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Influence of freezing damage on impedance parameters in Magnolia shoots*

INTRODUCTION

The electrical model of plant tissue is proposed as a system of specifically connected resistances and capacitances (H a y d e n et al. 1969). A simplification of this model should be a system consisting of only one resistance and one capacitance connected parallelly. Some investigations have shown that the resistance measured in plant tissues with a.c. is a result of the resistance (*R*) and reactance $X=1/\omega C$, where $\omega=2\Pi f$ (B e i e r 1968, P i l a w s k i 1973).

By means of vector analysis (Fig. 1) and introduction of complex numbers to the calculation we are obtaining a formula for parallelly connected resistor and capacitor, called impedance (Z). A unit for impedance is Ohm (1Ω). Measurements are often performed in inverted units i.e. 1/Z. This calles admittance (Y). A unit for this is one Simens (1S). A model applied by S k i e r c z y ń s k a et al. (1973a) proved to be very consistent to the measurements on cell membranes of *Characeae*. There are many data pointing to a dependance of electrical admittance (impedance) of biological circuits on such factors as the kind of electrodes used, frequency, size and structure of the sample and physical factors such as

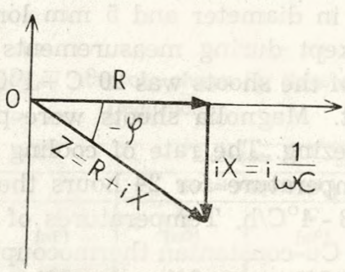

Fig. 1. Parallel combination of resistance (*R*) and capacitance (C) on complex number plane in vector form, φ — phase angle, $\operatorname{tg}\varphi=-\omega CR$, i — imaginary unit, $i^2=-1$

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water and K^+ and Na^+ ions content in the sample and temperature of the tissue (Hayden et al. 1969, Teske and Zając 1971, Pukacki 1979). A factor of highly significantly influencing the electrical parameters of plant tissue is its vitality (Plater and Greenham 1959, Teske 1965, Van den Driessche 1972, Tattar and Blanchard 1976). Investigation of the electrical characteristics of plant tissues permit a determination of changes in cell membrane permeability caused by temperature or other stress (Osterhout 1922, Luyet 1932).

MATERIAL AND METHODS

Plant material. The investigation has been made on one-year old shoots of *Magnolia acuminata* L., *Magnolia kobus* DC., and *Magnolia*× ×*soulangiana* Soulange-Bodin. These Magnolias are growing in the Kórnik Arboretum. Shoots of *M.*×*soulangiana* were also collected from trees from various places in Poland for one of the experiments.

Typical one-year old shoots, 12 - 16 cm long with properly formed internodes were collected from the central part of the crown during the autumn and winter.

Measurement of R, C, φ, Y. Measurements of electrical resistance and capacitance in Magnolia shoots were performed by means of sinusoidal oscillation PW-9 and an oscilograph OG-2-21 served as a compensation indicator. There was a voltage of 200 mV applied to the plant tissue and the current passing through the sample was 10^{-5} A.

Admittance measurements, as well as those of the phase angle and of the real frequency function within the interval from 5 Hz to 500 kHz were made by means of a BM-507 measuring device. The output voltage for those measurements was 20 mV and the current ca 10^{-6} A.

Other admittance measurements at a constant frequency ($f=80$ Hz) were made with a conductometer OK-102/1. Electrodes used for measurements were 0.5 mm in diameter and 5 mm long fixed on a plexiglass plate. Samples were kept during measurements wet in a polyethylene bag. The temperature of the shoots was $20°C \mp 1°C$.

Frost treatment. Magnolia shoots were placed into deepfreezers type Grünland for freezing. The rate of cooling was 3°C/h. After being kept in a constant temperature for 24 hours they were defrosted again with a similar speed 3 - 4°C/h. Temperatures of the frozen shoots were measured with 0.2 mm Cu-constantan thermocouples and recorded. Frozen shoots on which admittance has been measured were put into wet sand in climatic chambers (phytotron) in order to estimate their survival ability (Białobok and Pukacki 1974). Browing of the tissues was used as the criterion for rating damage.

RESULTS

A. INFLUENCE OF VARIOUS ELECTRODES ON THE *R*, *C*, φ AND Y VALUE

In the investigation of electrical characteristics of plant tissues great care should be taken as regards the kind of electrodes used for measurements. Glerum and Zazula (1973) and Hayden et al. (1969) applied chloridized silver electrodes for impedance measurement. Those electrodes are considered nonpolarizable. In the majority of investigations performed on woody plants steel electrodes were applied (Wilner 1964, Van den Driessche 1969, Glerum 1970, Skutt et al. 1972).

Three kinds of electrodes were used in the present work in order to check their influence on electrical admittance of plant tissues. They were as follows: nickel-plated steel, platinum and chloridized silver (Ag/AgCl) electrodes. The distance between the electrodes was always 1 cm.

Results presented in Table 1 show no differences between the admittance measurements of Magnolia shoots done with the platinum or nickel-plated steel electrodes. There is however a difference in the phase

Table 1

Admittance magnitude (*Y*) and phase angle (φ) for undamaged and dead Magnolia shoots as a function of frequency using two different electrodes

Frequency [Hz]	Before freezing				After freezing (dead shoot)			
	Pt		Nickel-plated steel		Pt		Nickel-plated steel	
	Y [μS]	φ	*Y* [μS]	φ	*Y* [μS]	φ	*Y* [μS]	φ
80	18.3	−15°	18.3	−11°	65.0	−25°	65.5	−17°
500	20.5	−8°	20.7	−8°	87.1	−11°	86.6	−9°
1 000	21.5	−7°	21.6	−7°	91.6	−8°	91.0	−6°
5 000	23.5	−9°	23.6	−9°	98.6	−5°	98.5	−5°
10 000	24.3	−11°	24.7	−11°	100.1	−4°	101.0	−4°
50 000	30.6	−19°	31.0	−19°	105.1	−5°	105.9	−5°

Table 2

Resitance (*R*) and capacitance (*C*) of Magnolia shoots for three different electrodes at various frequencies

Frequency [Hz]	Electrodes					
	Pt		Nickel-plated steel		Ag/AgCl	
	R [kΩ]	*C* [nF]	*R* [kΩ]	*C* [nF]	*R* [kΩ]	*C* [nF]
80	35.0	16.6	36.0	10.0	32.0	4.0
500	28.6	2.0	32.0	1.5	30.0	1.1
1 000	27.0	1.1	30.0	0.9	28.0	0.8
5 000	21.0	0.4	24.0	0.4	24.0	0.4
10 000	18.6	0.2	20.0	0.2	20.0	0.2
50 000	15.0	0.01	16.0	0.01	15.6	0.01

angle (φ) at low frequencies. Those values are higher for platinum than for nickel-plated steel electrodes. This difference increases after freezing of the investigated shoots.

Measurements of resistance (R) and electrical capacitance (C) done with three types of electrodes displayed some differences (Table 2). C — values obtained in measurements with platinum electrodes were higher than with nickel-plated steel or Ag/AgCl ones. Those differences occured only at low frequencies of the applied current, between 80 Hz and 1000 Hz. Resistance did not change became of measurements with different kind of electrodes. These results suggest that admittance values measured with the nickel-plated steel electrodes could be influenced by capacitance polarization. The chloridized silver electrodes however cannot be used for a long time for admittance measurement in woody plants since they decay rapidly.

B. THE EFFECT OF FREQUENCY ON MEASUREMENT OF R, C, φ AND Y

Figures 2 and 3 present the results of resistance (R) and capacitance (C) measurements plotted against the current frequency (f). Platinum electrodes were aplied. Measurements were done on shoots of *Magnolia×soulangiana*. The data used were averages from three shoots and three measurements on each. One can observe that a change of frequency from 100 Hz to 100 kHz decreases the values of R and C. The R value decreases much more in live tissue (unfrozen) than in a freezing damaged shoots (Fig. 2).

The dependence of the shoot capacitance on the current frequency (Fig. 3) was similar to that of the $R(f)$ function. Capacitance decreases

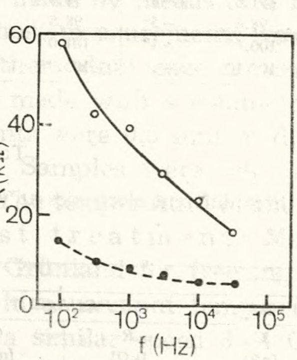


Fig. 2. The plots of Magnolia shoots resistance R as functions of current frequency. After freezing-dead shoots (broken lines) and before freezing (solid lines)

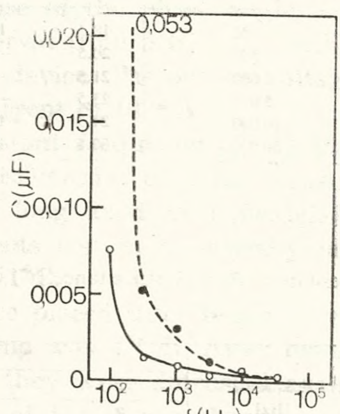


Fig. 3. The plots of Magnolia shoots capacitance (C) as functions of current frequency. Other wise as in Fig. 2

with the rise of frequency. This decrease is most rapid at low frequencies from 100 Hz to 1 kHz. Changes in capacitance due to damages in tissue caused by low temperature are opposite to those in resistance. Non--frozen Magnolia shoots at 500 Hz of frequency showed a 0.001 μF capacitance while after being injured (frozen) a 5-fold increase of capacitance occurred. At frequencies above 10 kHz the drop in capacitance was considerably slower and the difference between sound and damaged tissue was not so high.

Reciprocal comparison of capacitance and resistance (Fig. 4) depending on the degree of injury of shoots showed a high corelation ($r = 0.922$). Values of R and C presented in Fig. 4. are from measurements at 500 Hz. The more was the tissue damaged the less was its resistance and a higher simultaneous rise of its capacitance. The resistance of dead shoots was below 12 kΩ their capacitance above 0.008 μF. Living tissues had respectively over 25 kΩ and below 0.003 μF.

The resistance-capacitance model of plant tissues can also be investigated by means of phase angle measurements (φ). This angle has been presented in Fig. 5. plotted against current frequency. It is evident from the obtained curves that the investigated biological system has a typical capacitance character. Negative values of phase angle are supporting this opinion. They are lowest at 500 Hz in a living shoot and at 50 kHz in a killed (frozen) shoot. Above those values the phase angle increases in both cases. Largest difference between the φ-angle of healthy and damaged Magnolia tissues occured at a frequency of 50 kHz. It was $\varphi = -20$°C and $\varphi = -5$°C in the living and in the killed shoot respectively.

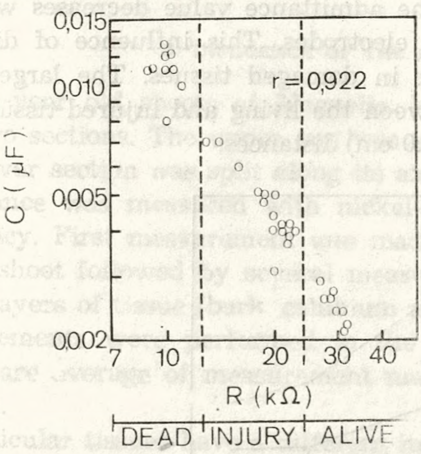


Fig. 4. Comparison of resistance (R) and capacitance (C) in Magnolia shoots as related to freezing damage of tissues

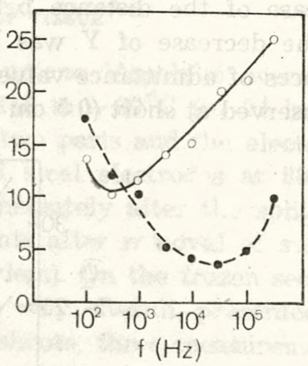


Fig. 5. The plots of Magnolia shoots phase angle (φ) as functions of current frequency. Otherwise as in Fig. 2

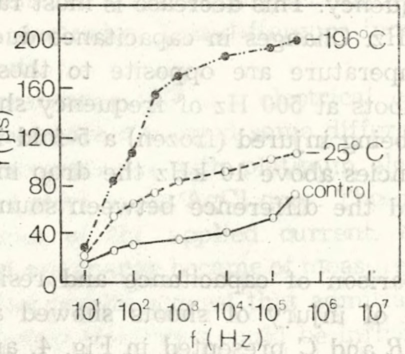


Fig. 6. The plots of Magnolia shoots admittance (Y) as functions of current frequency after exposure to −25°C and −196°C (liquid nitrogen) freezing tests, C — unfrozen control

Changes in admittance value (Y) in Magnolia shoots depending on current frequency (f) are presented in Fig. 6. Nickel-plated steel electrodes were used for this experiment. It resulted in an increase of Y in Magnolia shoots when the frequency changed from 10 Hz to 0.5 MHz. The increase was most rapid within the interval of low (10 to 500 Hz) frequencies. The more was the shoot injured by frost the faster was the increase of admittance in this range of frequencies.

C. THE EFFECT OF GEOMETRY OF A SAMPLE ON Y MEASUREMENT

1. Influence of the distance between electrodes. This influence has been checked at 80 Hz with nickel-plated steel electrodes stuck into the shoot (Fig. 7).

It has been established that the admittance value decreases with an increase of the distance between electrodes. This influence of distance on the decrease of Y was higher in damaged tissues. The largest differences of admittance values between the living and injured tissues were observed at short (0.5 cm and 1.0 cm) distances.

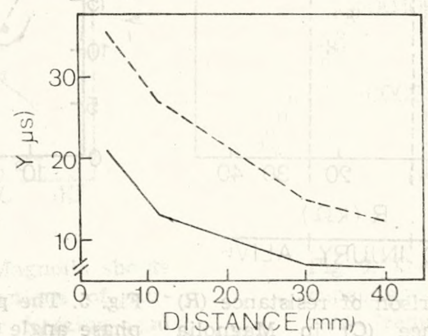


Fig. 7. Dependence of admittance (Y) on the interelectrode distance of *Magnolia kobus* shoots. After freezing in −30°C (broken lines) and before freezing (solid lines)

Table 3

Admittance values of Magnolia shoots at different diameters, before and after freezing

No. of internodes	d* [mm]	Electrical admittance			
		Before freezing		After freezing	
		Y [μS]	y [μS/mm²]	Y [μS]	y [μS/mm²]
1	2.27	11.50	2.8	41.9	10.3
2	2.68	13.90	2.4	51.6	9.1
3	3.00	15.85	2.2	55.6	7.8
4	3.27	16.00	1.9	50.5	6.0
5	3.50	16.35	1.7	47.3	4.9
6	3.72	17.40	1.6	47.4	4.3
7	3.99	19.80	1.5	48.0	3.8
8	4.28	20.95	1.4	47.0	3.2

Y – values of the shoot admittance, *y* – unit admittance calculated for shoots area, *d* – diameter of the shoots,
* – mean values obtained for 10 shoots.

2. Influence of the diameter of shoot. Relation between the admittance in Magnolia kobus shoots and their diameter is given in table 3. Measurements were done on shoots with nickel-plated steel electrodes 4 mm of length and distanced 7 mm. Current frequency was 80 Hz. Results obtained point to an evident influence of shoot diameter on the measured admittance in unfrozen control shoots. The correlation coefficient was here $r=0.986$. There was however no such relationship for measurements of admittance done of shoots frozen to —30°C, $r=$ $=0.005$. The unit admittance (y), calculated from the formula: $y=$ $=Y \cdot S^{-1}$ [$\mu S \cdot mm^{-2}$] (where S is the area of cross section of the shoot) decreased with the increase of diameter, both in unfrozen and in frozen shoots.

D. INFLUENCE OF THE KIND OF TISSUE

One-year old shoots of *Magnolia ×soulangiana* 'Amabilis' were cut into two sections. The upper one was subjected to —30°C for 24 hours. The lower section was split along its axis in two parts and the electrical admittance was measured with nickel-plated steel electrodes at 80 Hz frequency. First measurement was made immediately after the splitting of the shoot followed by several measurements after removal of subsequent layers of tissue (bark, cambium and xylem). On the frozen section measurements were performed in the same way. Result presented in Fig. 8. are average of measurement made 5 shoots, three measurements on each.

Particular tissues have a different influence on the admittance value. It was largest for bark and xylem. The difference between the admittance value of a sample with cambium and without it was low (3 μS — Fig. 8). This small influence of the cambium on the current conducting layer within the shoot. During the winter rest period the layer of cam-

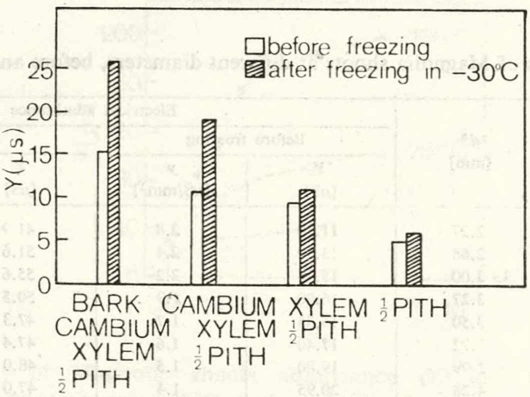


Fig. 8. The contribution of bark, cambium, xylem and pith in admittance of Magnolia shoots

bium in Magnolia shoots is very thin in comparison to other tissues. On the other hand in shoots treated with low temperatures the highest participation in total admittance was due to cambium. After the removal of this tissue admittance dropped from 18.3 μS to 10.7 μS. Differences in admittance between the unfrozen control and frozen xylem and pithy tissue were however slight.

E. ROLE OF THE WATER CONTENT IN SHOOTS

It has been investigated in *Magnolia* × *soulangiana* 'Amabilis' shoots. One-year old shoots were slowly drying outdoors. Their admittance were measured simultaneously with a check of their water content (by

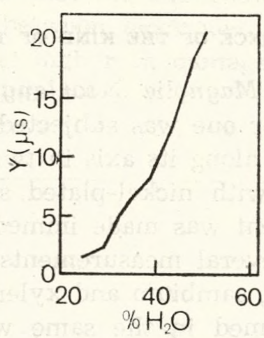


Fig. 9. Relationship between moisture content of Magnolia shoots and admittance. Means for 20 shoots, Y at 80 Hz

means of weighing). According to the data obtained admittance decreased with a drop in water content (Fig. 9). When this content was about 50% of fresh weight, the average admittance was 20 μS. It decreased to a half of that value when the water content was decreased to 40%.

F. K^+ AND Na^+ IONS IN THE SHOOTS

Role these ions in the admittance of plant tissue was investigated on *Magnolia* × *soulangiana* shoots. The content of K^+ and Na^+ in them was determined photometrically with the method given by H u m p h r i e s (1956). Admittance was measured with nickel-plated steel electrodes at 80 Hz. Prior to determination of the influence of those ions on the *Y* value in shoots their content of potassium and sodium in particular tissues was measured (Fig. 10). It has been established that greatest amount of those elements is in bark and cambium, and the lowest in xylem and pith.

An analysis of the influence of potassium and sodium on the admittance of unfrozen and frost injured Magnolia shoots based on the above results was done. They were collected from 47 specimens of *M.* × *soulangiana* planted all over the country. Due to the fact that over 80% of

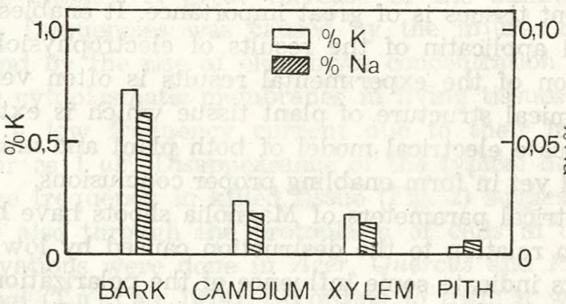
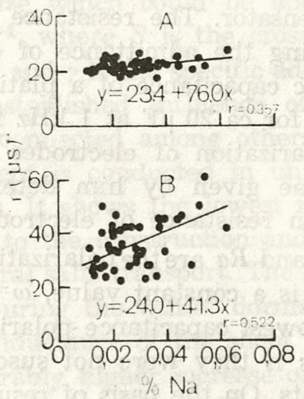


Fig. 10. Percentage content of potassium and sodium in different Magnolia shoot tissues



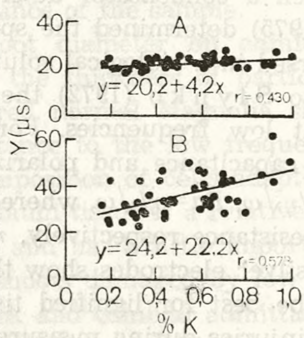


Fig. 11. Effect of potassium content in bark tissues on the admittance of Magnolia shoots. *A*-before freezing, *B*-after freezing in −30°C. Each point is an average for one individual

Fig. 12. Effect of sodium content in bark tissues on the admittance of Magnolia shoots. Otherwise as in Fig. 11

the investigated elements are contained in bark and cambium (Fig. 10), analysis was limited to these two kind of tissues. There are averages obtained from measurements of 10 shoots. Admittance was measured also on 10 shoots, there placed on each, both before and after frost treatment.

Results showed the significant influence of K^+ and Na^+ content in Magnolia tissues on the measured admittance in non-frozen shoots (Fig. 11, 12). This influence was much more in shoots frozen in —25°C. Regression lines present this dependence. An increase of admittance with an increase in the potassium and sodium content in the investigated tissues can be observed.

DISCUSSION

Knowledge of the influence of physical factors on the electrical parameters of plant tissues is of great importance. It enables an expansion of the practical applicatin of the results of electrophysiological studies. An interpretation of the experimental results is often very difficult to the physicochemical structure of plant tissue which is extremly complicated. An adequate electrical model of both plant and animal tissue has been elaborated yet in form enabling proper conclusions.

Several electrical parameters of Magnolia shoots have been presented in this paper in relation to the destruction caused by low temperatures. Obtained results indicate some influence of the polarization of electrodes on the measured admittance value (Table 1 and 2). One of the theories explaining the error in admittance measurements caused by this polarization is the Stern theory of doubled electrical layer. This layer on a metalic electrode works like a condensator. The resistance and reactance of such a condensator determining the admittance of electrodes. Glaser (1975) determined the specific capacitance of a platinum electrode immersed in a biological solution for ca 20 μF at 1 kHz frequency. According to Slynko (1972) the polarization of electrodes is mostly expressed at low frequencies. Formulae given by him determine the polarization capacitance and polarization resistance of electrodes as follows: $Ca = 1/\eta\sqrt{\omega}$, $Ra = \eta/\sqrt{\omega}$, where Ca and Ra are the polarization capacitance and resistance respectively, η — is a constant value, $\omega = 2\Pi f$. The chloridized silver electrodes show the lowest capacitance polarization and they could be best for lignified tissues if they were not susceptible to mechanical injuries during measurements. On the basis of results of this study as well as according to some literature data (Glerum and Zazula 1973) it could be suggested that the influence of nickel-plated steel electrodes on the admittance measurement due to their polarization was small and non significant. When very exact measurement are needed an application of nonpolarizing electrodes (e.g. Ag/AgCl) seem reasonable.

Appropriate frequency of the applied current is essential for the admittance measurements in Magnolia shoots. With the rise of this (*f*) the resistance (*R*) and capacitance (*C*) of the shoots are decreasing. Similar relation was observed in some *Algae* (Skierczyńska 1969, Skierczyńska et al. 1973a, 1973b). Changes of resistance and capacitance of biological objects depending on frequency are explained in the above related papers with the relaxation processes to which the proteine molecules, ions and entire cells are subjected in a changing electric field. This way every cell become a large ion dipole (Pilawski 1973). According to the assumption of Hayden et al. (1969) a plant tissue could be simplified to an analogous RC circuit. This kind of circuit shows an evident dependence of its admittance components $Y=G+B$ i.e. the active (*G*) and passive (*B*) conductance, the frequency since both include the cycle frequency (ω), (Skierczyńska et al. 1973a). The increment of admittance happened when the frequency rose both in sound and frost damaged tissues. A great increase of the admittance in frozen shoots at low frequencies was caused by the injures of cytoplasmatic membranes and by the rise of electrolyte concentration in the cell wall channels. The cytoplasmatic membranes in living tissues are a hard impediment for a low frequency current due to their high capacitance, determined for ca 1 μF. Disappearance of the typical dependence of resistance on the frequency in killed tissue (Fig. 2) suggests that the current can pass also through the protoplasm of cells in damaged shoots. Similar observations were done in *Acer, Quercus* and *Pinus* tissues damaged by fungi (Tattar 1974). According to them it was connected to an increase of ion mobility and concentration.

The plant tissue admittance presents an evident dependence on the sample size which could be approximately written in a formula: $Y = \gamma \cdot S \cdot L^{-1}$, where S is the cross section area of the shoot sample, L is its length and γ is the specific admittance of the sample.

The established influence of shoot diameter on admittance value must be connected among others to the thickness of particular tissues. The current is conducted in uninjured normal Magnolia shoots mostly by xylem. It shows the lowest resistance to the low frequency current. It is due to the construction and composition of cells adapted for water and mineral salts transport. The cambium tissue is a relatively thin layer of cells during the winter dormancy and has a little importance for the entire conductance of the shoot. In shoots damaged by low temperature a considerably higher increase of bark and cambial admittance is observed than in the xylem. This supposition is justified by the observed strong damages of these tissue in Magnolias (Białobok 1974).

Ions are emerging from the frost damaged cells to the adjacent areas. It has been proven by Van den Driessche (1969) that the amount of K^{+}, Ca^{2+} and Mg^{2+} ions getting outside was proportional to the degree to which the tissue was injured by frost. There was only a slight influence of the K^+ and Na^+ ions concentration on the admittance value in unfrozen shoots established in the present paper. A higher influence however was observed for potassium in frozen shoots ($r = 0.57$, Fig. 11). This observation can be explained by the fact, that fewer ions are taking part in current conductance in healthy tissue since the way of the low frequency current 80 Hz does not lead through the cell inside (H a y d e n et al. 1969). An evidently higher potassium and sodium content in bark and cambial tissue than in xylem should be also of importance with respect to that.

The ion dissociation and mobility (K^+, Na^+) depends essentially on water relations. A decrease of water content in the tissue of 5% causes a 30% drop of admittance as related to the value measured before the loss of water. It is obvious that water as the electric load bearing medium has essential influence on admittance in Magnolia shoots.

The hydrogen and hydroxy ions concentrations in plant tissues have however less influence on electrical resistance (T a t t a r et al. 1972). Temperature influences the dissociation and mobility of the ions i. e. also the admittance of the shoots. It rises with the arise of temperature (P u k a c k i 1979).

It can be concluded on the basis of the investigation related above that there are many factors influencing the value of plant tissue admittance. However use of the admittance measurements for the estimation of the degree of shoot damages caused by frost in woody plants should be realiable. However it is necessary to create constant conditions for those measurements as regards humidity, temperature, shoot diameter (with some tolerance), distance between electrodes and an adequate (low) frequency between 50 - 1000 Hz. When those recommendation were observed a high correlation of the admittance value of the shoots with their frost resistance has been found (B i a ł o b o k and P u k a c k i 1974, P u k a c k i 1978, 1981).

SUMMARY

Investigation on several electrical parameters of plant tissues were conduced on one-year old shoots of two Magnolias: *M.* × *soulangiana* and *M. kobus*. The resistance (R), capacitance (C), phase angle (φ) and admittance (Y) have been determinated depending on: the kind of electrodes used, a.c. frequency (f), sample size, kind of tissue and water and K^+ and Na^+ ions content with respect to the injures made by low temperature.

1. It has been observed that the effect of polarization of the resistance and capacitance values of shoots appears in the interval of low frequencies (80 - 500 Hz). As concerns admittance however, no differen-

ces between the values obtained by means of the nickel-plated steel and platinum electrodes were found.

2. The resistance (*R*) and capacitance (*C*) of Magnolia shoots decrease when current frequency rises. In frozen damaged shoots the capacitance is 5 times as high as in the unfrozen ones. As concerns R the result is inverted: there is a considerable decrease of R in damaged shoots with a simultaneous lesser influence of frequency on resistance. The $Y(f)$ function (admittance) rises with a rise of frequency and degree to which the shoot was damaged by frost. The big decrease of resistance or increase of admittance in shoots injured by freezing is caused by the damage of cytoplasmatic membranes and a connected to that increase of electrolyte concentration in cell wall channels. The negative of the phase angle $(-\varphi)$ obtained in the course of the experiments point to a capacitance character of the investigated biological system.

3. It has been shown that admittance decreases with the extention of the distance between the electrodes. The influence of the sample diameter was opposite. The movement of ions in plant tissue is influenced not only by the sample size but also by the structure of the tissue. The largest admittance in sound tissue was in bark and xylem and in frozen tissue in the cambium.

4. An increase of water and K^+ and Na^+ ion content in the tissue increases the admittance. The influence of potassium and sodium on the Y-value was more significant in the frozen shoots than in the unfrozen ones.

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LITERATURE

1. Beier W., 1968. Biofizyka. PWN. Warszawa.
2. Białobok S., 1974. Variation of cold hardiness of woody plants. Final report FG-Po-238. Inst. of Dendrology, Kórnik.
3. Białobok S., Pukacki P., 1974. Relationship between measurements of electrical admittance of shoots and frost hardiness of *Viburnum* species. Arboretum Kórnickie 19: 207 - 220.
4. Glaser R., 1975. Wstęp do biofizyki. PZWL. Warszawa.
5. Glerum C., 1970. Vitality determinations of tree tissue with kilocycle and megacycle electrical impedance. Forest. Chron. 46: 63 - 54.
6. Glerum C., Zazula R., 1973. Influence of various electrodes and tissues on the electrical impedance of woody stems. Can. J. Plant Sci. 53: 385 - 389.
7. Hayden R. I., Moyse C. A., Calder F. W., Crawford D. P., 1969. Electrical impedance studies of potato and alfalfa tissue. J. Exp. Bot. 20: 177 - 200.
8. Humphries E. C., 1956. Mineral components and ash analysis ex modern methods of plant analysis. Ed. Paech and Tracey 1: 468 - 502.
9. Luyet B. I., 1932. Variation of the electric resistance of plant tissues for alternating currents of different frequencies during death. J. Gen. Physiol. 15: 283 - 287.

10. Osterhout W. I. V., 1922. Injury, recovery and death in relation to conductivity. Lippincott, Philadelphia.
11. Pilawski A., 1973. Wstęp do biofizyki. PZWL. Warszawa.
12. Plater C. V., Greenham C. G., 1959. A wide-range A.C. bridge for determining injury and death. Plant Physiol. 34: 661 - 667.
13. Pukacki P., 1978. Selekcja magnolii z różnych regionów Polski odpornych na niskie temperatury. Arboretum Kórnickie 23: 269 - 298.
14. Pukacki P., 1979. Dependence of electrical impedence of Magnolia shoots on temperature. Arboretum Kórnickie 24: 187 - 192.
15. Pukacki P., 1982. Freezing tolerance of Polish Norway spruce provenances. 26: 149 - 161.
16. Skierczyńska I., 1969. Właściwości elektryczne komórek *Characeae*. Praca habilitacyjna. Uniwersytet M. Curie-Skłodowskiej. Lublin.
17. Skierczyńska I., Żołnierczuk R., Bulanda W., 1973a. Impedance of *Nitellopsis abtusa* cells at low frequencies. J. Exp. Bot. 24: 38 - 46.
18. Skierczyńska J., Spiewala E., Żołnierczuk R., Bulanda W., Wardak A., 1973b. The measurements of the membrane resistance of *Characeae* by alternating and direct currents. J. Exp. Bot. 24: 1015 - 1023.
19. Skutt H. R., Shigo A. L., Leesard R. A., 1972. Detection of discolared and decayed wood in living trees using a pulsed electric current. Can. J. Forest Res. 2: 54 - 56.
20. Slynko P. P., 1972. Osnovy nizkočastotnoj konduktometrii v biologii. Izd. Nauka, Moskva.
21. Tattar T. A., Shigo A. L., Chase T., 1972. Relationship between the degree of resistance to a pulsed electric current and woody in progressive stages of discoloration and decay in living trees. Can. J. Forest Res. 2: 236 - 245.
22. Tattar T. A., 1974. Measurement of electric currents in clear, discolored, and decayed wood from living trees. Phytopathology 64: 1375 - 1376.
23. Tattar T. A., Blanchard R. O., 1976. Electrophysiological research in plant pathology. Ann. Rev. Phytopathol. 14: 309 - 325.
24. Teske A. A., 1965. Investigation on plant tissue impedance. Results of experiments with *Daucus carota* L. Acta Soc. Bot. Pol. 34: 149 - 159.
25. Teske A. A., Zając Z., 1971. The dependance of plant tissue impedance on temperature. Folia Soc. Scientarum Lulinensis, Sectio B. 12: 9 - 14.
26. Van der Driessche R., 1969. Measurement of frost-hardiness in two-year--old Douglas fir seedlings. Can. J. Plant. Sci. 49: 159 - 172.
27. Van den Driessche R., 1972. Prediction of frost hardiness Douglas fir at three nurseries by on electrical impedance in stems at different frequencies. Can. J. For. Res. 3: 256 - 264.
28. Wilner J., 1964. Seasonal changes in electrical resistance of apple shoots as a criterion of their maturity. Can. J. Plant. Sci. 44: 329 - 331.

PAWEŁ PUKACKI

Wpływ uszkodzeń mrożeniowych pędów magnolii na parametry impedancji

Streszczenie

Badania nad poznaniem niektórych parametrów elektrycznych tkanek roślinnych prowadzono na jednorocznych pędach trzech magnolii: *Magnolia acuminata* L., *M×soulangiana* Soulange-Bodin i *M. kobus* DC. Określano wartość oporu właści-

wego (*R*), pojemności (*C*), kąta przesunięcia fazowego (*φ*) i admitancji (Y) pędów w zależności od: rodzaju elektrod pomiarowych, częstości prądu (*f*), wymiarów próbki, rodzaju tkanki i zawartości wody i jonów K^+ i Na^+, na tle zmian destrukcyjnych wywołanych niską temperaturą.

1. Stwierdzono, że polaryzacyjny wpływ elektrod na wartość oporu i pojemność pędów występuje w zakresie niskich częstości (80 - 500 Hz). Natomiast w przypadku admitancji nie stwierdza się różnic między wartościami otrzymanymi przy pomocy elektrod stalowych niklowanych a platynowych.

2. Opór (*R*) i pojemność elektryczna (*C*) pędów magnolii maleje wraz ze wzrostem częstości (*f*), przy czym w pędach uszkodzonych na skutek mrożenia pojemność jest wyższa (pięć razy) niż w zdrowych. Natomiast w przypadku *R* jest odwrotnie, uszkodzone pędy wykazują silny spadek oporu przy jednoczesnym mniejszym wpływie częstości na *R*. Funkcja Y(*f*) wykazuje wzrost admitancji przy wzroście częstości prądu i stopnia uszkodzenia mrożeniowego pędów. Silny spadek oporu (*R*) czy też wzrost Y przemrożonych pędów spowodowany jest uszkodzeniem błon cytoplazmatycznych i związanym z tym wzrostem stężenia elektrolitów w kanałach ścian komórkowych. Otrzymane ujemne wartości kąta przesunięcia fazowego (*φ*) wskazują, że badany obwód biologiczny ma pojemnościowy charakter.

3. Wykazano, że wraz ze wzrostem odległości między elektrodami admitancja maleje, natomiast wpływ średnicy jest odwrotny. Oprócz wymiarów próbki na ruch jonów w tkankach ma również wpływ ich budowa. W zdrowych tkankach największe przewodnictwo wykazują tkanki kory i drewna w przemrożonych kambium.

4. Stosunki wodne i jonowe w tkankach w istotny sposób wpływają na przewodnictwo elektryczne. Wzrost zawartości wody i jonów K^+ i Na^+ w tkankach zwiększa admitancję. Wpływ stężenia potasu i sodu na Y jest bardziej istotny w pędach przemrożonych niż w zdrowych.

ПАВЕЛ ПУКАЦКИ

Влияние повреждения побегов магнолии морозом на величину импеданса

Резюме

Исследования по изучению некоторых электрических параметров растительных тканей были выполнены на однолетних побегах трех магнолий: *Magnolia cuminata* L., *M. soulangiana* Soulange-Bodin и *M. kobus* DC. Определяли значение удельного сопротивления (*R*), емкости (*C*), угла фазового передвижения (*φ*) и адмитанса (Y) побегов в зависимости от: вида измерительных электродов, частоты тока (*f*), размеров образца, вида ткани и содержания в ней воды и ионов K^+ и Na^+, на фоне деструктивных изменений вызванных действием низких температур.

1. Найдено, что поляризационное влияние электродов на значение сопротивления и емкости проявляется у побегов в диапазоне низких частот (80 - 500 Hz). В случае адмитанса не выявлено различий между значениями полученными с помощью стальных никелированных и платиновых электродов.

2. Сопротивление (*R*) и электрическая емкость (*C*) побегов магнолии уменьшается по мере роста частоты (*f*), причем в побегах поврежденных в результате замораживания емкость в пять раз выше, чем в контроле. В случае *R* наоборот, поврежденные побеги характеризуются значительным падением сопротивления при одновременном

меньшем влиянии частоты на *R*. Функция Y (f) подтверждает рост адмитанса при увеличении частоты так и степени повреждения побегов морозом. Значительное падение сопротивления (*R*) или рост Y промороженных побегов является следствием повреждения цитоплазматических мембран и связанным с этим ростом концентрации электролитов в клеточных стенках. Полученные отрицательные значения угла фазового передвижения (φ) указывают, что исследуемая биологическая цепь имеет объемный характер.

3. Было доказано, что по мере роста расстояния между электродами, значение адмитанса уменьшается, в то время, как диаметер оказывает обратное влияние. Кроме размеров образца на движение ионов в тканях оказывает также их строение. В здоровых тканях самой большой проводимостью характеризуются ткани коры и древесины, а в промороженных камбия.

4. Содержание в тканях воды и ионов существенным образом влияет на электропроводность. Рост содержания воды и ионов K^+ и Na^+ в тканях увеличивает адмитанс. Влияние концентрации калия и натрия на Y более существенно в промороженных побегах, чем в здоровых.