Non-destructive determination of impedance spectrum of fruit flesh under the skin

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Abstract. Impedance spectrum of fresh (intact) apples and of artificially bruised (pressed) apples was determined on the surface of skin with ECG electrodes (Fiab Spa). The magnitude and the phase angle of impedance were measured with a HP 4284A precision LCR meter. The open-short corrected spectra were approached a model consisting of serial resultant of an ohmic resistance and three distributed elements. Approach was performed with complex non-linear least squares method by MathLab program. Variance analysis was performed (P<0.05) on impedance parameters (SPSS 12.0 for Windows). Parameters of the first distributed element can describe the impedance of apple skin, and parameters of the second and the third element can characterize the impedance of apple flesh. Parameters of the second and the third element are in good agreement with impedance parameters obtained from spectra measured directly on apple flesh without skin. The value of parameters resulted from measurement on apples with skin are sensitive to the degree of artificial bruises.

1. Introduction
The electrical impedance spectrum – in low frequency range – of biological tissues depends on the state of cellular structure [1], therefore the parameters evaluated from measured spectrum can be used for quality assessment of fruits and vegetables [2]. In the majority of works the impedance is measured with pin electrodes [2], [4], [5] and there are few measurements with non-destructive electrodes [3].

In this work an attempt is made at determination of impedance spectrum of apple flesh from the spectrum measured on the surface of the whole apple covered with skin. The impedance parameters obtained from this mathematical method are compared with impedance parameters resulted from direct measurement on the flesh tissue without skin. The sensitivity of apple flesh impedance parameters to the level of mechanical injury of tissue under the skin is also investigated.

2. Materials and methods
Idared apples were purchased on the local market. The impedance spectrum on the surface of intact whole objects with skin was measured. After this the apples were peeled and the impedance of the flesh was direct measured at the same place, where the impedance on skin was measured.

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The bruises of apples under the skin were artificially established. Apple flesh named as “pressed” was caused by press of apple skin with force less than force belonging to the bioyield point. Under such low force only the shape of cells changes and the cell membrane remains unbroken [6]. “Pulpy” apple flesh was caused by pressing force much higher than force at bioyield and lower than force at rupture point. In this case the cell membrane is broken and the intercellular and intracellular parts are mixed.

Impedance of ten apples from each group – intact, pressed and pulpy with and without skin– was determined. The magnitude and the phase angle of impedance were measured with an HP 4284A precision LCR meter in a frequency range from 30 Hz up to 1 MHz. The measuring voltage was 1 V. The measured spectra were open and short corrected, to eliminate the stray capacities and inductances. Fiab Spa Ag/AgCl ECG electrodes with 10 mm diameter were used. The electrodes were touched to apple skin or to apple flesh, and the distance between the centres of electrodes was 2 cm. A special Signal gel was put between the electrodes and the skin of investigated objects for the good electrical contact.

The corrected impedance spectra of whole objects with skin were approached with an electrical model consisting of serial resultant of three distributed elements and one ohmic resistance

$$ R + \frac{R_1}{1 + (i \tau_1 \omega)^{\psi_1}} + \frac{R_2}{1 + (i \tau_2 \omega)^{\psi_2}} + \frac{R_3}{1 + (i \tau_3 \omega)^{\psi_3}} $$

where $R$, $R_1$, $R_2$ and $R_3$ are resistances, $\tau_1$, $\tau_2$ and $\tau_3$ are relaxation times, $\psi_1$, $\psi_2$ and $\psi_3$ exponents characterize the distribution of relaxation times, $\omega = 2\pi f$ and $f$ is the measuring frequency and $i = \sqrt{-1}$ is the imaginary unit. A model consisting of only two distributed elements and one resistance was fit to the spectra of apple flesh. The approaching procedure was performed with complex non-linear least squares (CNLS) method by MathLab program.

Variance analysis, a Dunnett T3 test was performed (P<0.05) on impedance parameters (SPSS 12.0 for Windows, SPSS Inc., Chicago, IL, USA).

3. Results and discussion

The measured and the corrected spectra of apple with skin (Figure 1.) were approached with expression (1). Impedance spectra measured on peeled apples were approached with a model consisting of only two distributed elements in a serial connection with each other and with one ohmic resistance. The first distributed element can characterize the impedance of apple skin. The second and the third elements can give the impedance parameters of the apple flesh tissue. The ohmic resistance, $R$, gives the resistance of measured object at infinite high frequency.

Figure 1. Typical measured impedance magnitude and phase angle on apple with skin

A typical approach of spectrum measured on apple with skin can be seen on the Figure 2. Similar good curve fitting (not shown) was resulted from approaching the impedance of apple flesh without skin, but in this case the calculated impedance contained only two components.
In intact apples R parameter was higher for apple flesh (Table 1.) than for apple with skin. This difference can be explained by a slightly mixing if intercellular and intracellular parts after peeling the apple. The strong decrease of R value with increasing bruise of apple flesh can be caused by more extensively mixing of inter- and intracellular parts. Practically for the pulpy apple flesh there is not difference between the two R values measured by the two methods.

The resistance and the relaxation time of apple skin decreased as the degree of bruise increased, but the exponent does not depend on it (Table 1.). It seems that the press of apple skin with relative low force can cause structure changes in it.

### Table 1. R parameter and impedance parameters of apple skin (average and standard deviation). The same letter in a column means there is no significant difference (P<0,05) in the values of parameters.

| State of apple flesh | Measured on apple flesh | Measured on apple with skin | Measured on apple with skin |
|----------------------|-------------------------|-----------------------------|-----------------------------|
|                      | R (kohm)                | R1 (kohm)                   | $\tau_1$ (ms)               | $\psi_1$                   |
| Intact               | 2.26±0.54 a             | 1.05±0.26 b                 | 3500±2204 a                 | 6.15±5.93 a                |
| Pressed              | 1.79±0.15 a             | 0.79±0.90 b                 | 700±184 b                   | 0.50±0.23 b                |
| Pulp            | 0.70±0.24 b             | 0.61±0.07 b                 | 36.5±35.1 c                 | 0.03±0.03 c                |

The resistance, $R_2$ is a little higher in apple with skin than in apple flesh for the all three groups of apple tissue (Figure 3. (a)). The relaxation time parameter also is higher for apple flesh with skin, than for peeled apple tissue (Figure 3. (b)). The standard deviation is higher for both resistances and relaxation times obtained from approach on apple with skin in comparison with standard deviation of these parameters from spectrum of peeled apples (Figure 3. (a) and (b)).

The resistance, $R_1$ is higher for peeled apple flesh, than for apple flesh with skin (Figure 4. (a)), but the relaxation time and exponent are higher for unpeeled apple tissue (Figure 4. (b) and (c)). These differences also can be understood by the mixing of intra and intercellular tissues after peeling or after artificial bruise.

### 4. Conclusion

In conclusion it can be stated that this mathematical procedure resulted similar parameters for apple flesh from measured spectra on apple with skin to parameters from directly apple flesh measurements.
The resistance and relaxation time parameters of the second distributed element can be used for characterizing the state of apple flesh.

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