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Investigation on plant tissue impedance Results of experiments with *Daucus carota* L.

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The measurement of the electrical impedance of plant tissues was carried out by means of an a.c. bridge (Fig. 1). The bridge could be easily balanced in the frequency range: 20 Hz — 100 kHz. The maximal error caused by the factors depending on its construction amounted (for standard tissue slices and 10 V/cm field) to: $\frac{\Delta R}{R} 100 = 1\%$ in the range $10^2 - 10^5$ Hz. $\frac{\Delta C}{C} 100 = 5\%$ in the range $10^2 - 10^3$ Hz, and $\frac{\Delta C}{C} 100 = 1\%$ for $10^4 - 10^5$ Hz. The tissue holder is shown in Fig. 2. This arrangement allows a cylindrical cut of the tissue to be clamped

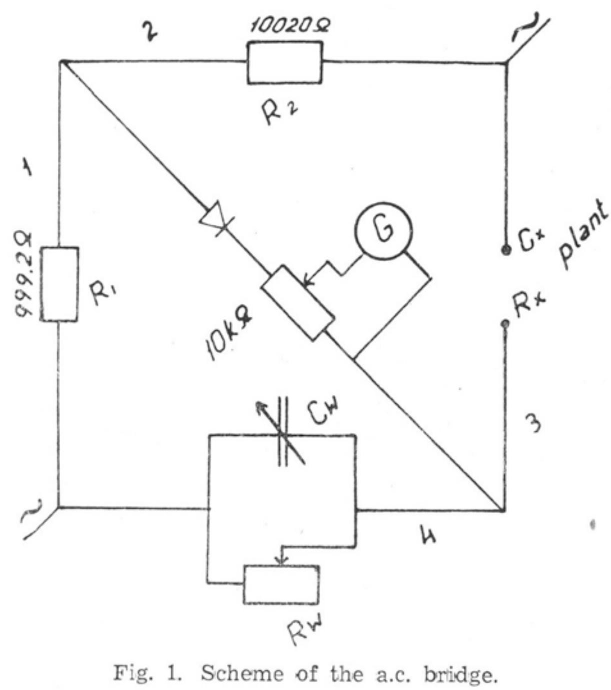

Fig. 1. Scheme of the a.c. bridge.

between two platinum electrodes (a, b). The pressure on the tissue was regulated until good contact between tissue and electrodes was obtained. The holder with the tissue was kept in a glass box with high air humi-

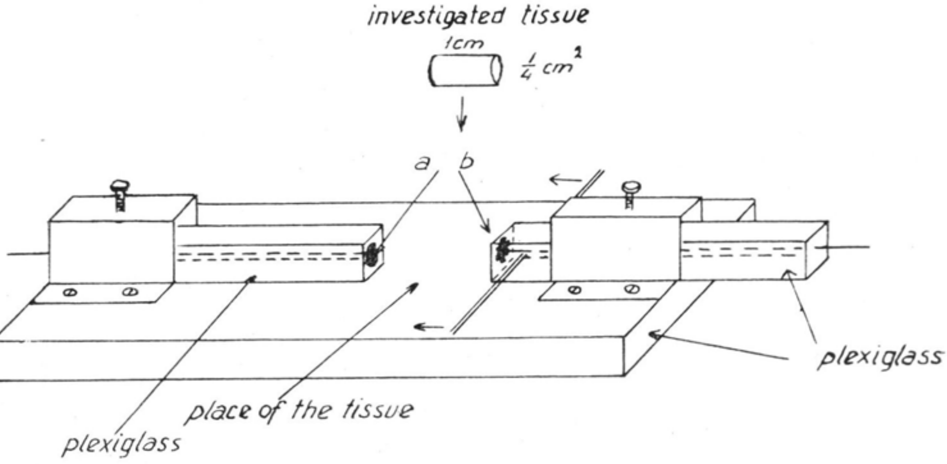

Fig. 2. The tissue holder.

dity. The experiments were done on root storage tissue of *Daucus carota* L. The dimensions of the investigated pieces of tissue are shown in Fig. 2. The cuts were taken from the upper and external part of the root in such a way that the longitudinal axis of the pieces was parallel to that of the root. Although the used plants were not growing in standard and controlled conditions, the form of the curves obtained was the same for all specimens.

APPLIED FIELD. THE OPTIMAL PRESSING FORCE

During the measurements an electric field of 10 V/cm was applied to the tissue. This value was chosen for the following reason. Too low fields make the measurement difficult and diminish the precision, high values are inappropriate because of the injurability of the tissue. Table A shows that in a field increasing from low values the resistance diminishes. But the drop proceeds continuously and even at 40 V/cm the

Table A

Influence of the field value on the resistance

Applied field V/cm	Resistance kΩ
1.0	22.0
5.0	22.0
10.0	21.7
15.0	21.4
20.0	21.2
30.0	20.9
40.0	20.3

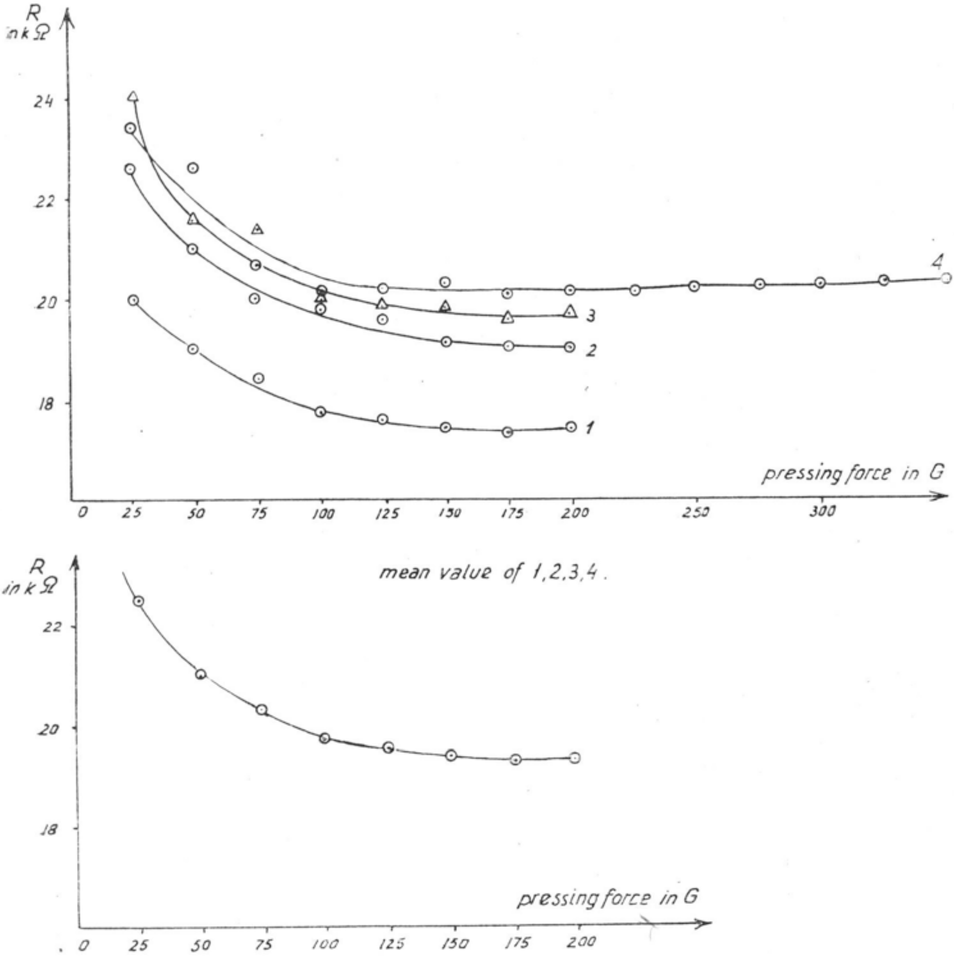

Fig. 3. Influence of pressing force on resistance.

change is only about 8% of the value at 1 V/cm (for 400 Hz). If we now consider that killing the tissue e.g. with ether produces a sudden decrease of about 80% for 10 v/cm, we may infer that the chosen value has no essentially injuring effect.

A similar question arises with respect to the force pressing the electrodes against the tissue. The problem is to avoid needless pressure on the tissue and yet assure good contact. This "optimal" force was found in the following way. As expected increasing pressure diminished the resistance considerably up to some value. But then, when the force still increased, this value changed only little. Fig. 3 (upper part) shows this for 4 series of measurements (400 Hz and 10 V/cm). The first measurement was made 5 minutes after taking the specimen, the last series was finished 1,5 hours later (this difference in time accounts for

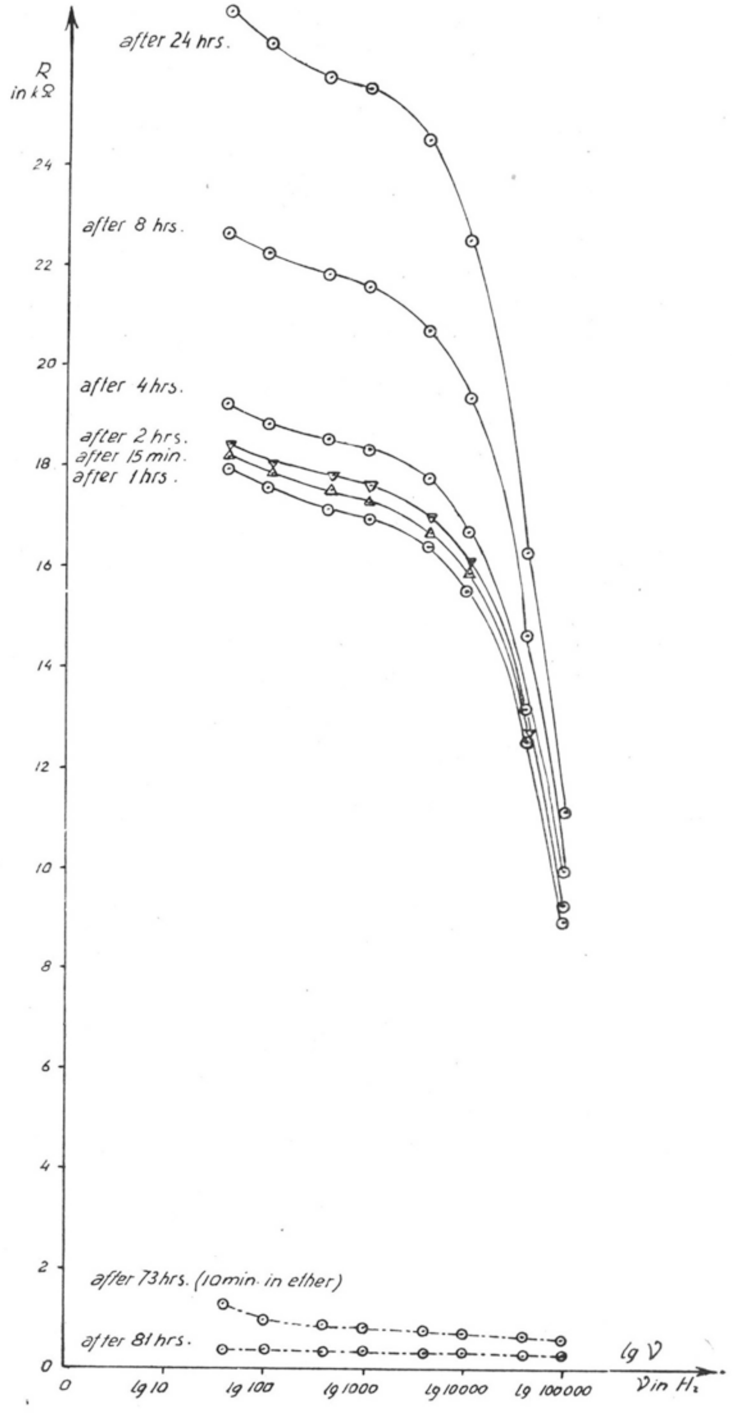

Fig. 4. Dependence of the resistance on the frequency (dotted lines — killed tissue).

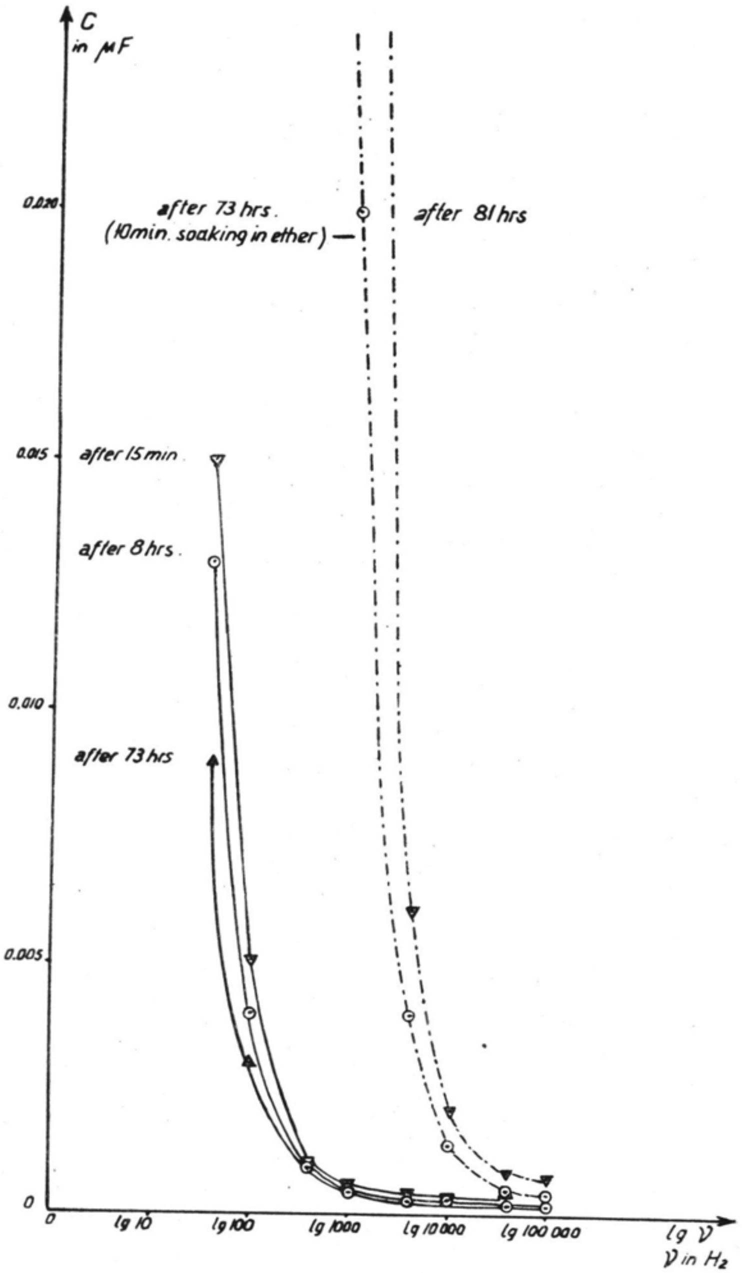

Fig. 5. Dependence of the capacitance on the frequency (dotted lines — killed tissue).

the vertical displacement). The smallest force giving constant resistance (constant with respect to increasing force) was taken as optimal. As seen from Fig. 3 its value is approximately 175 G, which corresponds to 0,7 Atm. The capacitance changed only little.

This was confirmed with cuts from various roots and for various frequences 40, 400 Hz, 4 and 40 kHz; field 10 V/cm). In all cases the force-resistance curve turned approximately into a straight line at about 175 G.

EXPERIMENTAL RESULTS

According to the previous remarks the applied field was 10 V/cm, the pressure 0,7 Atm.

A. Fig. 4, 5, 6 and 7 show the dependence of the resistance, capacitance, impedance and absolute value of the phase angle on the frequency of the current. All curves were taken with the same specimen. We stress the following points:

a) Time influence. As seen from the curves, with the elapse of time a displacement of the curves occurred: the capacitance became smaller, resistance and impedance increased, also the phase angle rose, though in a smaller degree. All these parameters but the last, changed more considerably at low frequencies. But the form of the curves showed only slight changes.

b) Phase angle and frequency. It is noteworthy that there is a high dependence of the phase angle on the frequency; besides a minimum was found at about 400 Hz.

c) Changes produced by killing the plant. Soaking the tissue for 10 minutes in ether completely changed the course of all curves. Figs. 4—7 (dotted lines) show the sharp decrease of the resistance, impedance and phase angle whose minimum now occurred at 10 000 Hz; the capacitance, on the contrary, rose considerably. With the elapse of time the difference to living tissue became still greater, but the form of the new curves remained almost the same.

This increase of the capacitance also occurred in the case when, after the tissue had been in the box for a fortnight, it was then plunged into ether. In order to confirm that this increase is indeed produced by killing the tissue, the effect of chloroform, ethanol, ether and boiling* for 20 min. was investigated. In all cases decrease of the resistance and clear increase of the capacitance was observed (Fig. 8).

* Because of the softening effect of boiling the pressing force was reduced to 25 G.

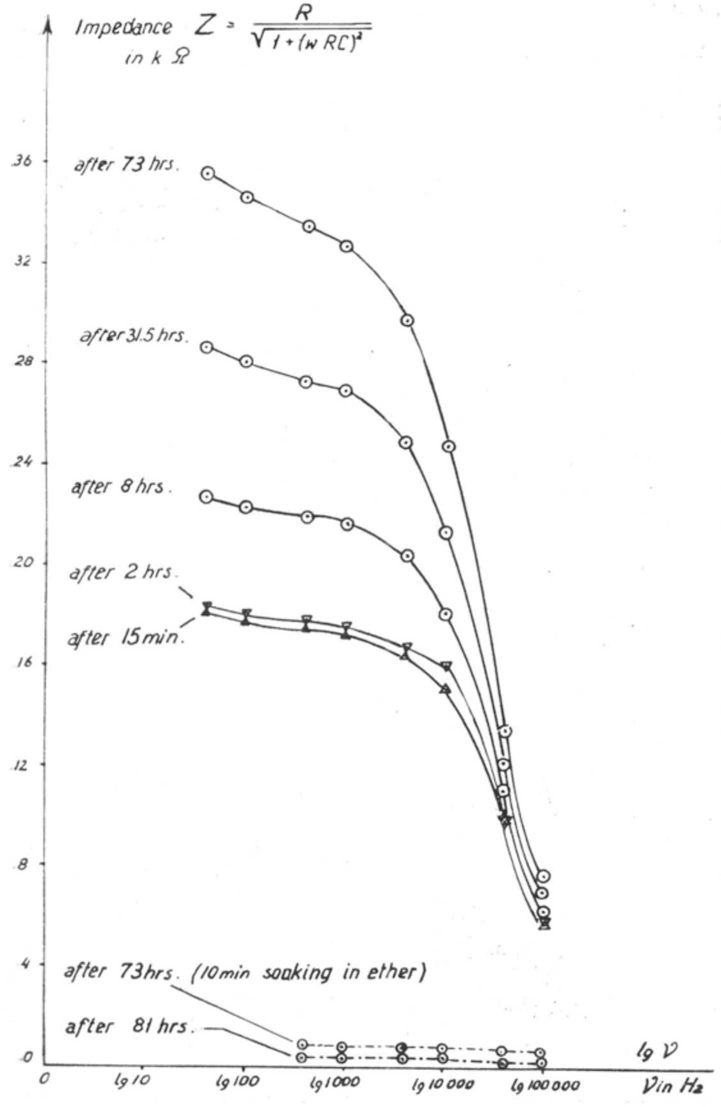

Fig. 6. Dependence of the impedance on the frequency (dotted lines — killled tissue).

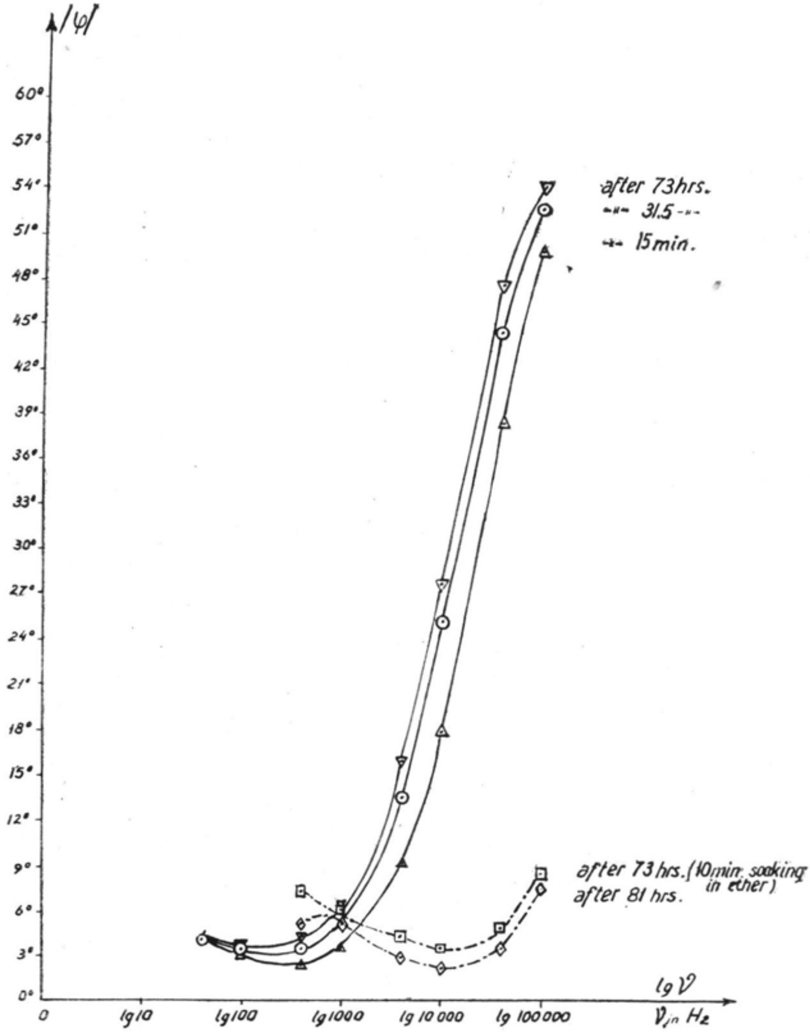

Fig. 7. Dependence of the phase angle on the frequency (dotted lines — killed tissue).

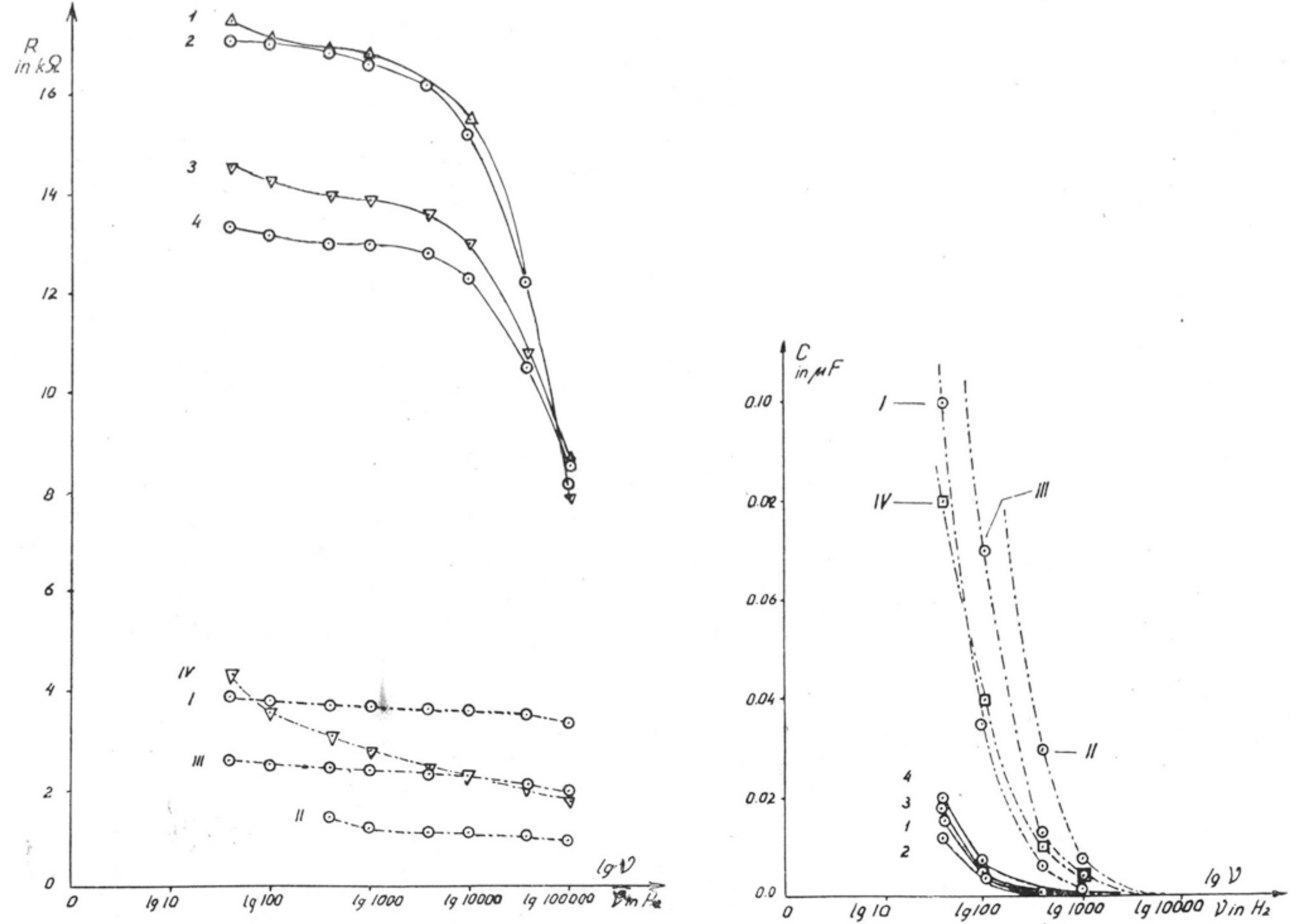

Fig. 8. Resistance-frequency and capacitance-frequency curves of living and killed tissue. Curve 1, 2, 3, 4 — specimen A, B, C, D (living tissue); Curve I: specimen A after 20 min. of boiling, Curve II: specimen B after 5 min. soaking in chloroform, Curve III: specimen C after 5 min. soaking in ether, Curve IV: specimen D ofter 5 min. soaking in ethanol.

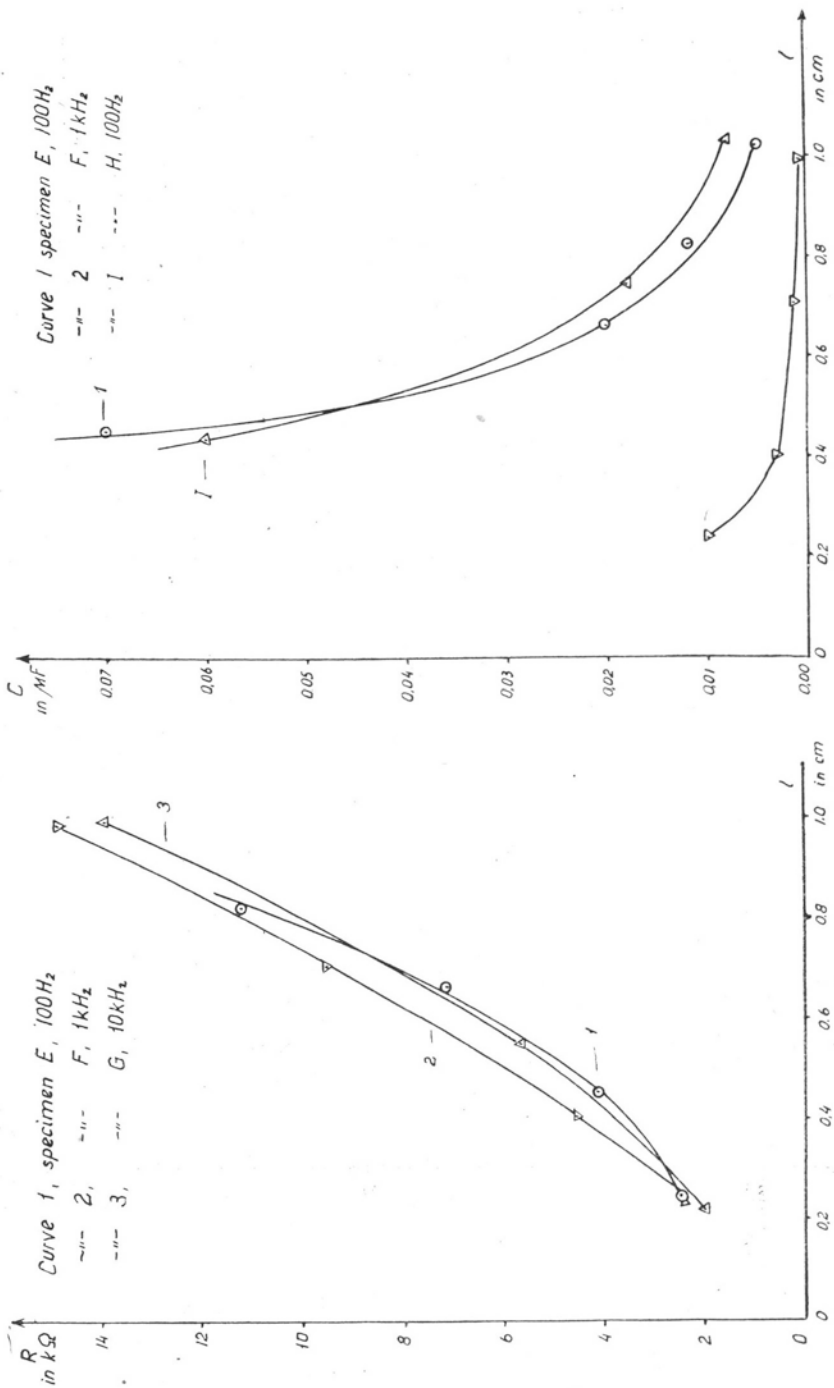

Fig. 9. Dependence of resistance and capacitance on the length of the specimen.

B. Fig. 9 gives the dependence of the resistance and capacitance on the length of the specimen. Each curve corresponds to a fixed frequency. To conserve the field value of 10 V/cm the voltage on the bridge was adequately diminished. The pressing force was 175 G.

Further investigations and an interpretation of the obtained results are intended.

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Badania nad impedancją tkanki Daucus carota L.

Streszczenie

Praca zawiera opis aparatury i metody pomiaru impedancji tkanki korzenia *Daucus carota*. Przedstawione są rezultaty tych pomiarów (rezystancji, pojemności, zawady i kąta fazowego) dla tkanki żywej, w zależności od częstości prądu, czasu badania i długości wycinka.

Badano również impedancję tkanki martwej i otrzymano między innymi wzrost pojemności w porównaniu z tkanką żywą.