Entropy Analysis of the Bioelectrical Activity of Plants

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The paper introduces entropy analysis of bioelectrical activity based on harmonic signal distortion. Over a period of one year, the ultradian dynamics of the electrical activity of higher plants and the response on low frequency electromagnetic fields and modulated light were recorded. Biological active frequencies increasing or decreasing the entropy of bioelectrical activity were identified.

Introduction

Bioelectricity are electric potentials and currents produced by or occurring within living organisms. The experiments of Luigi Galvani and Alessandro Volta in the 18^{th} century proved the connection between electricity and muscle contraction in frogs and other animals. Today, electrical effects originating in active cells of the heart and the brain are commonly monitored and analyzed for diagnostic purposes.

In 1873, John Burdon-Sanderson [1] discovered bioelectrical activity in the leaf of the Venus flytrap due to stimulation. Recent studies evidence that intracellular electrical signals serve for information transmission in plant cells [2]. Electrical signals have been shown to accompany many processes in plant life, including respiration [3], water uptake and transport [4], leaf movement [5] and stress response [6]. Electrical signals also play an important role in physiological activities e.g. gas exchange, pollination, fertilization and gene expression [7].

Plant tissue is a good conductor of electricity, so that electrical resistivity is used for quantification of root structures and functioning. Studies of the spatiotemporal characteristics of the electrical network activity of the root apex evidence the existence of excitable traveling waves in plants [8], similar to those observed in non-nerve electrogenic tissues of animals. Electrical activity is mostly observed in the transition zone of the root apex, and points to a possible physiological role of synchronized electrical activity in this region.

Stefano Mancuso [9] has found rising evidence that the root apex is the key to the intelligence of higher plants. He argues that plants use the root system as a complex network instead of a single powerful brain. The plant-neurobiological paradigm of Mancuso assumes that plants have electrical activity similar to neurological ones. Recent research evidences that plants are endowed with feeling [10], complex social relations and can communicate with themselves and with animals, show behaviors similar to sleeping and playing.

Obviously, not only higher plants show intelligent behavior, but also unicellular organisms. For example, the plasmodium of the slime mould physarum polycephalum has the ability to find the minimum-length solution between two points in a labyrinth – a kind of tasks we used to think only animals could perform. Physarum polycephalum shows cognition without a brain, but also without neurons at all [11].

It is well known that the boundary frequencies of the electrical activity of the human brain are common to other mammals [12]. Furthermore, the frequencies of electrical brain activity and the natural frequencies of the electromagnetic activity of the Earth's atmosphere [13] are of the same range. This coincidence suggests that the frequencies of electrical brain activity could be of more fundamental concern and not limited to mammalian neurophysiology and, perhaps, higher plants, being embedded in the electromagnetic environment of the Earth, operate with the same frequencies of electrical activity.

Mammals including human have electrical brain activity [14] of the Theta type in the frequency range between 3 and 7 Hz, of Alpha type between 8 and 13 Hz and Beta type between 14 and 37 Hz. Below 3 Hz the brain activity is of the Delta type, and above 37 Hz the brain activity changes to Gamma. It is the physical separation of different states of brain activity that is essential for its stability. The violation of this separation can cause neurological disorders. In the case of human neurophysiology, Theta-Alpha or Alpha-Beta violation can cause speech and comprehension difficulties [15], depression and anxiety disorders [16].

Hence, the stability of the frequency boundaries separating Theta activity from Delta, and Beta activity from Alpha and Gamma is essential for neurophysiological health. The frequencies 3.0 Hz, 8.2 Hz, 13.5 Hz and 36.7 Hz define the boundaries. What is so special about these frequencies?

In [17] we have shown that the ratios of the boundary frequencies of the brain waves approximate Euler's number and its square root. Being attractors of transcendental numbers, they allow avoiding any resonance between the brain wave boundaries and thus stabilize the central nervous system. Indeed, the natural logarithms of the ratios of the boundary frequencies are close to integer and half values:

$$\ln\left(\frac{8.2}{3.0}\right) = 1.00 \qquad \ln\left(\frac{13.5}{8.2}\right) = 0.50 \qquad \ln\left(\frac{36.7}{13.5}\right) = 1.00$$

Furthermore, in [18] we have shown that these boundary frequencies approximate integer powers of Euler's number relative to the natural frequencies of the proton and the electron:

$$\ln\left(\frac{8.2\,\mathrm{Hz}}{\omega_e}\right) = -46 \qquad \ln\left(\frac{13.5\,\mathrm{Hz}}{\omega_p}\right) = -53$$

where $\omega_e = 7.76344 \cdot 10^{20}$ Hz and $\omega_p = 1.42549 \cdot 10^{24}$ Hz are the angular frequencies of the electron and the proton:

$$\omega_p = \frac{\mathrm{E}_p}{\hbar} \qquad \omega_e = \frac{\mathrm{E}_e}{\hbar}$$

where $\mathrm{E}_p = 938.272$ MeV and $\mathrm{E}_e = 0.511$ MeV are the rest energies of the proton and the electron [19], and $\hbar$ is the reduced Planck constant.

The fact that the brain wave boundary frequencies fit with integer powers of Euler's number relative to the natural frequencies of the proton and the electron indicates that *quantum* physical stability of the frequency boundaries is essential for brain activity.

Similar frequencies we find also in the Earth's electromagnetic spectrum, for example the Schumann resonances. Solar X-ray bursts can cause their variations [20]. In this case, the fundamental 7.8 Hz increases up to 8.2 Hz reaching exactly the stable Theta-Alpha boundary. The second Schumann mode 13.5 Hz coincides precisely with the Alpha-Beta boundary. It is remarkable that solar activity affects this mode much less or does not affect it at all because of its Euler stability. The third Schumann mode currently has a frequency of 20.3 Hz and must increase to 22.2 Hz in order to reach the next island of electron stability. By the way, such an increase is observed recently.

The coincidence of the boundary frequencies of brain activity with Schumann resonances demonstrates how precisely the electrical activity of biological systems is embedded in the electromagnetic activity of the Earth. Important to know that Euler's number and its roots make possible this embedding, because they are attractors of transcendental numbers and form islands of stability. They allow for exchanging information between systems of very different scales – the biophysical and the geophysical. Considering the universality of this embedding, it is very likely that it includes also the bioelectrical activity of plants.

In 1892, Otto Haake [21] showed that light can trigger the bioelectrical activity of plants. Changes in the light conditions may trigger variation in the potential of the guard cell membrane. In 1923, Alexander Gurwich discovered the phenomenon of mitogenetic radiation of biophotons – ultraweak biophysical photon emissions – detected in the UV-range of the spectrum [22]. He observed that these emissions can accelerate cell proliferation. In 1979, Vlail Kaznacheev [23] demonstrated experimentally that IR-A and UV-A biophotons are carriers of intercellular communication. In 1994, Fritz Popp [24, 25] discovered the regulatory significance of coherent biophotonic emissions and of non-random lognormal distributions of physiological parameters. Therefore, we recorded not only the ultradian dynamics of the electrical activity of the plants, but also their bioelectrical response on modulated red and infrared light.

Due to the potential use of bioelectrical phenomena for indicating the physiological condition of plants in agricultural fields, there have been several attempts to analyze these signals and extract their features using statistical and signal processing methods [26].

In his book 'What is Life?', Erwin Schrödinger stated that life feeds on negative entropy, or negentropy [27]. Biosystems are indeed fare from thermodynamic equilibrium, and the second law of classic thermodynamics does not apply to them. Within the thermodynamics of open systems developed by Ilya Prigogine [28], entropy can only be exchanged and, like energy, can neither be generated nor eliminated. From this point of view, Schrödinger's negentropy is a local decrease of entropy that appears as a consequence of entropy exchange of the biosystem with the environment. The ability of lower the own entropy through entropy exchange with the environment seems to be a universal criterion of vitality.

Therefore, for bioelectric signal processing, we applied entropy analysis based on harmonic signal distortion. Over a period of one year, we recorded the ultradian dynamics of the electrical activity in leafs of Orchidaceae phalaenopsis, Aloe vera, Ocimum basilicum and Panax ginseng, including the response on low frequency electromagnetic fields and modulated light.

Methods

Approaches to the study of electrical activities in plants include intracellular and extracellular measurements. The latter can detect the electrical signals produced by the tissue, and is applicable to the monitoring of an individual plant. The bioelectric resting potential across a cell membrane is typically about 50 millivolts. As electrical signals in plants are weak, they usually must be amplified and the recording device must have a high input impedance [29]. Therefore, for recording the bioelectrical signals in plant tissues we used a digital oscilloscope and attached the measuring electrode to a leaf.

For the purpose of shielding against uncontrolled external electromagnetic sources during the measurement, we placed the plant or the leaf in a container made of 1/16 aluminum sheet, similar to the described in [30] polyhedrons. Inside the container we placed also a coil generating a low frequency electromagnetic field. Figure 1 illustrates the experimental setup. Modulated red LED-light we applied as well. For light and field modulation, we chose the brain activity boundary frequencies and further frequencies of electron and proton stability in the range from 3 Hz to 15 kHz.

In [31] we have shown that destabilizing parametric resonance in oscillating systems of any complexity can be avoided if all frequency ratios correspond to integer powers of Euler's number. Essential for lasting stability in *real* systems is the

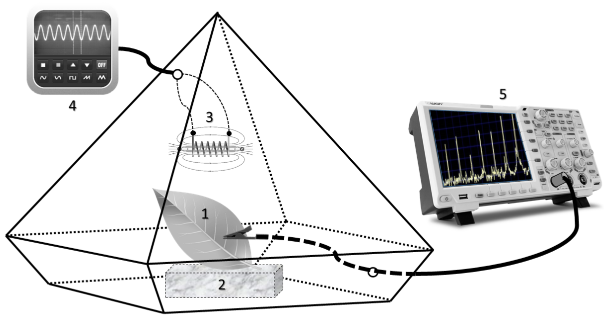

Fig. 1: The experimental setup: The plant or the leaf (1) was placed on a wooden platform (2) in a polyhedral container made of 1/16 aluminum sheet. Inside the container we placed also a coil (3) alimented by a frequency generator device (4). The bioelectrical signals were recorded by a digital oscilloscope (5).

prevention of proton and electron resonance. Therefore, also biosystems prefer frequencies corresponding to the electron or proton natural frequency divided by integer powers of Euler's number:

$$f_p = \frac{\omega_p}{e^n} \qquad f_e = \frac{\omega_e}{e^m}$$

where f_p and f_e are frequencies of proton respectively electron stability. The exponents n, m are integer.

As we already mentioned, the brain wave boundary frequencies are of electron and proton stability. However, it may be that some frequencies of bioelectrical processes in plants surpass the range of brain waves. Therefore, we applied also higher frequencies of electron and proton stability for field and light modulation (table 1).

n	$f_p = \omega_p/e^n$	m	$f_e = \omega_e/e^m$
46	15,011	39	8,965
47	5,522	40	3,298
48	2,032	41	1,213
49	747	42	446
50	275	43	164
51	101	44	60
52	37	45	22
53	14	46	8
54	5	47	3

Table 1: Frequencies (rounded) of proton f_p and electron f_e stability, which we applied for field and light modulation, and the corresponding integer exponents n, m of Euler's number.

For the purpose of control, we recorded the bioelectrical activity of the same plant or leaf alternately inside and outside the container. In a dark room, we applied also red and infrared light emitted by LEDs having 660 nm and 850 nm peak wavelengths, which was modulated by the same frequencies of electron and proton stability (table 1).

The measuring electrode of the oscilloscope picked up the bioelectrical signal directly from the leaf (fig. 1). The internal FFT-processor of the oscilloscope automatically stored the frequencies and amplitudes (voltages) of the harmonics to built-in memory. Based on the frequencies and amplitudes of the first 8 – 16 harmonics (depending on the field and light modulation frequency), the harmonic distortion HD of the bioelectrical signal was calculated:

$$\mathrm{HD} = \frac{\sqrt{(V_2^2 + V_3^2 + \cdots + V_n^2)/n}}{V_1}$$

where V_n is the n^{th} harmonic voltage and V_1 is the fundamental component. For example, a pure symmetrical triangle wave has HD of 12%, a square wave has 48%, and a sawtooth signal possesses 80%.

In this way, the distortion of a waveform relative to a pure sinewave can be measured by splitting the output wave into its constituent harmonics and noting the amplitude of each relative to the fundamental. The HD indicates the degree of order – disorder associated with the frequency spectrum of a signal. Therefore, we interpret the HD in terms of Shannon's information entropy [32].

Shannon's idea of information is that the value of a communicated message depends on the degree to which the content of the message is surprising. If an event is very probable, it is no surprise; hence the transmission of such a message carries very little information. From this point of view, HD is surprising, because it violates the expected $1/n^2$ decrease of the amplitudes of higher harmonics.

In order to process the HD-calculation automatically, we wrote a software that reads the FFT-datafile directly from the oscilloscope and stores the calculated HD values on SSD.

Results

We started recording the ultradian dynamics of the HD of bioelectrical signals in leafs of Orchidaceae phalaenopsis, Aloe vera, Ocimum basilicum and Panax ginseng in May 2020. To date we made a total of 1014 measurements of the bioelectrical response on low frequency electromagnetic fields and modulated light of these plants alternately inside and outside the shielding container (fig. 1).

The HD of the bioelectrical signals we measured varied between 67 and 88%. Figure 2 shows the ultradian dynamics of the HD measured on leafs in laboratory outside the container under conditions of natural illumination. The ultradian dynamics of HD measured on a leaf of the Orchidaceae phalaenopsis shows the typical increase in HD around noon and the decrease at sunset (fig. 2a) under otherwise constant environmental conditions. Fig. 2b shows clearly the continuous decrease of HD immediately after the weekly watering of Panax ginseng at 10 am. Even if it rained, but the plant in the laboratory did not get any water, the HD declined slightly. The increase of HD after 10 am in fig. 2c coincides with a powerful thunderstorm. All investigated plants showed similar reactions of HD on thunderstorm.

EXPONENT	FREQUENCY, Hz	HD Basil, %	HD Aloe, %
E46	15,011	83	77
P39	8,965	75	81
E47	5,522	81	76
P40	3,298	74	83
E48	2,032	79	69
P41	1,213	77	80
E49	747	76	71
P42	446	68	74
E50	275	85	81
P43	164	76	84
E51	101	79	67
P44	60	78	83
E52	37	83	81
P45	22	77	82
E53	14	84	75
P46	8	68	82
E54	5	78	69
P47	3	72	81

Table 2: Frequencies applied for field modulation inside the container (fig. 1) and the corresponding daily HD minima for Ocimum basilicum and Aloe vera. In accordance with tab. 1, P-exponents indicate frequencies of *proton* stability while E-exponents indicate frequencies of *electron* stability.

Fig. 2d illustrates how the HD dynamics of Orchidaceae phalaenopsis follows the weather conditions. The decrease in HD during the first 2 hours coincides with increasing cloudiness and the minimum HD with 1 hour of rain. As the cloudiness decreases after the rain, the HD will increase until the plant has been watered. Immediately afterwards the HD falls to the daily minimum. This reaction of the HD to weather conditions confirms that Orchidaceae phalaenopsis as well as Panax ginseng like a humid atmosphere but do not like intense sunlight. Fig. 2e shows the HD dynamics of Ocimum basilicum at the same day. In contrast to Orchidaceae phalaenopsis, increasing cloudiness provokes a significant increase of the HD in the electrical activity of O. basilicum. As the cloudiness decreases after the rain, the HD decreases as well, and the watering causes only a 1% fluctuation of HD. During and after the sunset the HD continuously increases. Obviously, Ocimum basilicum and Aloe vera are light-loving plants and show a significant decrease in HD with moderate sunlight and an increase in HD with a lack of light. All these conformities evidence the suitability of HD measurements for estimating trends in bioelectrical activity of plants.

In addition to these measurements, we studied the ultradian dynamics of HD on the same plants inside the shielding container (fig. 1), where we installed a coil for generating weak electromagnetic fields modulated by brain wave boundary frequencies and other frequencies of electron and proton stability (tab. 1). Inside the container, the plants did show very simple ultradian dynamics of HD with only one minimum and no usual reaction on weather conditions. Fig. 2f shows the HD minimum of Ocimum basilicum at noon. The frequency 453 Hz was applied for field modulation. The signal was sinus.

It is remarkable that the plants showed stable changes in the daily HD minimum as a function of the modulation frequency. Table 2 shows the frequencies of proton (P) and electron (E) stability applied for field modulation inside the container and the corresponding daily HD minima for Ocimum basilicum and Aloe vera. Apparently, O. basilicum prefers P-frequencies, and A. vera E-frequencies. The application of modulated light lead to similar results.

Conclusion

In this paper we introduced HD analysis of bioelectric signals as method of entropy variation measurement that could be applied as an efficient alternative agronomic tool at the service of producers for decision support and as tool of food quality control. Our study evidences that HD analysis of bioelectrical signals is a reliable method for evaluating the vitality of higher plants.

It is very likely that the HD of a bioelectrical signal is not just a measure of its entropy, but a way of bioelectrical intercellular communication. In this case, the relatively high HD values we measured could turn out to be an indicator of information density. Perhaps, the relative amplitude of each harmonic encodes some biologically significant information. This possibility and the ability of plants to communicate with other organisms could be the subject of further research.

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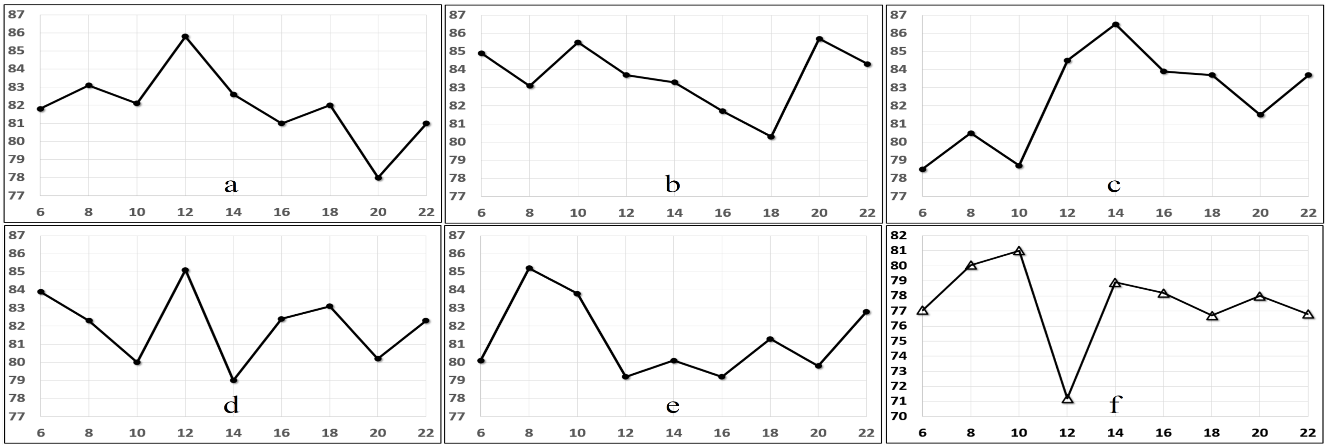

Fig. 2: Some examples of the ultradian dynamics of HD (vertical axes in %) measured on leafs in laboratory under conditions of natural illumination (a - e) and inside the aluminum container (f) in intervals of 2 hours starting at 6 am until 10 pm (horizontal axes). For detailed description, please read the main text.

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