Optical Properties of Human Jawbone and CERABONE® in the Terahertz Range

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The refractive indices n(ω) and absorption coefficients α(ω) of the human jawbone and bone substitute Cerabone® were determined in vitro by the terahertz time-domain spectroscopy in a wide frequency range from 0.2 to 2.5 THz. It is shown that the refractive index of the human jawbone changes between the values of 2.24 and 2.36, and Cerabone® between 2.4 and 2. 65. Depending on frequency the absorption coefficient of the human jawbone increases from 1.7 cm^{-1} to 178.5 cm^{-1}, showing several resonance absorption lines after 1.6 THz. The absorption coefficient of Cerabone® increases from zero to 80 cm^{-1}, and the resonance absorption occurs at 1.7 THz. The obtained results allowed us to determine the proximity of the physical properties of the Cerabone® with the natural bone matrix.

I. INTRODUCTION

Recent advances in medical research are aimed at solving the problems associated with increasing the duration and quality of human life. The developed technologies contribute to the creation of materials for artificial organs and tissues. Currently, the treatment, repair and replacement of various parts of the human body including skin, muscle, blood vessels, nerves, bone apply a variety of materials – metals, polymers, ceramics.

In action on the human body implants are classified as: 1) toxic (when the surrounding tissues mortify at the contact), these are most metals; 2) bio-inert (nontoxic but biologically inactive) - based ceramics Al_2O_3, ZrO_2; 3) bioactive (nontoxic, biologically active, fused with the bone tissue) - the type of biopolymer composites based on calcium phosphate. The widely applied bioactive materials are bio-glass and materials based on hydroxyapatite (HAP) [1]. The chemical formula for dense and porous ceramic hydroxyapatite is HAP- $Ca_{10}(PO_4)_6(OH)_2$ (Fig.1a). Bio-ceramic hydroxyapatite is completely absorbed by a living organism. A few years after implantation of hydroxyapatite, it should be completely dissolved and be replaced by a new bone, that is, the prosthesis should be replaced by the newly formed bone tissue. This is the case of the ideal type of artificial implant, since the problems of strength and biocompatibility do not arise at all. However, the negative effect of the implant is that the "resorption" - in the blood, lymph and tissue fluids pass large amounts of calcium (Ca) and phosphorus (P), and it is unknown how the Ca and P may affect the human body as a whole.

Cerabone® natural bovine bone grafting material (Fig.1b) of the German production is produced from bovine bone mineral phase, which has maximum similarity to human bone (chemical composition, porosity, and surface morphology). During the manufacturing process based on the high-temperature heating, all the organic components, proteins are removed, eliminating the potential for immunological reactions. Basic properties of Cerabone® are as follows: (a) slowly dissolves and quickly integrates with the bone; (b) shows a three-dimensional long-term stability of the implant; (c) does not lead to inflammatory reactions; (g) exhibits the optimal cell adhesion and the absorption of blood; (b) safe and sterile; (b) easy to handle.

The improvement of artificial materials will lead to the emergence of new alternatives and thus will contribute to the improvement of existing methods for treating many diseases. Artificial bone should correspond as precisely as possible the replaced part of the skeleton with the chemical and physical properties. Unfortunately, the level of modern technology does not allow to create a material that is entirely consistent with the natural bone matrix.

The most widespread practical use of terahertz (THz) waves (frequency range from 0.1 to 30 THz) is found in THz time-domain spectroscopy and in the THz imaging [2, 3]. It is known that the time of vibrational motion of biological molecules have the order of picoseconds, and therefore, the frequency of vibrations is in the terahertz frequency range. Intermolecular interactions are usually weaker than the intramolecular and only THz spectroscopy in the time domain is sensitive to resolve their spectrum in the THz range. THz wave is of non-invasive (since the photon energy of terahertz waves at several orders of magnitude is smaller than the photon energy of the X-ray wavelength) and non-contacting nature, which can penetrate into the non-conductive materials and to provide additional spectroscopic data for the accurate diagnosis and analysis of the material.

In the present work we used the method of the THz time domain spectroscopy (TDS), to research the proximity of the physical properties of the Cerabone® (bone transplantation material) with the natural bone matrix - the human jawbone - in the frequency range 0.2–2.5 THz.

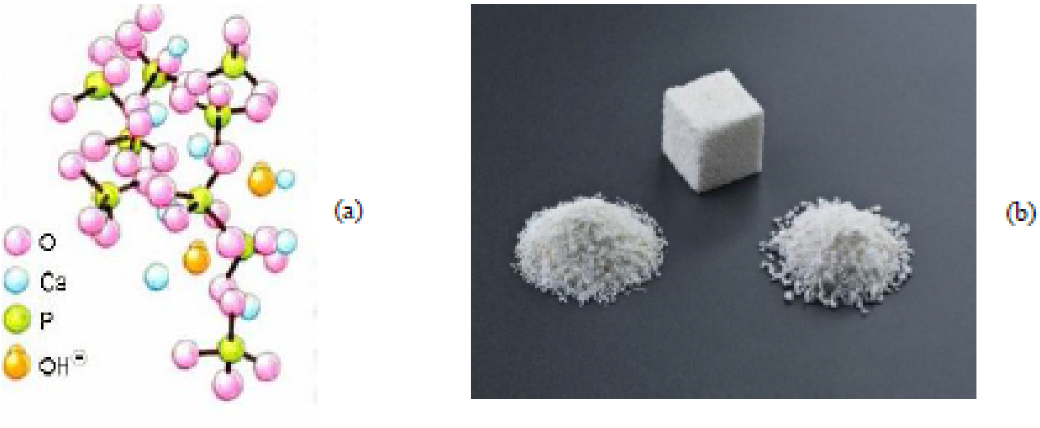


Fig.1. Detail of the crystal lattice the bioactive material – hydroxyapatite $Ca_{10}(PO_4)_6(OH)_2$ (a), and photo Cerabone®(b).

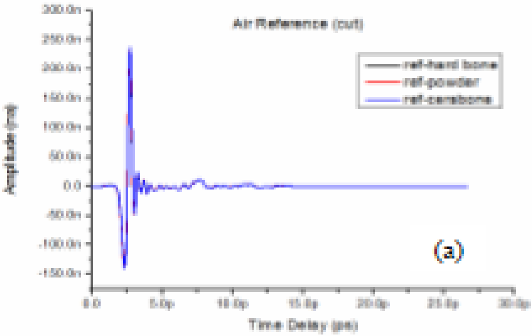
II. EXPERIMENTAL RESEARCH OF CERABONE® AND HUMAN JAWBONE BY THz SPECTROSCOPY METHOD

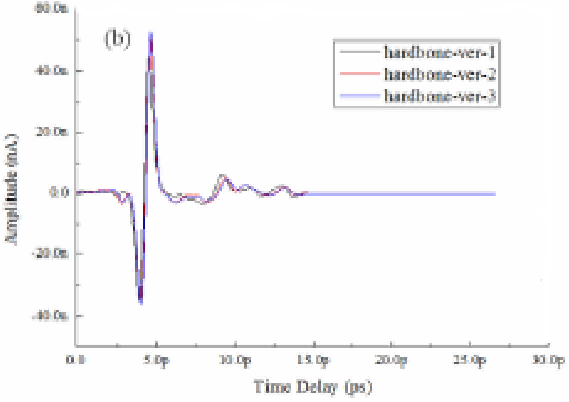
THz spectroscopy method in the time domain allows to register the temporary form of the THz pulse after its interaction with the sample, and to determine the complex spectrum of the material using the fast Fourier transform. However, to determine the physical properties of the sample, the absorption coefficient α (ω) and the refractive index n(ω) over the entire spectral THz frequency range, it is necessary to conduct two measurements. Temporary forms of the reference pulse $E_1(t)$, transmitted through free space - the air, and then the pulse $E_2(t)$ passed through the test materials (Fig. 2, Fig.3) were measured.

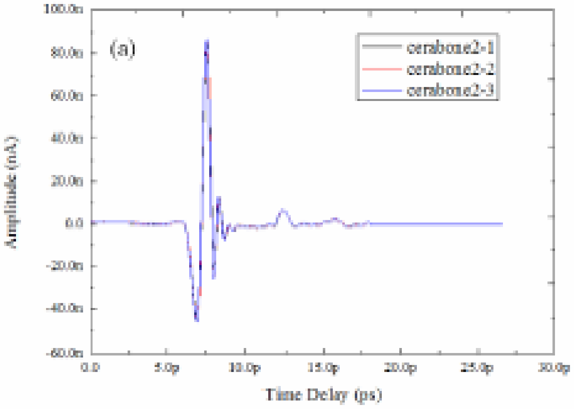
To measure optical properties of Cerabone® and human jawbone a THz time-domain spectrometer was applied. The fiber femtosecond laser (Fx-100, IMRA) with a pulse width of 113 fs, with a central wavelength of 800 nm and a repetition rate of 75 MHz and a power of 120 mW was used as a laser source for pumping and detecting terahertz pulses. Radiation from the fiber femtosecond laser was divided into two parts by a polarizing beam splitter: the pump and probe beams. The pump beam after the delay line was focused on GaAs photoconductive antenna. Antenna was used as a source of subpicosecond pulses of THz radiation. THz radiation, using parabolic mirrors, was collected and focused on the test material. THz radiation passed through the test material was directed to the ZnTe crystal. The coherent detection of temporal shape of the electric field of THz pulses was performed using cell, which consisted of electro-optical ZnTe crystal orientation (110), 1 mm thick, $\lambda/_4$ plate and a polarizer, a Wollaston prism, separating the s- and p-polarization. The detector was controlled with a probing beam, the response of which was proportional to the amplitude and sign of the electric field of the THz pulse. Amplitude $\left|\tilde{T}(\omega,n)\right| = \left|\frac{\tilde{E}_2(\omega)}{\tilde{E}_1(\omega)}\right|$ and phase $\Phi(\omega) = \Phi_2(\omega) - \Phi_1(\omega)$ of complex transfer function of the sample $\tilde{T}(\omega)$ obtained experimentally from the relationship of Fourier transform of the measured terahertz fields $E_1(t)$ and $E_2(t)$ and $\Phi_2(\omega)$, $\Phi_1(\omega)$ [4]. The refractive index and the absolute absorption coefficient of the substance in a frequency range from 0.2 to 2.5 THz are obtained from the expressions

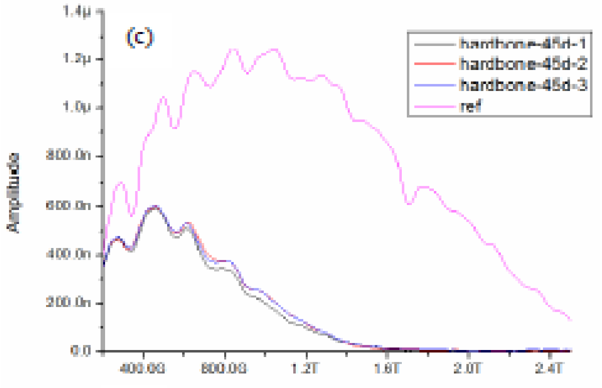
$$n(\omega) \cong 1 + \frac{c}{\omega d}\Phi(\omega), \qquad \alpha(\omega) = -\frac{2}{d}\ln\left[\left|T(\omega)\right|\frac{[1+n(\omega)]^2}{4n(\omega)}\right]$$

The temporal waveforms of THz pulses are shown in Fig. 2 (a) as the references. The Fig. 2 (b) and Fig. 3 (a) are the THz pulses passing through the jawbone and Cerebone, respectively. The THz waveform in frequency is shown in Fig. 2(c) and Fig. 3(b). The absolute absorption and the refractive index of the jawbone and the Cerebone are obtained and shown in Fig. 2(d,e) and 3(c.d), respectinvely.

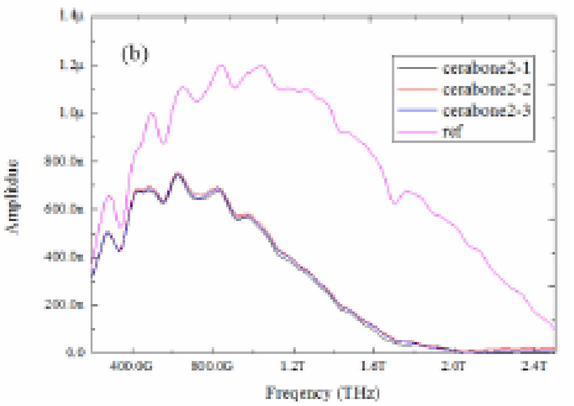








(d)



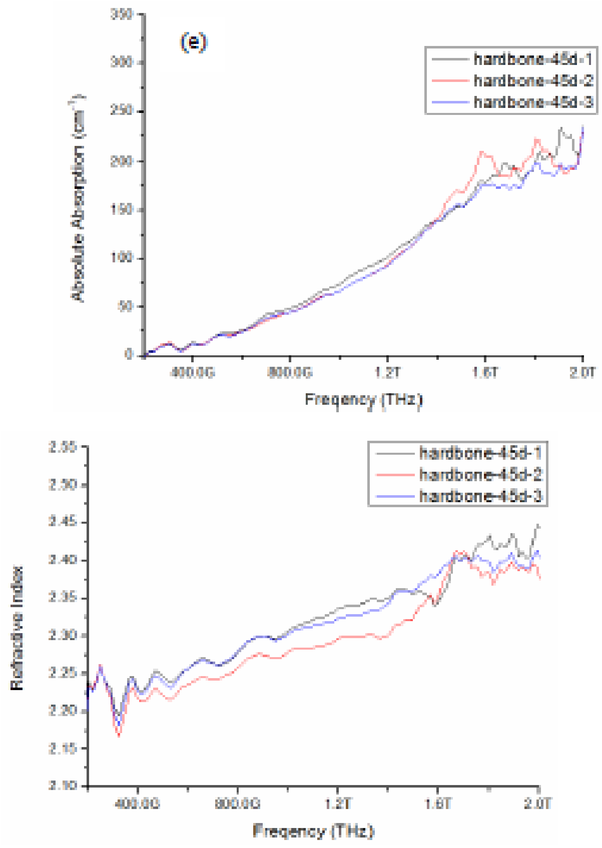


Fig.2. Temporal waveforms of THz pulses transmitted through (a) the air and (b) jawbone, and its amplitude spectra after a FFT (c); absorption coefficient (d) and refractive index human jawbone (e).

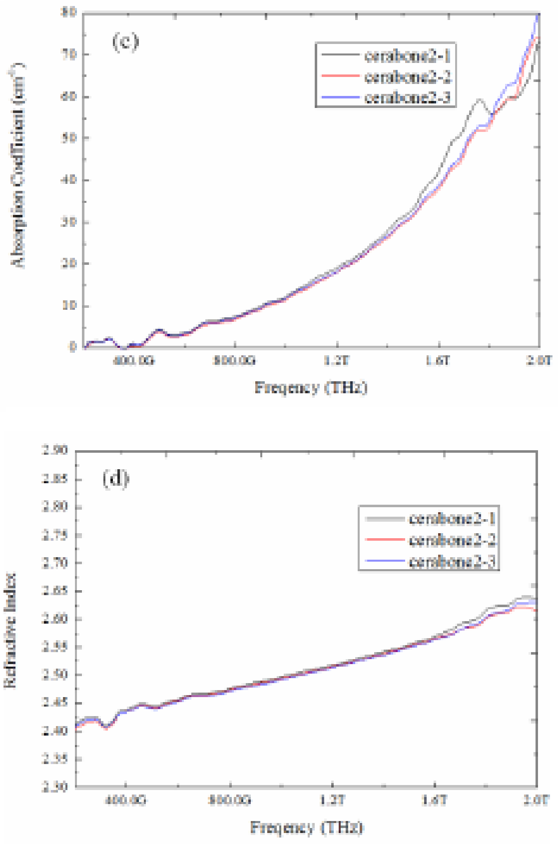


Fig.3. Temporal waveform of the THz pulse transmitted through Cerabone® (a), and its spectrum after a Fast Fourier Transform (b), the absorption coefficient (c) and refractive index Cerabone® (d).

III. CONCLUSION

It is shown that the refractive index of the human jawbone changes in a wide frequency range from 0.2 to 2.5 THz between the values of 2.24 and 2.36, and Cerabone® between 2.4 and 2.65. The absorption coefficient of the human jawbone depending on frequency increases from 1.7 cm^{-1} to 210 cm^{-1} showing several resonance absorption lines after 1.6 THz. The absorption coefficient of Cerabone® increases to 80 cm^{-1}, and the resonance absorption occurs at 1.7 THz. This is the first representation of the frequency-dependent refractive index and absorption coefficient of jawbone and Cerabone®.

IV. REFERENCES

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