Dielectric Properties of Insect Tissues

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Abstract. In order to explain some effects of microwave irradiation on insects it is necessary to consider a mathematical model. The knowledge of dielectric properties of a typical insect tissue is crucial for such a model. A method based on shift of resonant frequency and of quality factor measurement in a resonator both before and after the insertion of samples was used. The method (measurements at a frequency of 2375 MHz) has been described in detail. A large number of measurements were performed on different kinds of typical insect tissues (cuticle, fat body, muscles, reproductive organs and eggs) for their dielectric properties. The values obtained compare well to those reported in the literature for some mammals. Differences seemed to depend on different water-to-fat content ratios. However, no simple dependence on the water content was found. Values obtained from insect tissue material have been discussed in detail.

Key words: Dielectric properties — Microwave irradiation — Modelling of electromagnetic field

Introduction

Most of the effects of microwaves on biological systems described so far are due to the so-called thermal effect of the formers. A large scale of damage to diverse structures and tissues (Ondráček 1977; Žďárek et al. 1976; Ondráček and Ďatlov 1979; Dardalhon et al. 1979; Carpenter and Livstone 1971; D'Ambrosio et al. 1980; Green et al. 1979; Rai et al. 1974.) have been noted in experiments during which different developmental stages of insects were exposed to microwaves. The alterations included malformations of appendages (wings, legs), disorders of the normal structure of cuticle and, consequently, is its function, atrophy or abnormal development of some muscular tissues, of inner reproductive organs, etc. Occasionally, some large and important body parts did not develop at all as a result of microwave exposure. Irradiated praepupae of the moth *Spodoptera littoralis* developed into pupae with their anterior part severely damaged. Some of the individuals lacked heads or thorax, while their abdomen was complete and alive. One of the possible explanations for this is the occurrence of a hot spot. Theoretical explanation of the formation of the latter, requires, among other, a deep under-

Table 1. Dielectric constant and loss factor values of some insect tissues.

Tissue	Dielectric constant	Loss factor tg δ
Dry cuticle — exuviae		
Tenebrio molitor — larvae	1.2—1.6	0.02
Cuticle — adult *T. molitor*	14—19	0.32—0.34
Fat body adult *T. molitor*	8	0.3
Fat body — adult		
Pyrrhocoris apterus	17	0.3
Muscles — adult *T. molitor*	50—57	0.22—0.26
Inner reproductive organs		
P. apterus females	41—51	0.22—0.26
Body liquid — haemolymph		
adult *P. apterus*	76	0.18
Whole eggs *P. apterus*	2.8—3.5	0.12—0.13
Homogenised eggs *P. apterus*	32—39	0.26—0.28

standing of dielectric properties of the damaged tissues. Literary data on the dielectric constant and conductivity are scarce and they generally are valid for frequencies other than those used in our experiments (Stuchly and Stuchly 1980; Nelson and Stetson 1974.). This prompted us to start measurements reported herein.

Materials and Methods

Tissue samples for measurements were taken from the flour beetle, *Tenebrio molitor*, and from the bug *Pyrrhocoris apterus*. The above two species have often been used for various experiments, and they are continually reared in the Institute of Entomology using methods described by Ondráček (1977). Samples were taken from different developmental stages of the two species. The cuticle of *Tenebrio molitor* was obtained from larval exuviae, samples of other tissues were prepared from killed insects. Some of the tissues were homogenized in a laboratory glass homogenizer in order to smash the tissue and cells. In addition to the measurements of dielectric properties, the water content was assessed by weighing. To avoid loss of tissues during the preparation only as many insects were always dissected as necessary to obtain the required volume of tissue. Measurements were repeated five to ten times with different samples. In Table 1 ranges of the values obtained are given. No statistical analysis was performed since we have considered the results representative enough with regard to the methods used and to the properties of living tissues.

The resonance method applicable to very small samples was used to measure dielectric properties. Other methods generally used with microwaves require replacement of a part of the circuit or of its wall with the sample, so that large sample volumes are necessary, whereas 50 μl are sufficient for the resonance method. The latter is based on the measurement of shifts in the resonant frequency insertion of a sample. Changes depend on following relations valid for a toroidal resonator:

$$\frac{f-f'}{f}=(\varepsilon-1)\frac{\int_{V^1}(E',E)\,\mathrm{d}V}{\int_{V}(E',E)\,\mathrm{d}V} \tag{1}$$

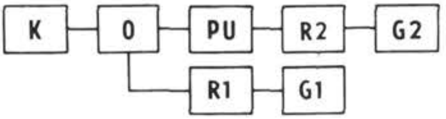

Fig. 1. Block diagram of the experimental layout. For details see the text.

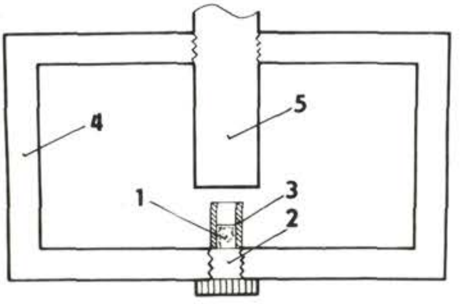

Fig. 2. A section of the modified hybrid resonator. 1 — sample, 2 — screw, 3 — glass tube, 4 — body of the resonator, 5 — tuning screw-extension.

$$\frac{1}{Q'}-\frac{1}{Q}=\varepsilon \operatorname{tg} \delta \frac{\int_{V'} (E',E)\,\mathrm{d}V}{\int_{V} (E',E)\,\mathrm{d}V} \tag{2}$$

where f is the resonant frequency; Q is the resonator quality; E is the complex amplitude of the electric field in the absence of any sample; f', Q' and E' are the respective quantities after the insertion of a sample; ε and tg δ are properties of the sample; V is the volume of the resonator; and V' is the volume of the sample. Equations (1) and (2) have been derived by perturbational calculations so that the sample must be small, and it must be inserted at the point of zero magnetic field between the pole extensions. A hybrid resonator TESLA constructed for frequency measurements may be used for this purpose. Samples are easy to insert into the resonator due to following modification of its bottom. A glass tube serving as a container into which samples are inserted was attached to a special screw passing through the bottom. A section through the modified resonator is shown in Fig. 2.

The layout of experimental device is very simple, consisting of a clystron oscillator (K), a branch for frequency measurements (0) measured with the same resonator (R_1), a variable attennuator (PU), and a measuring resonator itself (R2) in which the analysed sample is placed. An Interflex galvanometer ($G_1=G_2$) was used as an indicator (Fig. 1.).

A resonance curve of the resonator was determined in order to obtain the resonant frequency and quality factor respectively. Since the calibration curve of the resonator is linear the method could be slightly modified in that instead of tuning the frequency of the generator in the resonant frequency range of the resonator the frequency remained constant and the measuring resonator was tuned. Results obtained by both modifications of the method were quite coincident at several control measurements. The so-called frequency factor method was used to analyse resonance curve. The frequency factor may be calculated from both of frequency and voltage values recorded:

$$\delta_L=\sqrt{\frac{e_m^2}{e^2}-1} \tag{3}$$

Table 2. Water content of some insect tissues.

Tissue	Water content (%)
Cuticle from exuviae	10—12
Prepared cuticle	15—17
Body fat	15—25 (depending on the content of fat droplets)
Muscular tissue	64—65
Reproductive organs	61—66
Haemolymph	90—92
Eggs	50—55

where e_m is the value of the maximum voltage; and e is the voltage at the given frequency. Introducing this factor into the equation for the resonant circuit yields:

$$\delta_L = 2\, Q_L \frac{\Delta f}{f_o} \tag{4}$$

where Q_L is the quality factor; Δf is the deviation from the resonant frequency; and f_o is the resonant frequency.

This method has the advantage that the resonance curve becomes transformed into a straight line with its zero point indicating the resonant frequency, and its slope being proportional to the quality factor. Data may then be processed by linear regression, so that calculations of the resonant frequency and quality factor respectively, are faily accurate. A TI 58 calculator was used to compute the resonant frequency and quality factor from values obtained.

Dielectric properties could be calculated using equations (1), (2), (3) and (4). However, integral calcualtions are very difficult to perform and complex intensity of a field can be determined for very special sample shapes only; this could not be done for practical reasons. Moreover in such a case calculations are only approximate, yielding no exact results (Pohl 1974). A calibration curve was therefore constructed with the dielectric constants of a water-ethanol mixture (see Achadov 1977) ranging from 6.5 for pure ethanol to 78 for pure water at 2400 MHz and 25 °C as the calibration points. Tgδ was then calculated from equations (2) and (1). The accuracy of this evaluation is not very high (several per cent), but it was quite sufficient for the purpose of our measurements.

Results

Values obtained for a frequency of 2370 MHz are presented in Table 1.

The water content of individual tissues as determined by weighing is given in Table 2.

Apparently, dielectric properties do not depend solely on the water content of tissues, although this is the most important factor affecting these values. Variability is due to variable fat content and likely to an error resulting from spoiling of the surface of the samples by haemolymph.

A comparison of values obtained on whole and homogenised eggs is of interest. The measurements were performed to explain differences in values of dielectric properties reported by Nelson and Stetson (1974) and Stuchly and

Stuchly (1980). Nelson and Stetson (1974) obtained values of the dielectric constant ranging between 2 and 10 over the entire frequency range (10^2—10^{10} Hz), while considerably higher values have been reported by Stuchly and Stuchly (1980). Nelson measured bulk samples of whole insects; this was adequate for purpose of his study, i.e. to estimate the possibilities of disinsecting stored grain by means of electromagnetic field. Our measurements suggested that differences are due to the organisation of the sample in the electric field: values for whole eggs were similar to those obtained by Nelson and Stetson (1974), while values for homogenised eggs approached those obtained by Stuchly and Stuchly (1980).

For our purposes, values obtained from homogenised tissues were used; the effect of organisation on the electric field inside the insect body shall be analysed within the mathematical model.

Discussion

Experiments with lethal effects of microwaves on insects revealed a relation between the so-called effective size of an object and a lethal dose of radiation. The effective size was calculated by transforming the mass of an organism to a sphere by means of density (1 g/cm^3). Since no electric values of insect tissues were available, our calculations were based on values obtained from human tissues (Ondráček 1977) assuming that they would mainly depend on the respective water content. Lethal doses for any insect species were determined with an error of approx. 13 %, by calculating the absorbtion of a spherical body with parameters $\varepsilon_r = 30.9$; $\sigma = 1.1$ Siemens/m and tg $\delta = 0.262$, these are the dielectric properties of the human brain tissue at 2450 MHz (Johnson and Guy 1972). In most cases however the approximation of an insect organism by a spherical form is encumbered by a consiredable error increasing the more the shape of an insect body differs from the sphere. In an elongate elipsoid, which is a better approximation of the shape of most insect bodies, absorption may vary in its different parts as suggested by results of experiments with *Spodoptera littoralis*. Similar conclusions could be drawn from experiments with the larvae of *Sarcophaga crassipalpis*; in this species irradiation deranged morphogenesis and induced morphological changes which could be divided into several categories (Žďárek et al. 1976). Carpenter and Livstone (1971) irradiated pupae of *T. molitor;* adult insects developing from those pupae showed various morphological damage. These authors have suggested that this was a manifestation of so-called specific, non-thermal effect of the field. However, in our experiments with low power densities as used by Carpenter and Livstone (1971) we were unable to reproduce results obtained by these authors. We therefore suggested that thermal effects produced by their method of irradiation were also operative. Other studies have indicated possible damage to only specific tissues of an organism (Dardalhon et al. 1979; D'Ambrosio et al. 1980; Green et al. 1979; Rai et al. 1974), offering various explanations of the causes. In addition to the specific effects mentioned above (Carpenter and Livstone 1971) hypothesis exist concerning serious damage to germ cells (histoblasts), especially during the larval-pupal and pupal-imaginal transformations (Rai et al. 1974), or different susceptibility of different tissue layers (Žďárek et al. 1976). We attempted to show that the function of the endocrine system might be disturbed by the thermal effect, but so far we failed to do so (Ondráček and Gelbič 1983).

"Hot spots" have not yet been reported in small biological objects, including insect organisms. Opinions concerning the origin of these spots differ. The main reason for negative attitudes is the great difference between the wavelength and the size of the organisms, and a relatively good thermal conductivity of biological tissues that should not allow a sufficient thermal gradient to develop. The available methods of temperature measurement that might provide immediate evidence of the phenomenon could not be used from various reasons. One suitable technique would be the use of a contactless infrathermometer or of thermovision. However the necessary device remains not available and we therefore wish to approach the problem using a mathematical model of distribution of the electromagnetic field in the organisms. Data obtained in the present work will be used to construct the model.

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