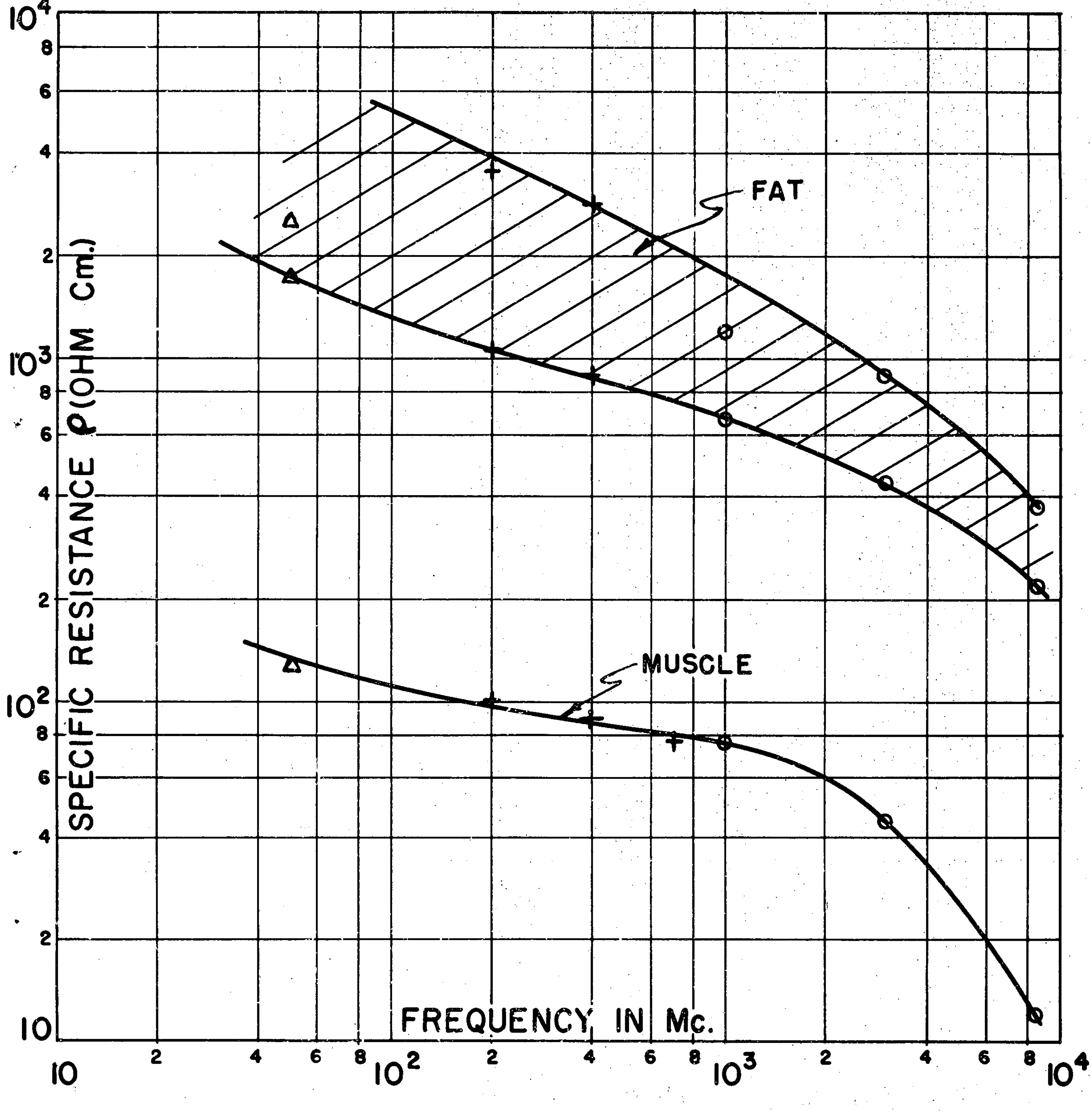


Figure 2


FAT
MUSCLE
SPECIFIC RESISTANCE ρ (OHM Cm.)
FREQUENCY IN Mc.
10
2
4
6
8
10²
2
4
6
8
10³
2
4
6
8
10⁴

In Figure 3 the conductivity versus the dielectric constant of fat (human autopsy material) is plotted. All data pertain to 900 Mc, but at other frequencies similar curves could be demonstrated. The graph explains that the conductivity of all normal samples shown here varies by a factor of five. Two samples, with a conductivity near 4 mMho/cm, pertain to tissues of abnormally high electrolyte content, related particularly to the cause of death. One sample, indicated by the arrow, was measured after dehydration in the oven. It should be noted that the dielectric constant varies by a considerably smaller range. This illustrates why, by comparison, good reproducibility of dielectric constant and a poor one of conductivity result. On the other hand, there is a systematic relationship between the conductivity and the dielectric constant data. The reasons for this behavior become apparent in the next figure.

In Figure 4 the dielectric constant of fatty tissue versus percentage of water contained in fat is plotted at 300 Mc. Water determinations were carried out in the routine manner. The relationship between the dielectric constant and the water content of fatty tissue is well-defined. With increasing water content the dielectric constant rises. This is anticipated since water has a high dielectric constant. The arrow between the two and the four mark indicates the value resulting from dehydration of fat.

Figure 3

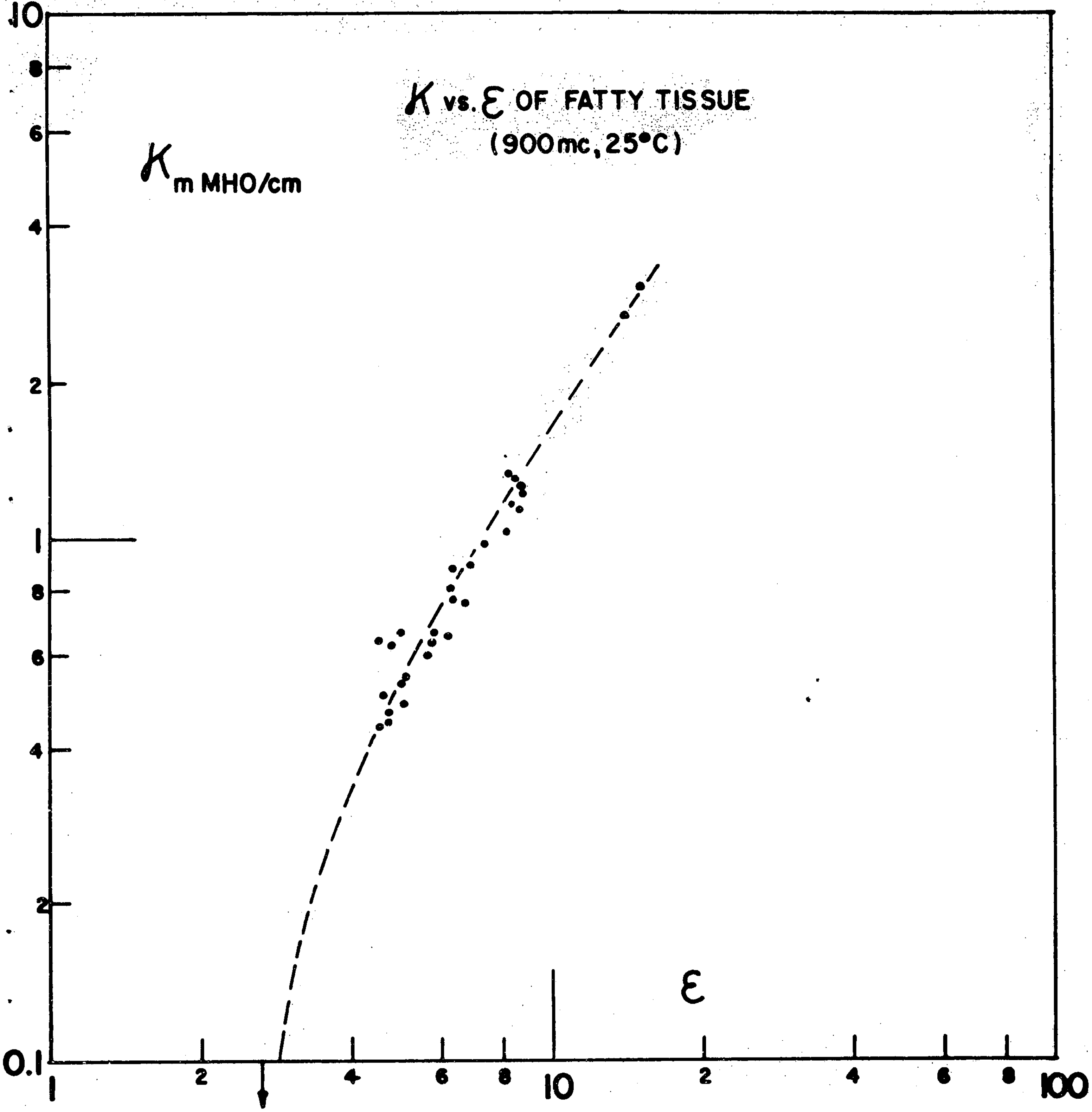
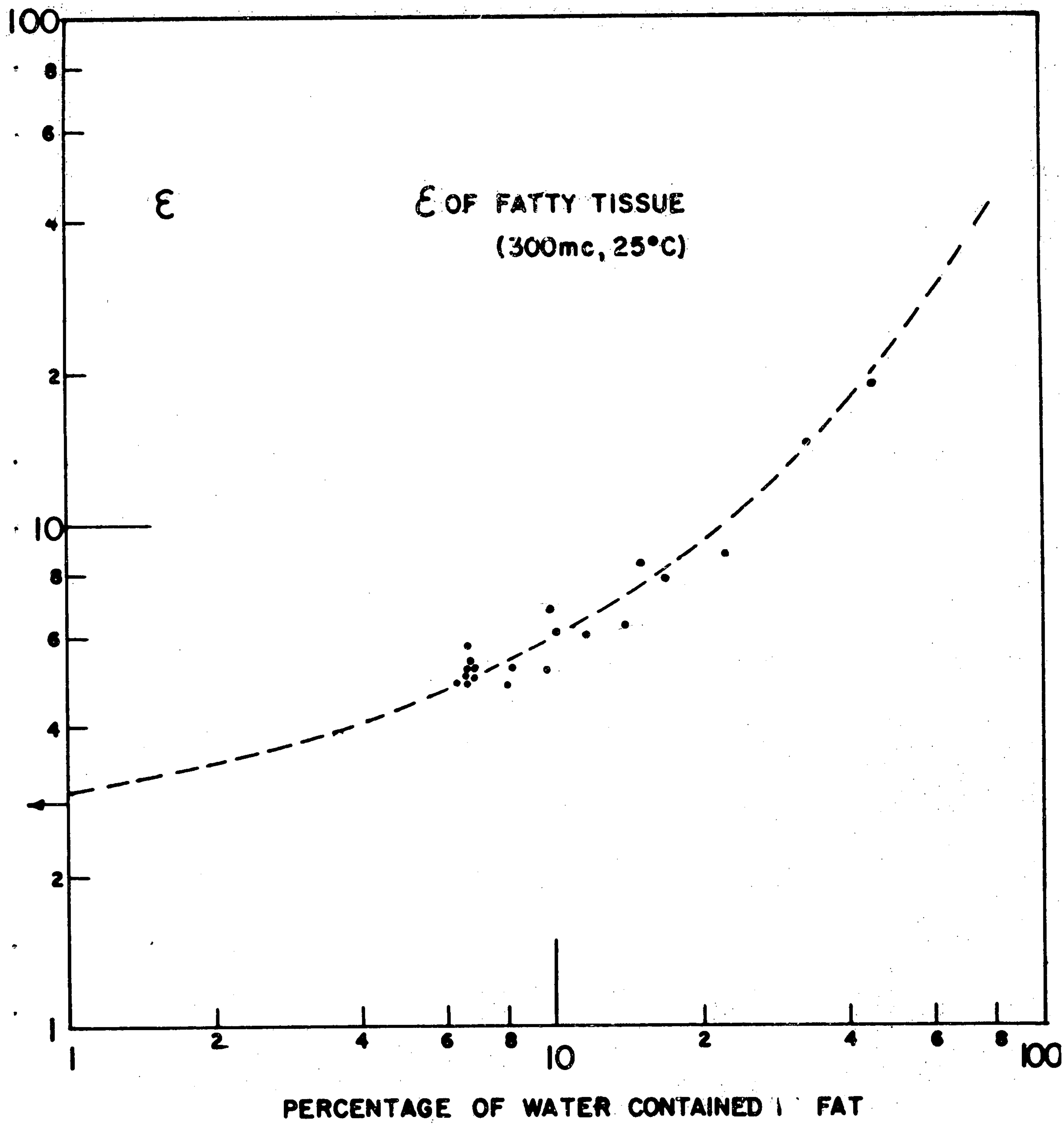

K vs. ε OF FATTY TISSUE
(900mc, 25°C)
K m MHO/cm
10
8
6
4
2
1
8
6
4
2
0.1
1
2
4
6
8
10
2
4
6
8
100
ε

Figure 4


ε
ε OF FATTY TISSUE
(300mc, 25°C)
100
8
6
4
2
10
8
6
4
2
1
1
2
4
6
8
10
2
4
6
8
100
PERCENTAGE OF WATER CONTAINED I FAT

The conductivity of fatty material versus the percentage of water contained in fat is plotted at 300 Mc (Figure 5). Even though somewhat more fluctuation occurs than in the previous figure, a clearly defined relationship is apparent. Again, increasing the water content increases the conductivity. It is noteworthy that the variation in water content is within the normal range through the major part of the curve. Two abnormal cases of high water content are included in the figure to establish the relationship between conductivity and water more clearly.

In summary of the above presented dielectric data:

1. Dielectric constant and conductivity of tissues of high and low water content are very different from each other.
2. Dielectric constant and conductivity of muscular and other tissues of high water content are quite reproducible, i. e. variation from sample to sample is small.
3. Dielectric constant and conductivity of fatty tissues vary considerably from sample to sample. However, a uniform and reproducible relationship

exists between

(a) dielectric constant and conductivity at any given frequency, and

(b) both dielectric constant and conductivity on the one hand and water content on the other.

Hence variability of dielectric data of fatty tissues reflects a corresponding variability in water content.

The above formulated conclusions are justified for the total frequency range of interest for radar purposes. They have been secured for the spectrum from 40 to 10,000 Mc.

Figure 6 presents selected material and condensation of conductivity values from all the material we have measured. The vitreous humor, yellow bone marrow and bone (the points around yellow bone marrow pertain to bone per se) indicate the extremes of the total range of data, and all the other data fall in between. The conductivity is almost constant up to 1,000 Mc, and then it increases very rapidly with frequency. Above 30,000 Mc the conductivity approaches constant values again. With these electrical data and the dielectric constants presented in Figure 7, we have all the essentials available for the determination of absorption coefficients.

Figure 5

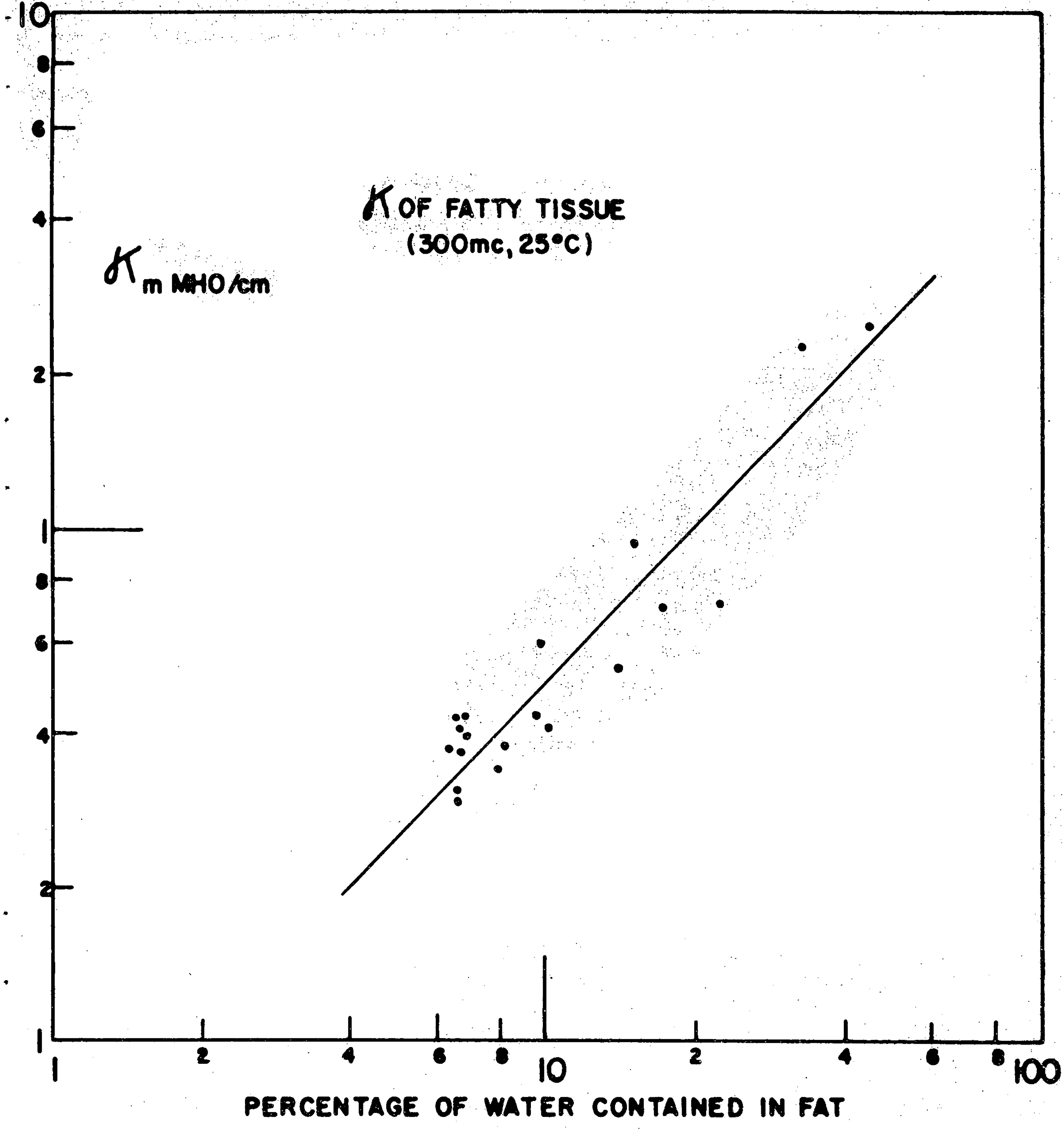

K OF FATTY TISSUE
(300mc, 25°C)
K m MHO/cm
10
8
6
4
2
1
8
6
4
2
1
1
2
4
6
8
10
2
4
6
8
100
PERCENTAGE OF WATER CONTAINED IN FAT

Figure 5

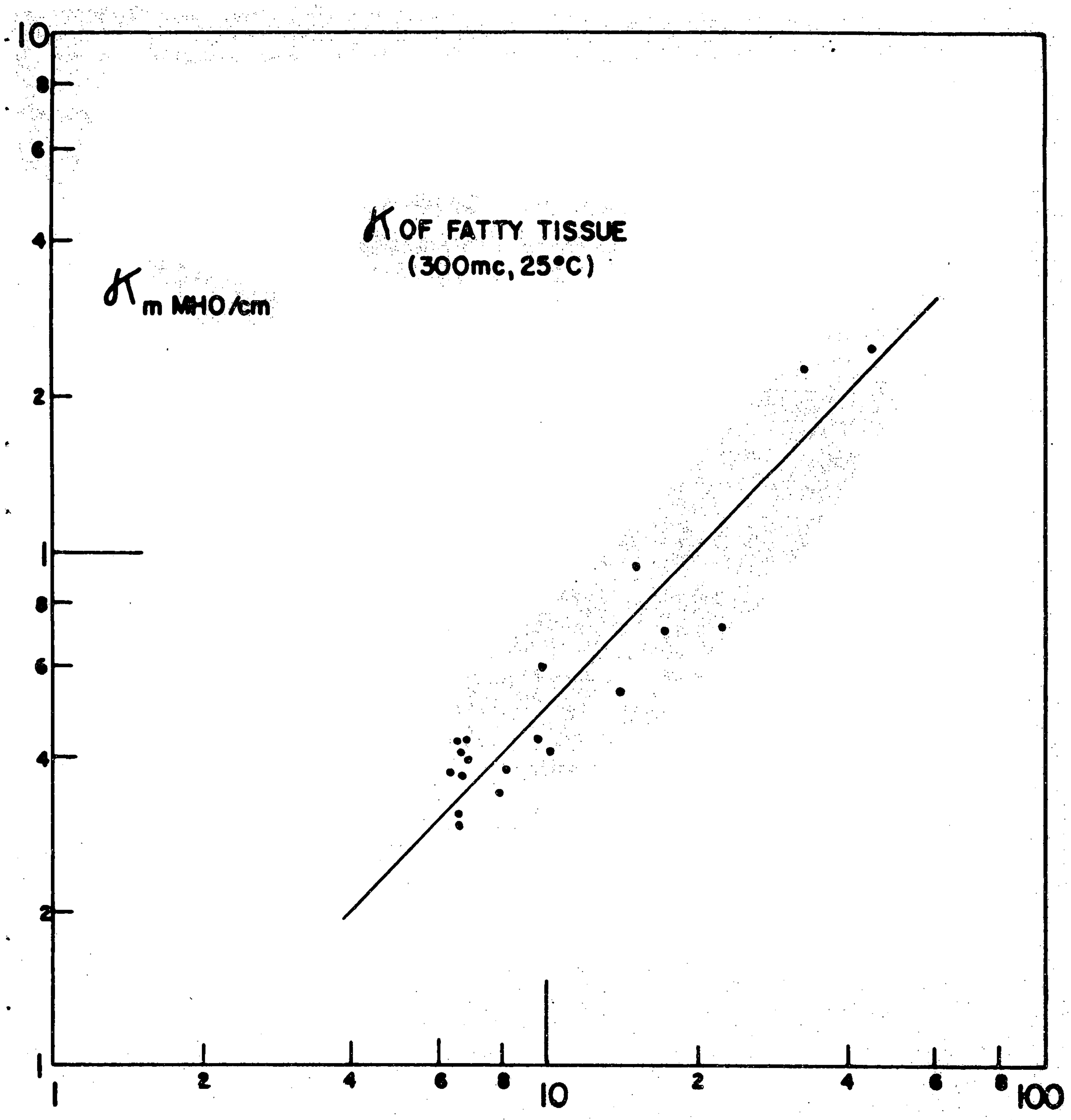
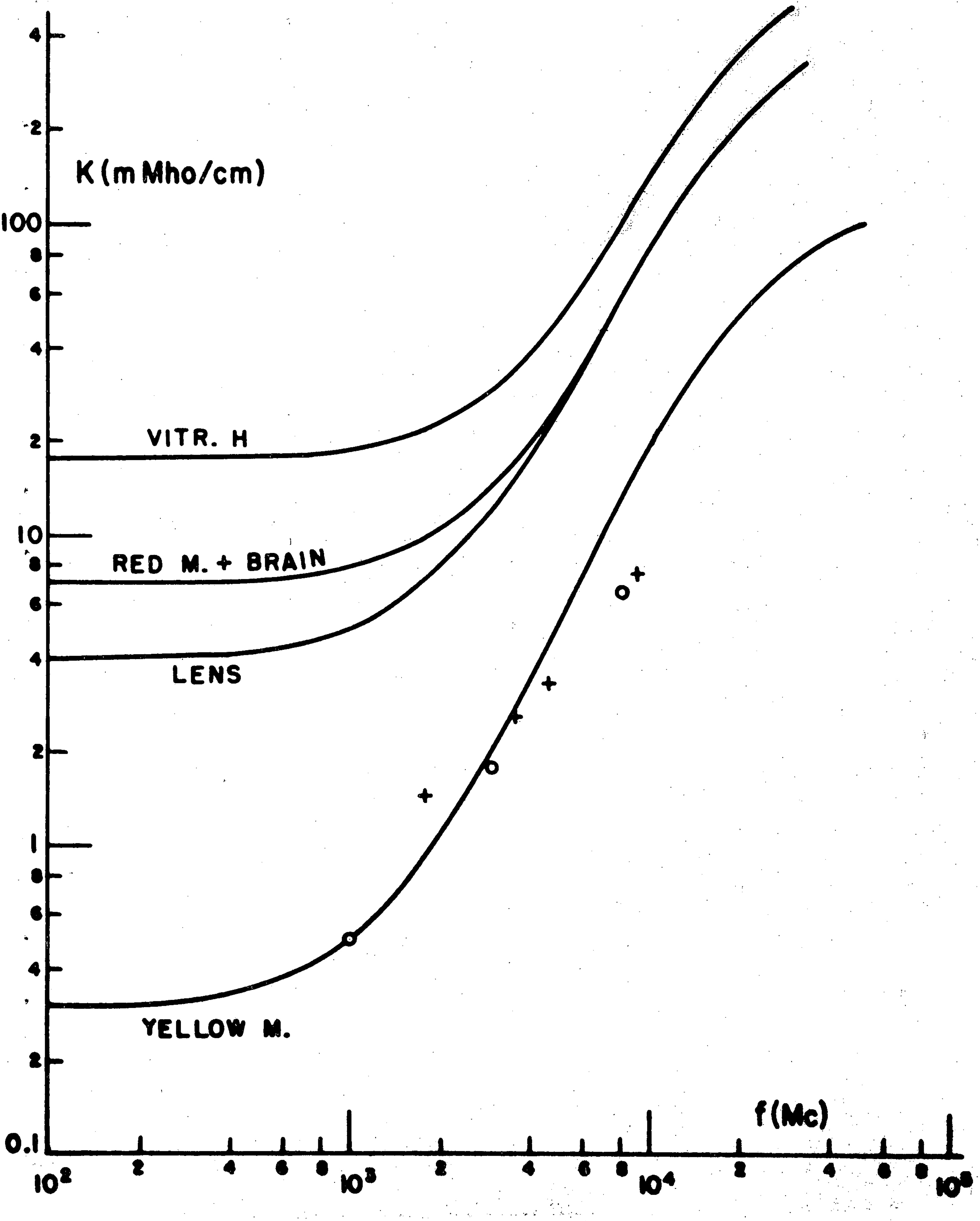

K OF FATTY TISSUE
(300mc, 25°C)
K m MHO/cm
10
8
6
4
2
1
8
6
4
2
1
1
2
4
6
8
10
2
4
6
8
100
PERCENTAGE OF WATER CONTAINED IN FAT

Figure 6


K (m Mho/cm)
4
2
100
8
6
4
2
10
8
6
4
2
1
8
6
4
2
0.1
VITR. H
RED M. + BRAIN
LENS
YELLOW M.
f (Mc)
10^2
2
4
6
8
10^3
2
4
6
8
10^4
2
4
6
8
10^5

The same materials shown in the previous figure are repeated in Figure 7, but, in this case, they relate dielectric constant data. The vitrous humor and the yellow bone marrow still establish the extremes of range. All other materials tested, which are too numerous to be included here, fall between these two extremes. Above 10,000 Mc, there is a pronounced decrease.

For the next series of figures we have translated the available dielectric data in absorption coefficients, or rather their inverse, i. e. depth of penetration values.

Figure 8 demonstrates the principal behavior of the penetration as function of wave length in air. The curve extending from the lower left hand corner (the infrared range) up to more than 1,000 centimeters pertains to muscular and similar tissue. This curve demonstrates two principal regions. One region pertains to a small change at relatively long wave lengths and seems to approach a plateau between 10 and 100 cm. But before achieving the plateau, the penetration drops off abruptly and finally approaches another constant values in the infrared range. This datum has been extrapolated with a pertinent theory and corresponds nearly identically with infrared experiments conducted by physiologists.

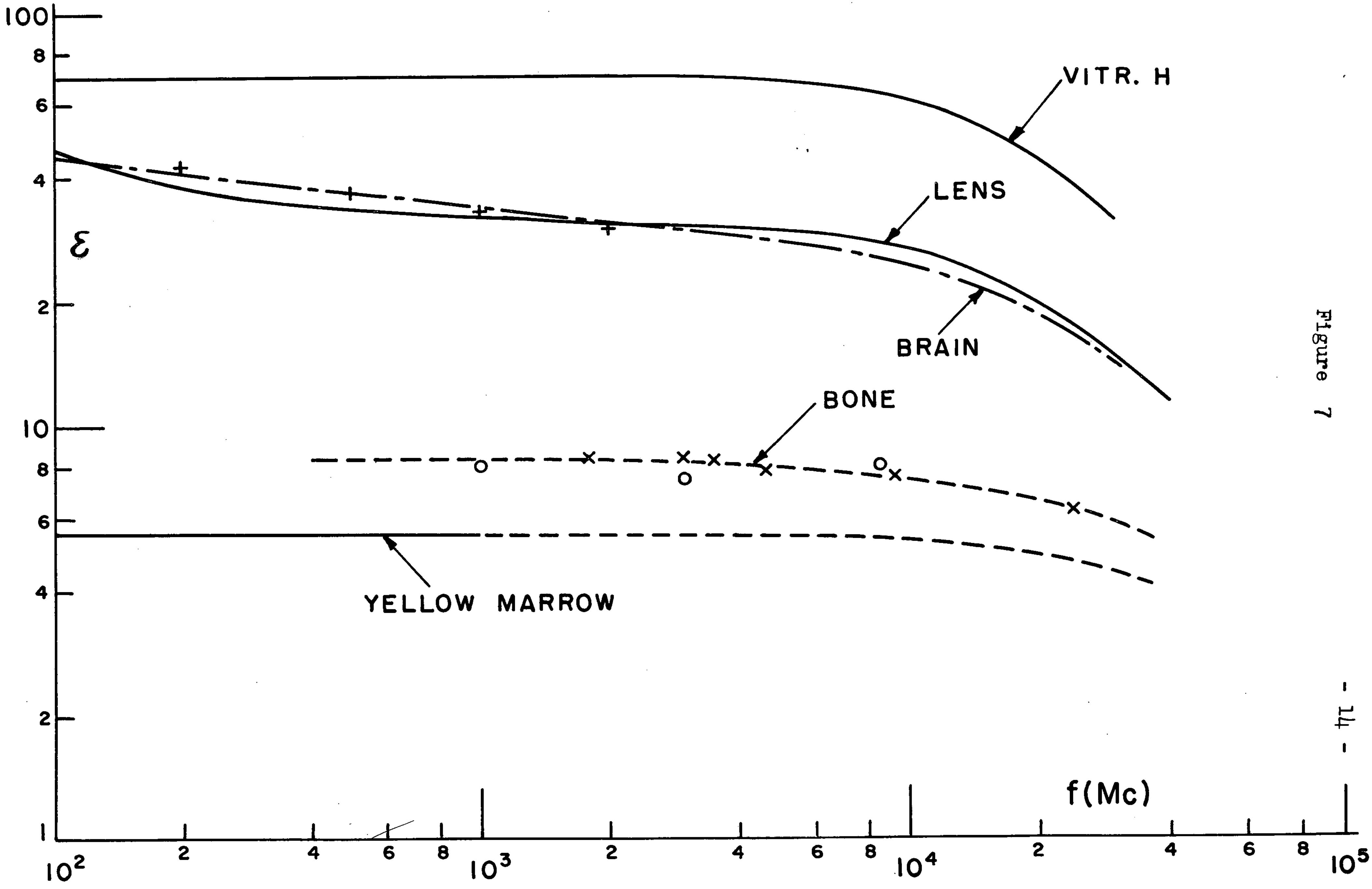
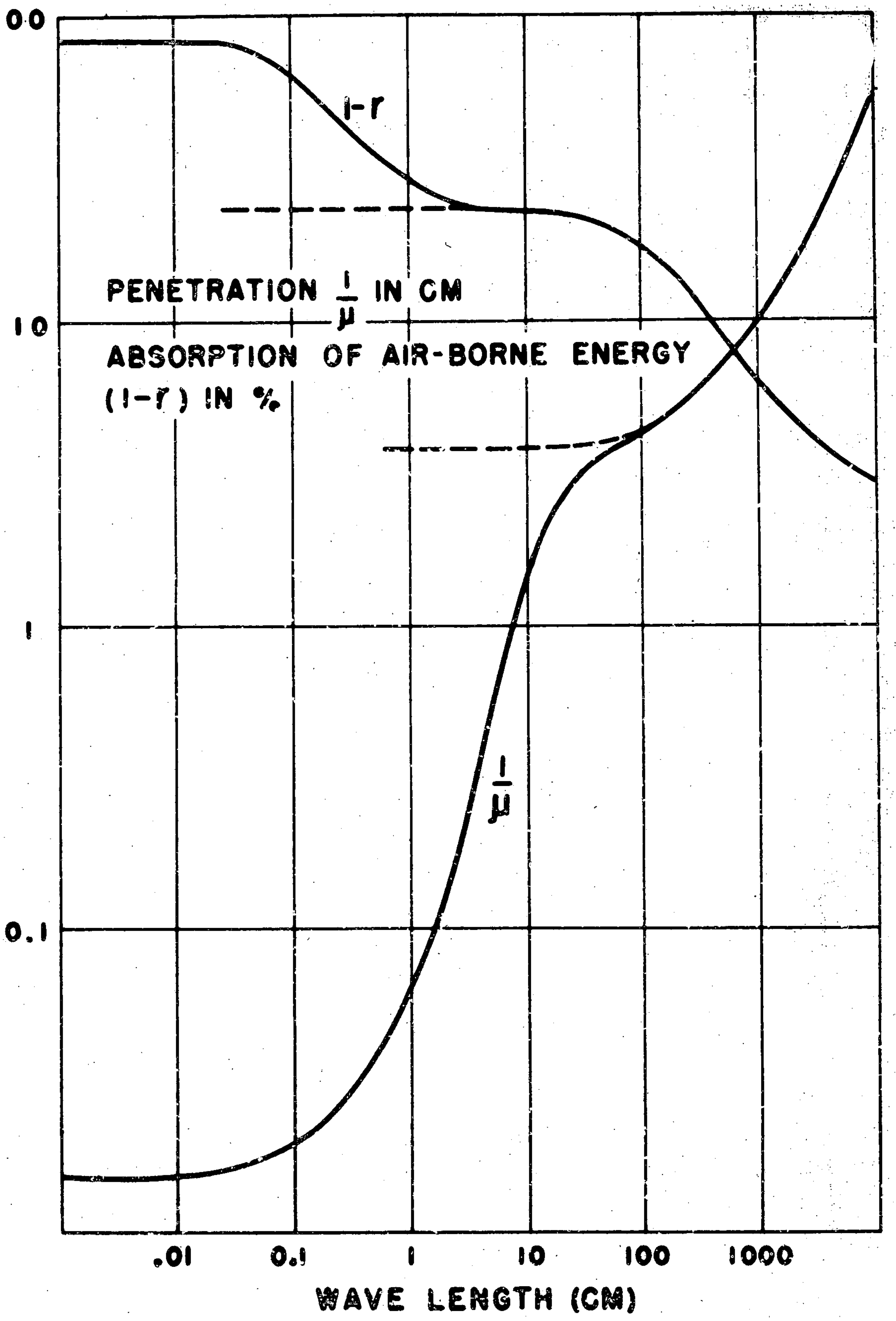

100
8
6
4
ε
2
10
8
6
4
2
1
VITR. H
LENS
BRAIN
BONE
YELLOW MARROW
f(Mc)
10^2
2
4
6
8
10^3
2
4
6
8
10^4
2
4
6
8
10^5

Figure 7

Figure 8


100
10
1
0.1
.01
0.1
1
10
100
1000
WAVE LENGTH (CM)
1-r
1/μ
PENETRATION 1/μ IN CM
ABSORPTION OF AIR-BORNE ENERGY
(1-r) IN %

While this frequency over a more limited range is the principal behavior, Figure 9 presents more detailed data. Depth of penetration of fatty tissue and tissues with a high water content, such as muscle are plotted in Figure 9 for various frequencies. The range of variability for fatty tissue, which does not appear on the graph, is higher and lower than the average curve by a factor of approximately 1.5. These curves are restricted to the immediate range of interest, i. e. from 100 Mc to 10,000 Mc. Observe that at frequencies below 1,000 Mc the depth of penetration changes relatively little. Above 1,000 Mc, the depth of penetration decreases very rapidly.

Figure 10 gives penetration values for different frequencies and compares brain tissue and red bone marrow with muscle. Note that the depth of penetration at 3,000 Mc is approximately eight or nine millimeters and then falls off rapidly. At 30,000 Mc penetration reaches a depth of only 0.3 millimeter.

Figure 9

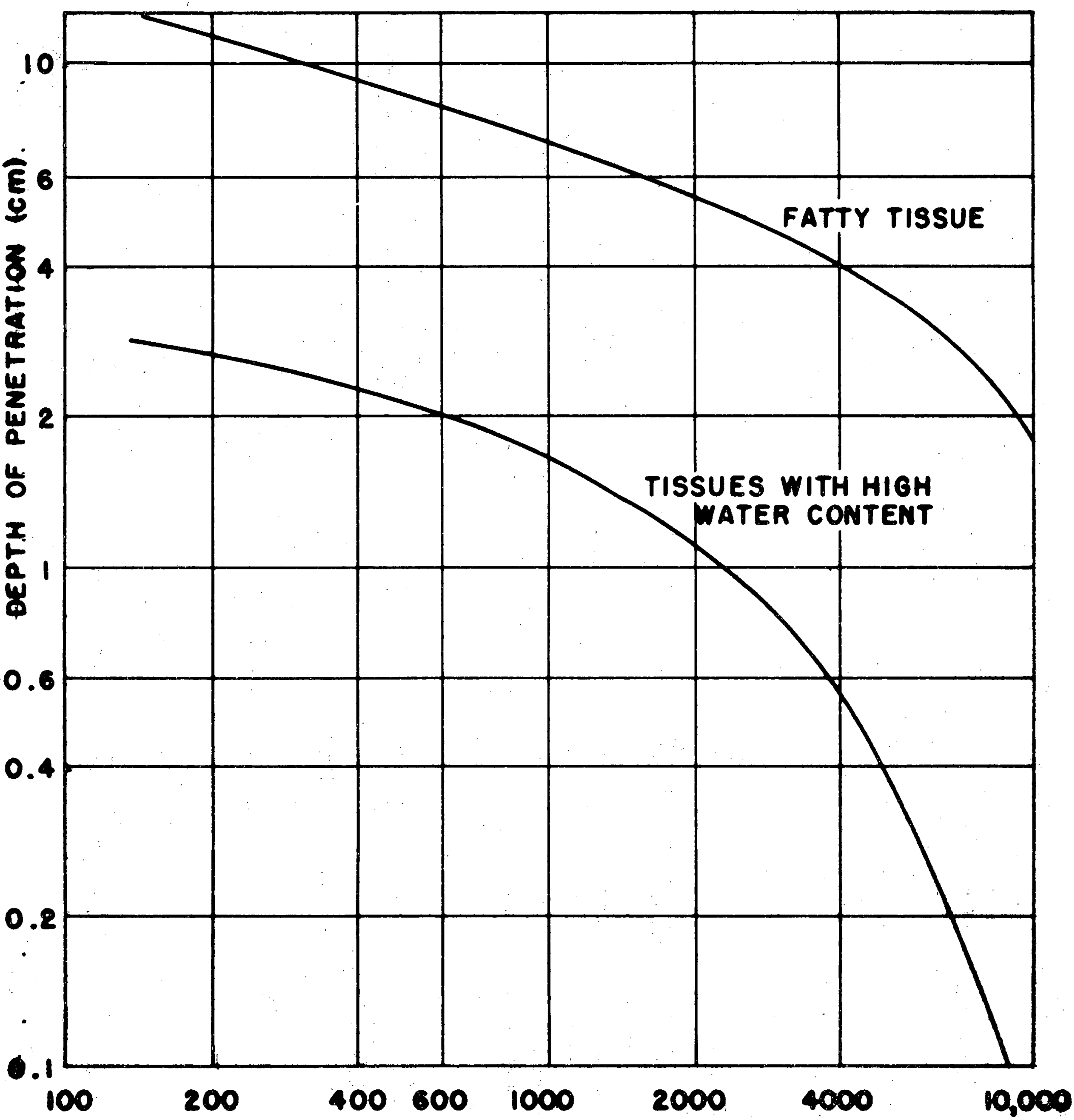
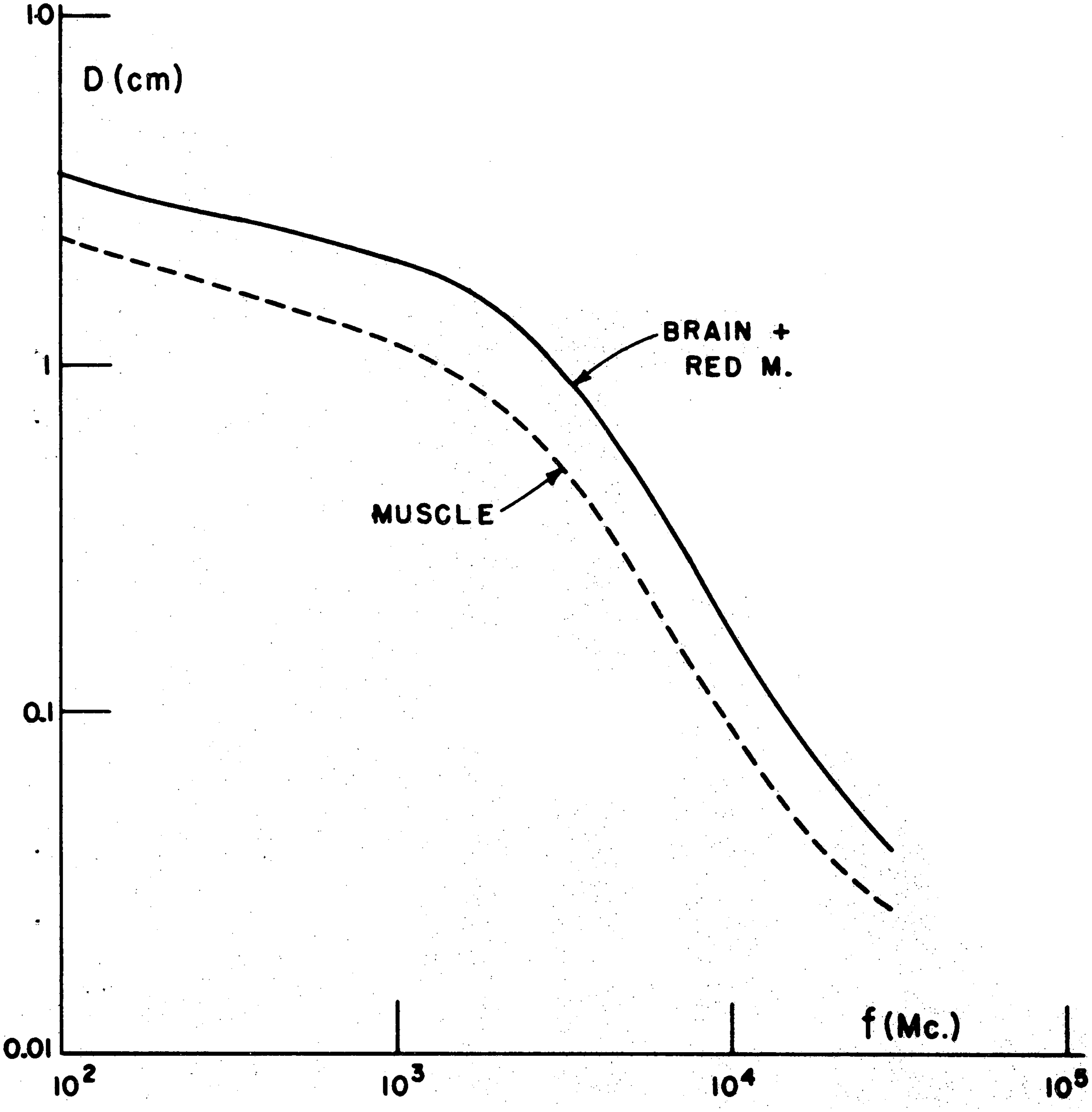

DEPTH OF PENETRATION (cm).
10
6
4
2
1
0.6
0.4
0.2
0.1
FATTY TISSUE
TISSUES WITH HIGH WATER CONTENT
100
200
400
600
1000
2000
4000
10,000
FREQUENCY IN MEGACYCLES

Figure 10



In Figure 11 the depth of penetration values apply to yellow marrow and bone. At 3,000 Mc the depth of penetration is about 5 cm. In other words, the ability to penetrate yellow marrow and bone is about tenfold or one order of magnitude higher than it is to penetrate muscle and red marrow.

In Figure 12 the depth of penetration is plotted over a very wide frequency range for the vitreous humor and lens of the eye. Note that both curves approximate a plateau around 1,000 Mc. The lens material behavior at very high frequencies is almost identical with that of the vitreous humor. At lower levels, however, the lens curve is somewhat higher reflecting its higher protein content and consequent lower conductance.

In discussing both the depth of penetration of the radiation and the resultant penetration of heat, both thermal conductance and radiation must be borne in mind as the two factors of importance. For example, when depth of penetration of radiation is great, then, for physical reasons, it might be anticipated that thermal conduction would be small in its influence on the effective penetration of heat.

Figure 11

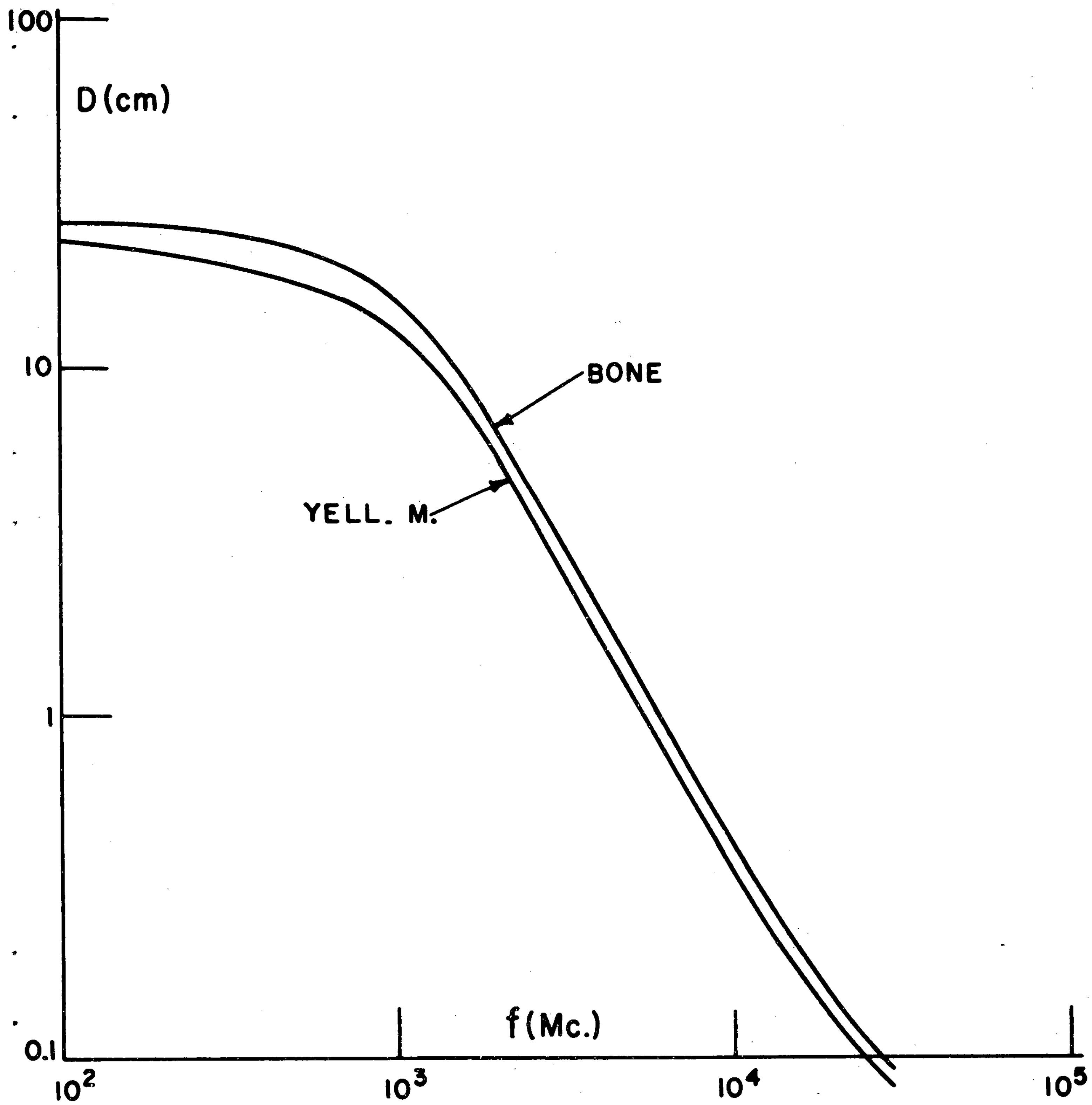


Figure 12

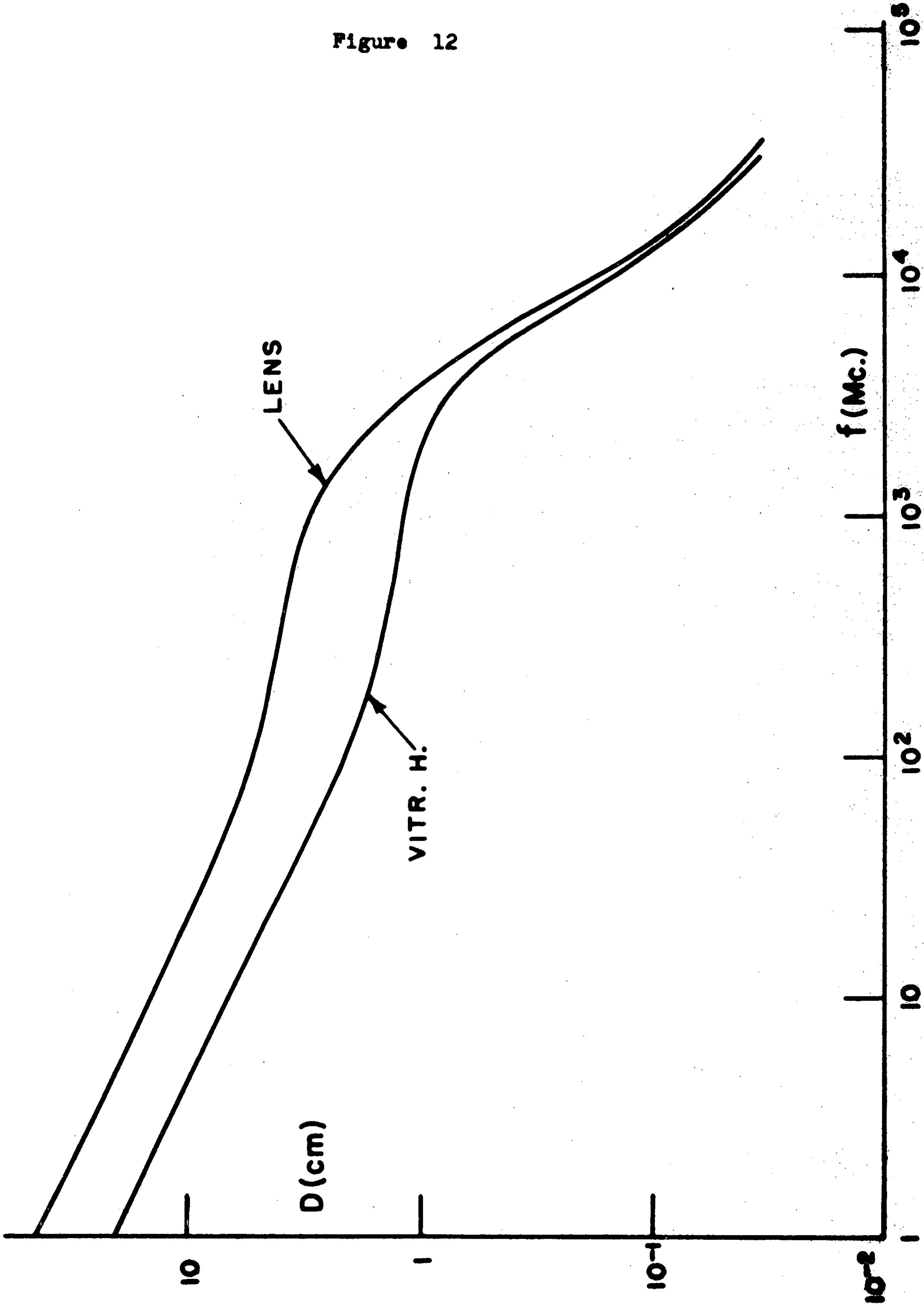
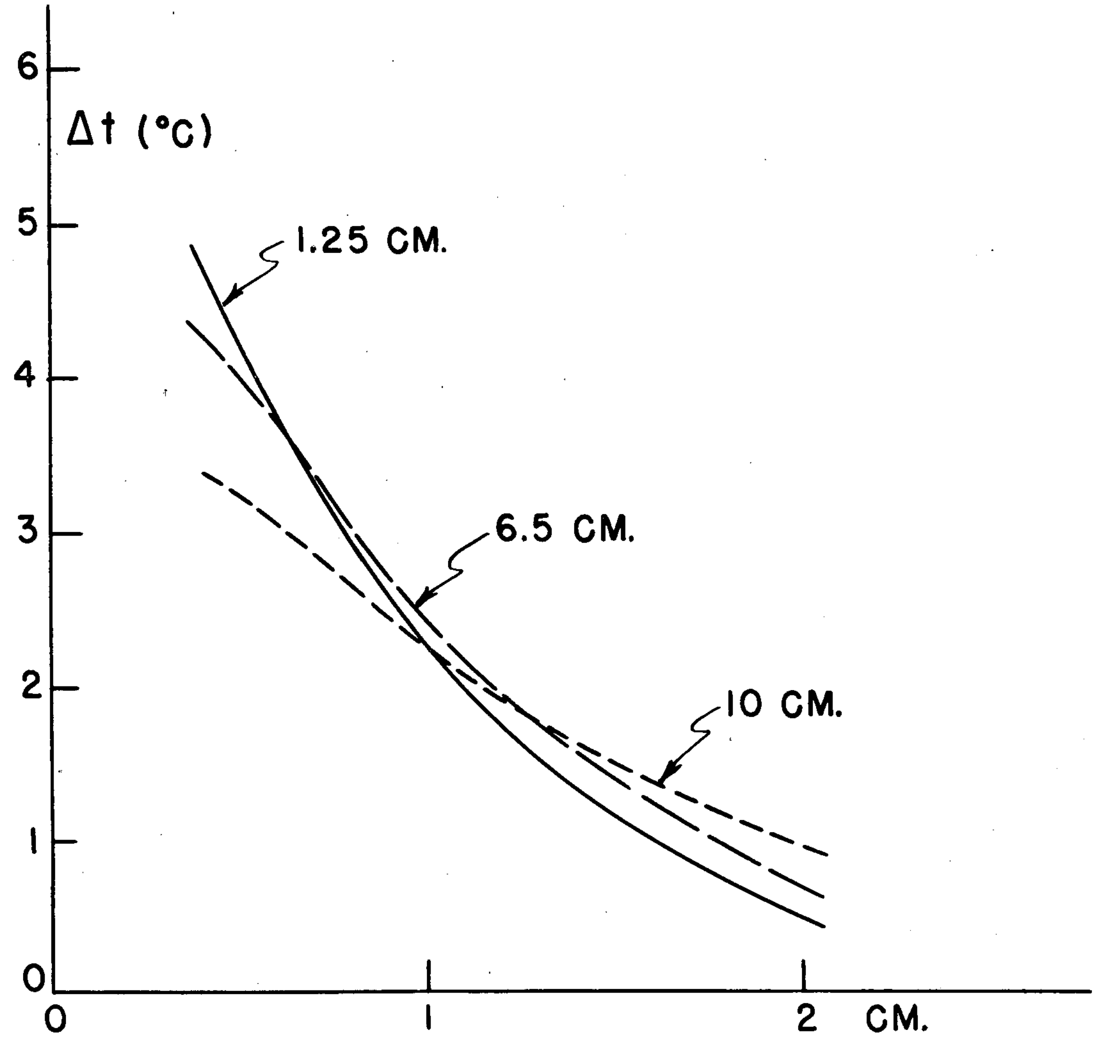


Figure 13



The opposite holds when the absorption coefficient is very high, i. e. depth of penetration is very low. This is demonstrated by three heating curves which Cook presented for wave lengths at 10, 6.5, and 1.25 cm (Figure 13). The curves resulting for 1.25 and 6.5 cm are essentially identical, even though depth of penetration values show great differences. In essence, this means that a radiation frequency substantially higher than 3,000 Mc acts merely as a surface heating device, similar to infrared, and that heat penetration must rely on conduction.

A few comments to summarize the presented absorption values seem in order:

1. Depth of penetration in muscular and similar tissues is about tenfold larger than in fatty and similar tissues. A complete survey of absorption characteristics reveals, however, that there are some tissues, such as brain, which place themselves in between.
2. Depth of penetration decreases with increasing frequency, slowly below 1,000 Mc and increasingly rapid above.

3. Depth of penetration in the majority of tissues with relatively high water content decreases below 1 cm as the frequency reaches above 3,000 Mc. Its ability to deliver heat inside the body relies to an increasing extent on heat conduction instead of "primary" production. Therefore, from a practical point of view, it becomes comparable with infrared in its effects on mankind.

For experimental work some suggestions result from the data:

a) As radiation frequency increases and penetration decreases, the likelihood of internal damage decreases, i. e. higher frequencies are less damaging than lower ones. This statement, of course, is only valid if the total penetrated energy is absorbed; i. e. if penetration values are small compared to physical dimensions of the test animal. The penetration values presented show that this is always true for mankind.

b) If experiments are carried out with animals of a physical size which is comparable or less than that of above reported penetration values, only part of the available energy flux will be consumed. As a result, any anticipated simple relationship between damage and radiation flux will be distorted.

For example, it would be virtually impossible to generate substantial temperature elevation in mice at 100 or 200 Mc. However, the same frequency must produce substantial internal heating in mankind if applied with the same flux. The implications of this pertaining to related experimental work are evident.

The third and last section of figures refers to data of reflectance and energy distribution.

In Figure 14 the percentage of absorbed energy is plotted as a function of frequency for muscular tissue alone. The plateau in the 1,000 Mc frequency range represents a value of approximately 40% absorbed energy. Note the increase in absorbed energy as frequency increases beyond 10,000 Mc.

In the presence of other tissues the situation becomes more complex (Figure 15). For example. the amount of absorbed energy varies with the thickness of the subcutaneous fatty layer. The variation is relatively slow at lower frequencies. As the frequencies increase, however, the amount of absorption becomes more erratic, resulting in a more complex situation.

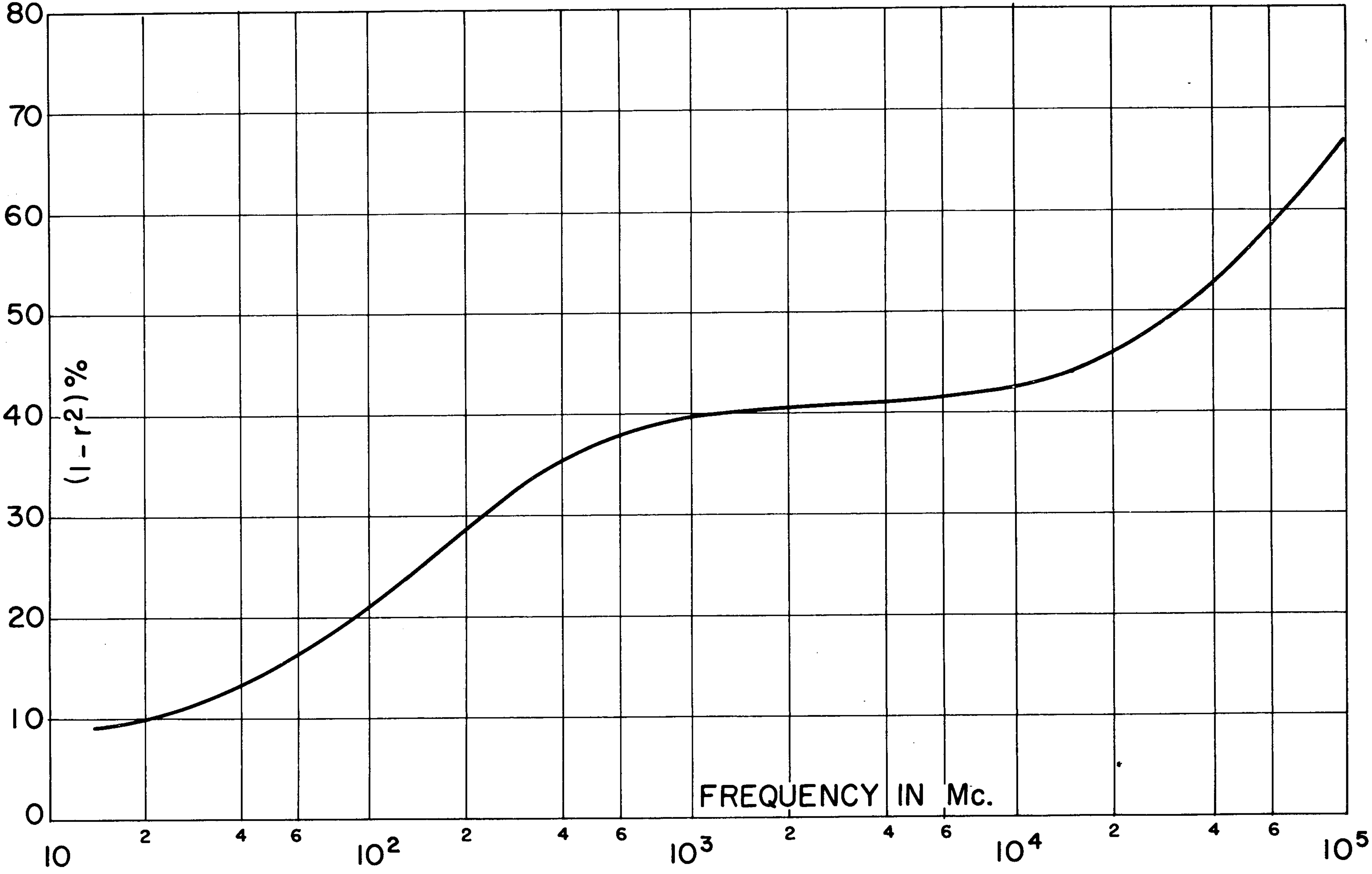

80
70
60
50
40
30
20
10
0
$(1-r^2)\%$
FREQUENCY IN Mc.
10
2
4
6
10^2
2
4
6
10^3
2
4
6
10^4
2
4
6
10^5

Figure 14

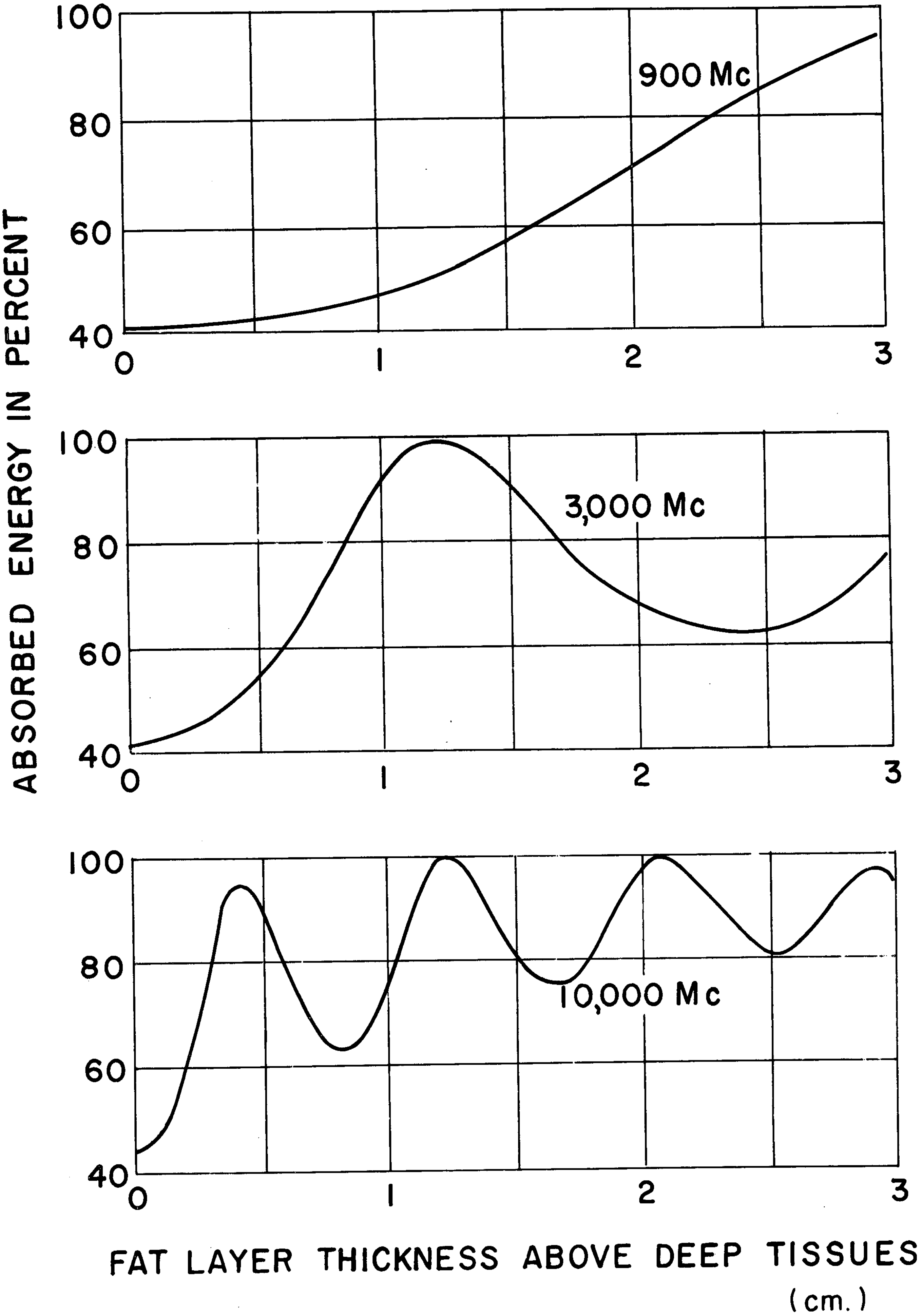

ABSORBED ENERGY IN PERCENT
100
80
60
40
0
1
2
3
900 Mc
3,000 Mc
10,000 Mc
FAT LAYER THICKNESS ABOVE DEEP TISSUES
(cm.)

Figure 16 is presented only to illustrate the extreme variability in absorbed energy when three tissues are considered together. The curves superimposed on one another represent the absorbed energy of skin, subcutaneous fat amd deep tissues. This is a realistic relationship which would occur in the body. Note that the total amount of absorbed energy can vary between 20 and 100 %, i. e. by a factor of 5. K denotes the skin thickness in cm; the abscissa indicates the thickness of the subcutaneous fat layer.

The situation in Figure 17 is somewhat idealized as only fat and muscle are considered. The inclusion of skin would further comlicate matters. Observe that at the interface between fat and muscle the relative heating is much lower in fat than in muscle. This merely indicates that the impedance of fatty material and muscular tissue is quite different. The consequent large reflection of energy into fatty material results in a reduction of the field strength at the boundary (fat-muscle), and a correspondingly smaller heat development there. Under proper conditions an appreciative reduction in field strength near the body may occur, while a large energy absorption may take place within the body itself. Thus, in principle, it appeats impossible to construct a dosimeter which measures absorbed energy reproducibly and can be carried on or near the human body. In our opinion measurements should be taken in the "distant field" to enable standardization of experiments.

Figure 16

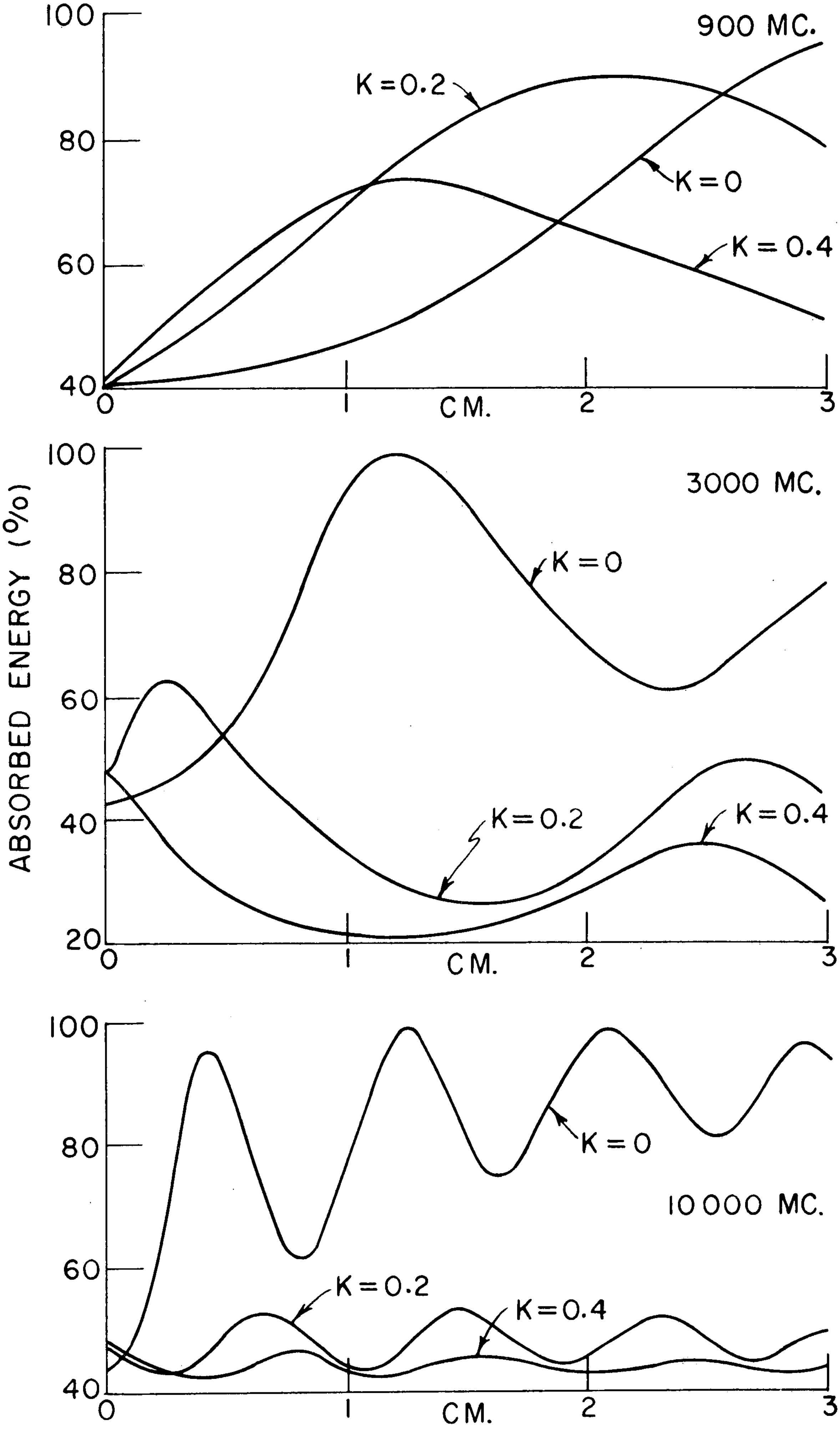
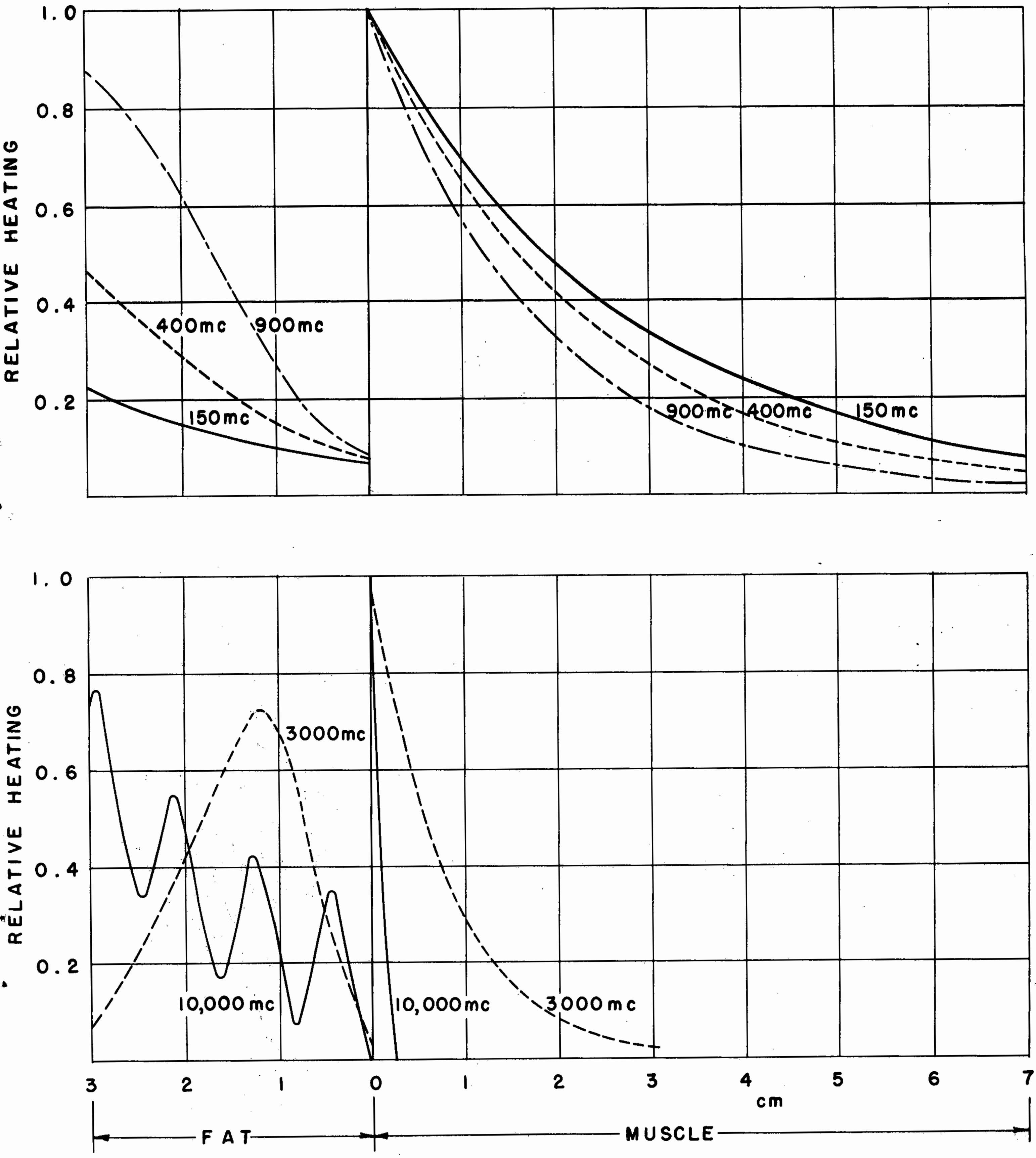

ABSORBED ENERGY (%)
900 MC.
100
80
60
40
0
1
2
3
CM.
K = 0.2
K = 0
K = 0.4
3000 MC.
100
80
60
40
20
0
1
2
3
CM.
K = 0
K = 0.2
K = 0.4
10000 MC.
100
80
60
40
0
1
2
3
CM.
K = 0
K = 0.2
K = 0.4

Figure 17


1.0
0.8
0.6
0.4
0.2
RELATIVE HEATING
400mc
900mc
150mc
900mc
400mc
150mc
1.0
0.8
0.6
0.4
0.2
RELATIVE HEATING
3000mc
10,000mc
10,000mc
3000mc
3
2
1
0
1
2
3
4
5
6
7
cm
FAT
MUSCLE

SUMMARY

In summary, the following conclusions may be drawn from the material presented above.

a) The absorption data reviewed cover a total range of about 1 to 10 at any particular frequency. Extremes are provided by the glass body of the eye, yellow marrow and dry fat. In between we find an almost continuous assembly of data.

b) The determination of absorption characteristics is a prerequisite to much experimental work. For example, in order to determine the dose to which animals much smaller than the depth of penetration or cellular organism are exposed, absorption coefficients are a prerequisite. Without this knowledge no quantitative statements are possible.

c) For most tissues frequencies substantially higher than 3,000 Mc cause mere surface heating, i.e. they act like infrared or sunlight. At lower frequencies, particularly below 1,000 Mc, much larger penetration is achieved. This statement is valid for all tissues.

d) From the complexity of reflectance and energy distribution it is concluded that no dose meter can be constructed which can be carried on or near the body surface and give sensible data. On the contrary, its readings may be far too low due to cancellation of field strength as a consequence of standing wave patterns.

e) Standing wave pattern in the body makes it senseless to talk about energy flux in the body and to use it as a measure of dosage. All dose or dose rate statements must refer to field or flux values in the distant field defined sufficiently far from the body to be affected by its presence.