Bioelectrochemistry 112 (2016) 9–15

Contents lists available at ScienceDirect

Bioelectrochemistry

journal homepage: www.elsevier.com/locate/bioelechem

Cyclic voltammetry of apple fruits: Memristors in vivo

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ARTICLE INFO

Article history:
Received 5 April 2016
Received in revised form 3 July 2016
Accepted 4 July 2016
Available online 5 July 2016

Keywords:
Memristor
Electrotonic potential
Bioelectrochemistry
Apple
Malus domestica
Golden Delicious
Arkansas Black

ABSTRACT

A memristor is a resistor with memory that exhibits a pinched hysteretic relationship in cyclic voltammetry. Recently, we have found memristors in the electrical circuitry of plants and seeds. There are no publications in literature about the possible existence of memristors and electrical differentiators in fruits. Here we found that the electrostimulation of Golden Delicious or Arkansas Black apple fruits by bipolar periodic waves induces hysteresis loops with pinched points in cyclic voltammograms at low frequencies between 0.1 MHz and 1 MHz. At high frequencies of 1 kHz, the pinched hysteresis loop transforms to a non-pinched hysteresis loop instead of a single line $I = V / R$ for ideal memristors because the amplitude of electrical current depends on capacitance of a fruit's tissue and electrodes, frequency and direction of scanning. Electrostimulation of electrical circuits in apple fruits by periodic voltage waves also induces electrotonic potential propagation due to cell-to-cell electrical coupling with electrical differentiators. A differentiator is an electrical circuit in which the output of the circuit is approximately directly proportional to the rate of change of the input. The information gained from electrostimulation can be used to elucidate and to observe electrochemical and electrophysiological properties of electrical circuits in fruits.

1. Introduction

The concept of memristance was introduced by Leon Chua [1]. The memristor is the fourth fundamental two-terminal circuit elements, in addition to the capacitor, resistor, and inductor [1]. Memristance or memory resistance can be described mathematically by the equation:

$$M(q(t)) = \frac{d\phi(q)}{dq} = \frac{V(t)}{I(t)} \quad (1)$$

where M is the memristance, V is voltage, I is electrical current, ϕ and q denote the flux and charge, respectively [1–5].

Memristors can participate in intracellular and intercellular electrical signal transduction in plants, trees and fruits between phytosensors and phytoactuators. Biological tissue in many organisms exhibits memristive behaviors [6–21]. Voltage gated potassium and sodium ion channels in neural networks are generic memristors [2,4,14–16].

We have found memristors in the electrical circuitry of the Venus flytrap, pumpkin seeds, potato tubers, *Aloe vera* and *Mimosa pudica* [7–11,20,21]. Pharmaceutical analysis showed that the tetraethylammonium chloride (TEACl) blocker of K^+ channels inhibits plant memristance [7–11,20]. In plants, uncouplers' carbonylcyanide-4-trifluoromethoxyphenyl hydrazone (FCCP) and carbonylcyanide-3-chlorophenylhydrazone (CCCP) decreased the amplitude of hysteresis in *I-U* plane [9–11]. Markin et al. [8] proposed analytical models of a memristor and a memristor connected parallel to a capacitor for analysis of bio-memristors.

Electrical processes play important roles in the electrophysiology and bioelectrochemistry of plants, roots, seeds [20–27]. Electrical signals can propagate along sophisticated electrical circuitry of fruits consisting of many electrical components developed by nature. Electrical circuits in plants, trees and fruits can operate over long distances. The activation of these electrochemical circuits can lead to various physiological, electrochemical, mechanical and biochemical responses [20–27].

This cellular signaling can be either active, representing an action potential, or passive, described as electrotonic potential. The action potential can propagate over the entire length of the cell membrane and along the conductive bundles of tissue with constant amplitude, duration, and speed. Electrotonic potentials in plants exponentially decrease with distance [27].

There are a lot of publications about plant electrophysiology, but only a few publications are related to fruits electrophysiology. There are no publications in literature about the existence of memristors in fruits.

Golden Delicious apple fruits are the most common and well-studied fruits. Apple fruit (*Malus domestica*) is one of the most important sink organs in sugar accumulation [28]. Zhang et al. [28] presented results on anatomy and ultra-structure of an apple fruit (*Malus domestica*

Abbreviations: C, capacitance; *DAQ*, data acquisition; PXI, PCI eXtensions for Instrumentation; *I*, electrical current; I_M, electrical current through a memristor; I_C, electrical current through a capacitor; *M*, memristance; *P*, electrical power; *q*, charge; *R*, resistance; TEACl, tetraethylammonium chloride; V_{in}, voltage of an function generator; V_P, voltage between electrodes in plants; V_R, voltage on resistor *R*; ϕ, magnetic flux.

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http://dx.doi.org/10.1016/j.bioelechem.2016.07.001
1567-5394/

Borkh. cv Golden Delicious). Velasco et al. [29] decoded the complete genome of the Golden Delicious apple and found about 57,000 genes. Kurenda et al. [30] studied effects of injection of ion channel inhibitors such as TEACl, gadolinium chloride, 9-anthracenecarboxylic acid and diethylstilbestrol on the inhibition of bio-speckle activity in apple tissue.

Memristors can exist in many different fruits. We selected apples because the complete genome [29] for the Golden Delicious apple fruits and its anatomy [28] are known. The main goal of this article is to find out if electrical circuits of apple fruits have memristors and electrical differentiators.

2. Materials and methods

2.1. Apples

Golden Delicious and Arkansas Black (*Malus domestica* Borkh.) apple fruits were received from Catbird Seat Garden Center (Madison, Alabama, USA) and from Isom's Orchard (Athens, Alabama, USA). Mass of an Arkansas Black apple was about 180 g (Mean 185.3 g, Median 175.0 g, Std. Dev. 21.7 g, Std. Err. 6.9 g, n = 27). Mass of a Golden Delicious apple was about 250 g (Mean 249.8 g, Median 239.5 g, Std. Dev. 22.2 g, Std. Err. 7.0 g, n = 25). The humidity averaged 45–50%. Temperature was 20 °C. All experiments were performed on healthy specimens.

2.2. Chemicals

Tetraethylammonium chloride (TEACl) was obtained from *Sigma-Aldrich* (New York).

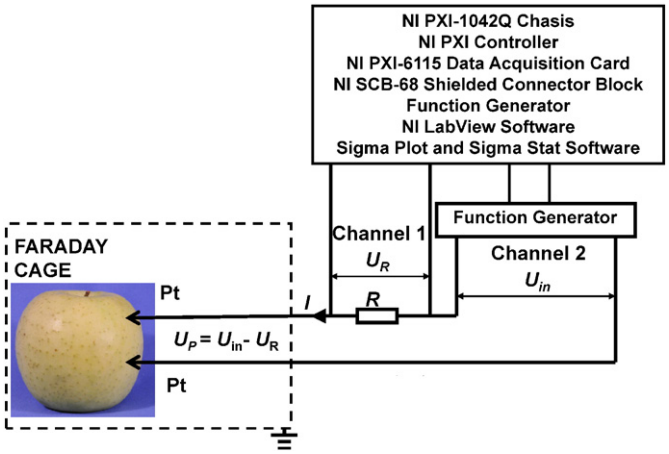
2.3. Electrodes

Ag/AgCl electrodes were prepared in the dark from Teflon coated silver wires (*A-M Systems, Inc., Sequim, WA, USA*) with a diameter of 0.2 mm by electrolysis of 5 mm long silver wire tip without Teflon coating in a 0.1 M KCl aqueous solution [26]. Identical Ag/AgCl reversible electrodes were used as working and as reference electrodes. Platinum electrodes were prepared from Teflon coated platinum wires (*A-M Systems, Inc. Sequim, WA, USA*) with diameter of 0.076 mm [7–10].

2.4. Data acquisition

Experimental setup for cyclic voltammetry is shown in Schematic 1. All measurements were conducted in the laboratory at constant room temperature of 20 °C inside a Faraday cage, which was mounted on a vibration-stabilized table [7]. High speed data acquisition of low-pass filtered signals was performed using microcomputer NI-PXI-1042Q (*National Instruments*) with simultaneous multifunction I/O plug-in data acquisition board NI-PXI-6115 (*National Instruments*) interfaced through a NI SCB-68 shielded connector block to electrodes as described earlier in Ref. [7]. The function generator FG300 (*Yokagawa, Japan*) was used for electrostimulation of plants [7].

All experimental results were reproduced at least 20 times. Software SigmaPlot 12 (Systat Software, Inc.) was used for statistical analysis of experimental data.



Schematic 1. Schematic diagram of the data acquisition and electrostimulation system.

3. Results

3.1. Electrotonic potentials

Electrostimulation of apples by a square pulse from a function generator induces percussive electrical signals (Fig. 1A, B). This phenomenon shows that electrical networks in apple tissue have electrical differentiators. A differentiator is an electrical circuit that is designed such that the output of the circuit is approximately directly proportional

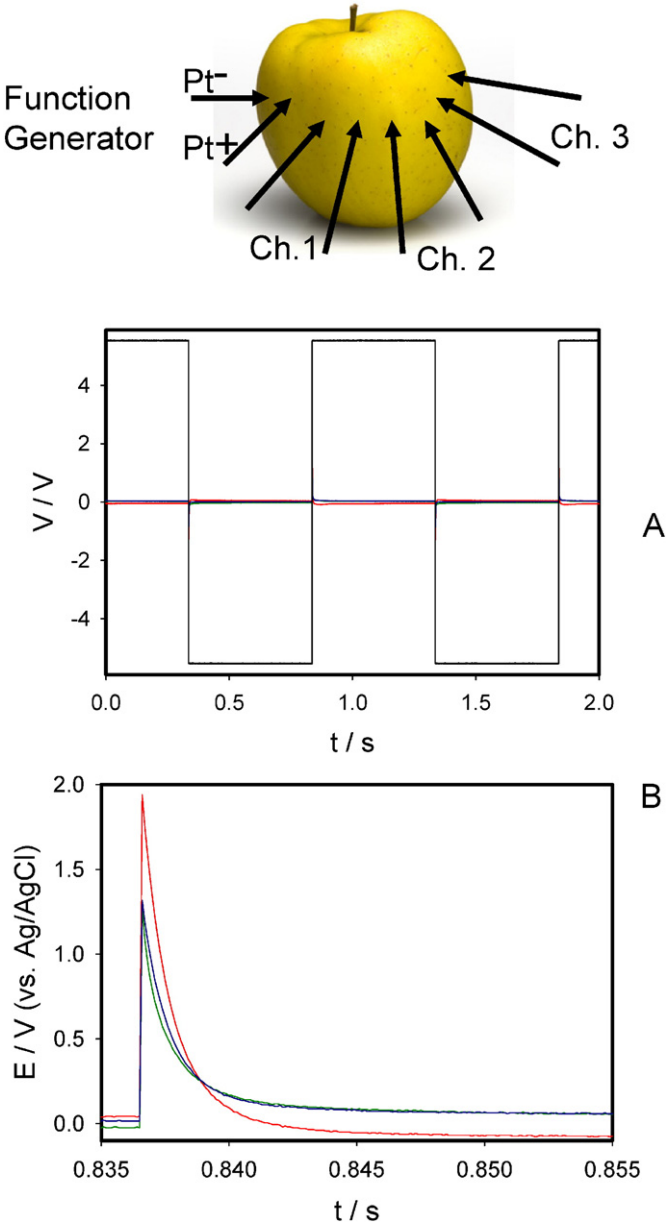


Fig. 1. Time dependencies of electrical signals in a Golden Delicious apple induced by a bipolar square pulse wave with amplitude ±5.5 V from a function generator. The frequency of scanning was 50,000 samples/s with a low pass filter at 25,000 scans/s. The frequency of electrostimulation was 1 Hz. Distance between Pt electrodes was 7 mm.