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BIOPHYSICS

Effects of Locally Applied Low-Intensity Electromagnetic Infrared and Millimeter Radiation on Plants

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Abstract—The paper puts forward the mechanism of action of local low-intensity infrared and millimeter electromagnetic radiation on plant tissues. Electric response of cucumber (*Cucumis sativus* L.) plants to the local exposure to low-intensity electromagnetic radiation (0.1–10 mW/cm^2) in the infrared and millimeter range using the method of extracellular derivation of the bioelectrical potential was measured. Plots were constructed of the bioelectric potential response amplitude against income electromagnetic radiation intensity. Action spectrum of electromagnetic radiation on the plant bioelectric potential normalized for income intensity and cucumber leaf transmission spectrum were obtained.

Keywords: cucumber plants, local electromagnetic radiation, millimeter wavelength range
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INTRODUCTION

The transition to precision farming in agriculture is associated with the use of novel technological and technical systems that guarantee effective monitoring of the plant state and the end product quality [1]. At the same time, plant adaptation to permanent climatic and anthropogenic factors, as well as their combinations [2, 3], depends on the plant development stage and on the type and intensity of the acting factor and the exposure time. The systems that would allow one to perform, in the action–response operational mode, quick and comprehensive analysis of the plant organism's state without damaging plant tissues are indispensable when addressing the problems of modern agricultural science and industry [1, 3–5]. One of the promising research techniques is the analysis of plant response to the changes in the wavelength and other informative parameters of nondestructive low-intensity electromagnetic radiation (EMR).

MATERIALS AND METHODS

The experiments were carried out using three-week old TSKhA 575 hybrid cucumber plants (*Cucumis sativus* L.) that were grown under the laboratory conditions according to the standard protocol [6]. The experimental installation outline is given in Fig. 1. The measurements were made using the method of extracellular derivation of surface bioelectrical potential using nonpolarizable silver/silver chloride electrodes 8 and 9 [7, 8]. He-Ne laser (λ = 3390 nm), diode lasers (λ = 760, 860, and 1300 nm), and millimeter EMR sources were used as coherent light sources. EMR intensity (0.1–10 mW/cm^2) was regulated with the polarization filter 16. To localize EMR within the 1–4 mm range, the lens system 17 was utilized. Gradual or stepped decrease in the millimeter electromagnetic wave intensity was achieved through the use of the attenuator 2. To produce light beams with different wavelengths, the UNVIF narrow-band filter 18 (Carl Zeiss, Germany) was also utilized. The obtained wavelengths were as follows, 769, 810, 851, 893, 936, 981, 1037, 1073, and 1130 nm, with the pass band ($\Delta\lambda$) of 15 nm. Additional local light irradiation was performed as a step with τ = 20 s.

RESULTS AND DISCUSSION

High ΔU values were observed at the wavelengths from 750 to 850 nm and from 1020 to 3390 nm (Figs. 2, 3), which correspond well with the cucumber leaf transmission spectrum in the infrared range (Fig. 4). Photo-induced response of the plant bioelectric potential triggered in the red spectral range (750–850 nm) is likely to be associated with cellular pigments, phytochromes [10]. Since plants responded to both laser irradiation and irradiation with narrow-band incoherent light in almost similar way, it seems that, in the case of green plants, the determining factor is the EMR wavelength, but not its coherence. Infrared radi-

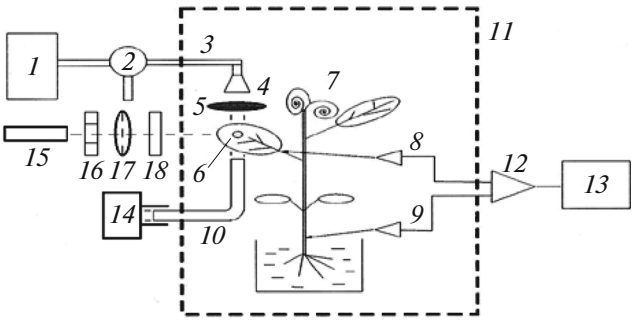

Fig. 1. Outline of the experimental installation used to perform local electromagnetic irradiation of plants and to determine bioelectric potential action spectrum and green leaf transmission spectra in the infrared range. *1*—Millimeter waves generator; *2*—measuring transducer (attenuator); *3*—wave guide; *4*—horn; *5*—"aqueous diaphragm"; *6*—local irradiation area; *7*—plant; *8*—measuring electrode; *9*—reference electrode; *10*—sensing elements; *11*—Faraday cage; *12*—electrometric amplifier; *13*—computer; *14*—power meter; *15*—infrared electromagnetic radiation sources; *16*—polarization filter; *17*—lens system; *18*—narrow-band light filter.

ation with the wavelength longer than 1000 nm is almost completely absorbed by the green leaf (Fig. 5). Lamina thickness in cucumber in the area of local electromagnetic irradiation was 0.2 mm on average. The comparison of the transmission spectrum of the cucumber leaf (Fig. 4) and water absorption spectrum (Fig. 6) also showed that infrared radiation (λ = 1020–3390 nm) is almost completely absorbed by water molecules and falls within the region of water absorption in the infrared range.

In our calculations made to assess the mechanism of the low-intensity EMR effect on the living plant tissue, we assumed that income energy is completely absorbed by the leaf (Fig. 5). Since water constitutes 80–90% of the plant cell [9, 10], we assume that leaf volume corresponding to the irradiated area contains only water. The quantity of heat emitted by the 5 mm irradiated zone of the cucumber leaf with the leaf lamina thickness of 0.1–0.2 mm during the 20 s exposure can be calculated according to the following formula:

$$Q = I_\lambda \tau \pi d^2 / 4, \quad (1)$$

where ΔT is the difference between the temperatures of the irradiated zone before and after exposure to radiation; c_p is specific heat capacity of water (c_p = 4.2 J/g K); m is water weight ($m = \rho h \pi d^2/4$, where ρ is water density, ρ = 1.02 g/cm^3, h is leaf lamina thickness, d is leaf local irradiation area diameter). The emitted heat may also be obtained from the following equation:

$$\Delta T = I_\lambda \tau / h c_p \rho, \quad (2)$$

where I is income radiation intensity and τ is exposure time. Normalized income intensity (I) is 0.6 mW/cm^2. From Eqs. (1) and (2) we get

$$Q = \Delta T c_p m. \quad (3)$$

From Eq. (3), we may get ΔT = 0.14–0.28 K.

Temperature increase by 10°C within the physiological range leads to a 2–5 times increase in the intensity of enzymatic reactions [9]. Given the standard bioelectric potential difference between the measuring electrodes being approximately 35 mV, we expect that an additional temperature increase by 0.3 K causes an increase in the absolute bioelectric potential value by 1–4 mV, which was in fact observed in the experiment. In the calculations, the exposed area warming-up rate and heat dissipation rate upon stopping the irradiation should be considered. The absence of additional heating after switching off EMR leads to a decrease in the absolute bioelectric potential value by ΔU = 1–4 mV. Given that infrared radiation is absorbed by the thin upper layer h of the leaf lamina, the time t during which the leaf irradiated area was being heated can be obtained from the following equation:

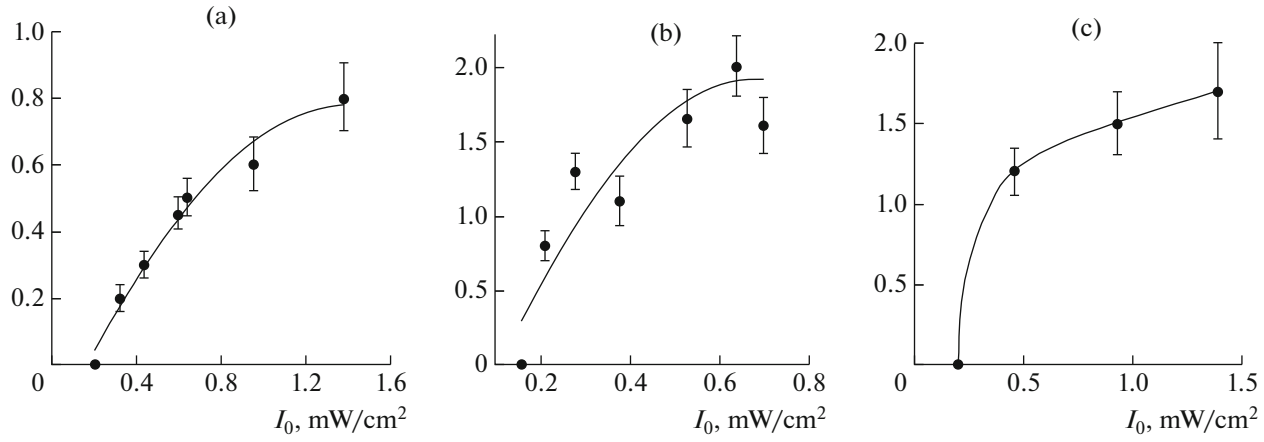

Fig. 2. ΔU amplitude dependence on the incoming radiation intensity, I_λ at certain wavelengths within the infrared range. (a) λ = 851 nm; (b) λ = 1037 nm, and (c) λ = 3390 nm.

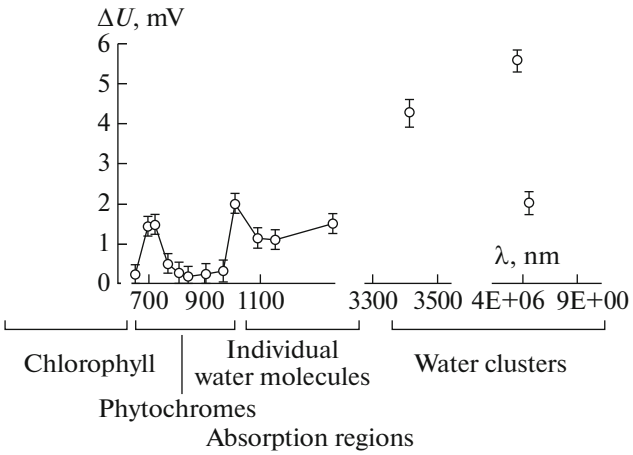

Fig. 3. Action spectrum or amplitude of bioelectric potential variables' response to local electromagnetic irradiation with different wavelengths.

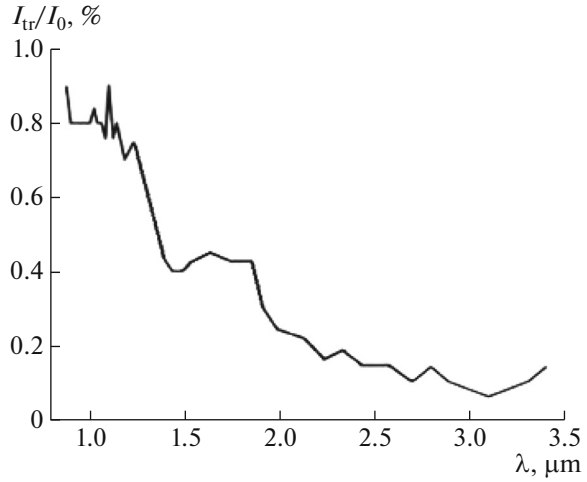

Fig. 4. Cucumber leaf transmission spectrum in the infrared wavelength range. I_0—incoming intensity of the local (plant leaf) electromagnetic radiation; I_{tr}—transmitted intensity.

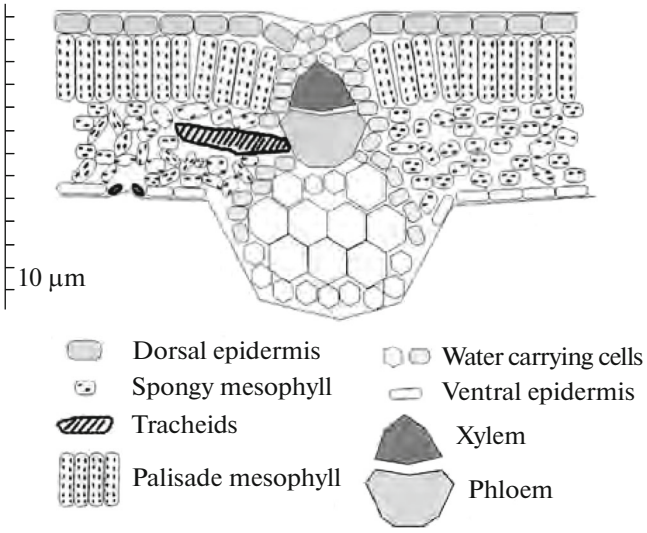

Fig. 5. Schematic representation of the cucumber green leaf anatomical section.

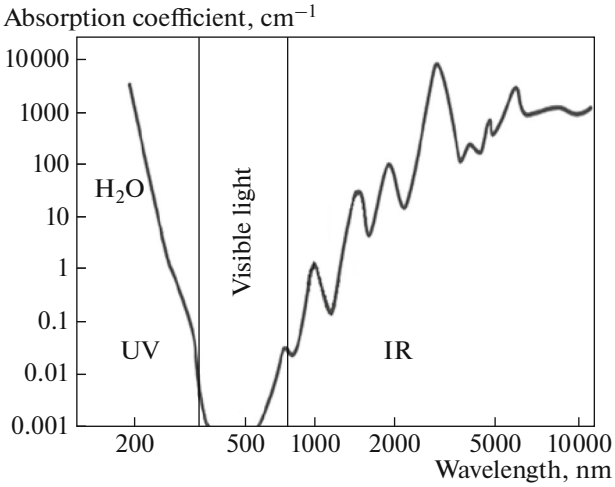

Fig. 6. Water absorption spectra at different wavelength ranges.

$$h^2 \approx \chi t, \quad (4)$$

where χ is coefficient of water molecules thermal diffusivity ($\chi \approx 1.5 \times 10^{-3}$ cm/s, under normal condition). In our study, given leaf thickness $h \approx 10^{-2}$ cm, the heating time $t \approx 0.1$ s.

In the absence of background light, we did not observe any response of the plant bioelectric potential to the infrared radiation in our experiment. In the presence of background radiation (with normally proceeding photosynthesis), infrared irradiation seems to cause local heating of water molecules within the zone of exposure of the green leaf and the ΔU response. When cucumber leaf was exposed to millimeter radio waves (Fig. 7) ($\lambda = 4$–8 mm, $\nu = 37.4$ GHz), bioelectric potential response was probably associated with the specificities of water absorption in the considered wavelength range [13, 14]. Leaf lamina local area exposure to millimeter EMR ($\lambda = 4$–8 mm, $\nu = 37.4$–74.8 GHz, and $I_\lambda = 0.2$ mW/cm^2) serves also as an example of such low-energy EMR action on the plant (depth of EMR penetration into living tissue, 0.3 mm [13]) when the useful effect (ΔU response) is achieved through the conversion of EMR energy into the energy of microheating of the water molecules in the solution (≤0.1°C), with the integral heating being insignificant. In this case, we may speak of the information effect of EMR of nonthermal intensity [4]. The effect of electromagnetic radiation on the plant seems to depend on the organism's state. If some vital function is several

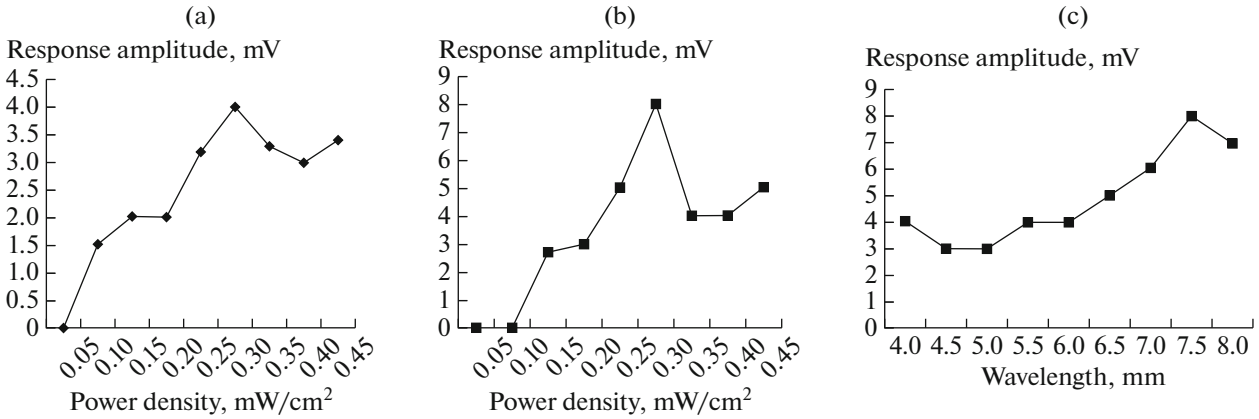

Fig. 7. Results of the analysis of local effects of low-intensity electromagnetic radiation with $\lambda = 4–8$ mm. (a, b) transfer characteristics at the wavelengths of 4 and 8 mm, respectively; (c) action spectrum for the amplitude of response to the exposure to local electromagnetic radiation with $\lambda = 4–8$ mm.

fold increased or decreased in the initial state compared to its standard values, then the exposure to radiation with the corresponding frequency may potentially restore the function's normal value by changing it in the opposite direction. The proposed technique allows one to take advantage of changing the size of local area exposed to EMR on the leaf surface and, within the whole plant, to carry out life-time diagnostics of the plant's state at a whole range of wavelengths, including those that are not associated with photosynthesis, and to identify the functionally important spectral regions that may be associated with improving the plant's vital functions.

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