Impact of Scattering in Quasi-Ordered Structures on THz Imaging

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Terahertz science and technologies demonstrate a wide range of imaging applications in physics, biology, medicine, industry, etc. [1-7]. Scattering has one of the most essential impacts on imaging quality [1-4]. The mostly applied methods for estimation of scattering parameters and imaging losses are analytical diffuse and small-angle approximation of radiative transfer theory, Monte Carlo (MC), discrete ordinates, and T-matrix numerical methods, finite-difference time-domain method (FDTD), and experimental methods, e.g., using integrating sphere [8-11].

Nevertheless, one should pay attention to local ordering of scatterers in the considered media, since it could lead to significant changes of scattering signal [1-2].

We have studied the impact of quasi-ordered scattering materials on THz imaging, using a combined computational approach, based on computational electrodynamics, radiative scattering theory and Monte Carlo simulations. We assumed that the scattering effects could be accounted for by finding a single scattering phase function for clusters of particles, which form quasi-ordered scattering material, and using it in MC simulation of scattering, considering the whole medium as a random structure of such clusters. We applied FDTD technique for solution of Maxwell's equations in the near-field (NF) zone with the NF to far-field (FF) transformation based on the calculation of the diffraction integral. It helped us to determine scattering phase function and include it in MC numerical simulations in order to find scattered radiance L(θ) and the corresponding imaging modulation transfer functions (MTF).

The described approach was used to estimate an impact of quasi-ordered media [7,12-13].

We estimated imaging MTF in case of clothes scattering material. The numerical simulations and experimental measurements were performed for the following system parameters: imaging frequency of the THz source (backward-wave oscillator) was 0.25 THz, distance between the imaging system and the bar-pattern test-object was 4 m; for the scattering materials with groups of four cylindrical particles with period 0.3 mm dielectric permittivity of a single particle of diameter 0.2 mm was 2.9; for the scattering materials with groups of seven cylindrical particles with period 1.34 mm dielectric permittivity of a single particle of diameter 1.34 mm was 1.6; the thickness of scattering layers was 0.7 mm in the first case, and 4 mm in the second. The experimental scheme and the results are demonstrated in Fig. 1.

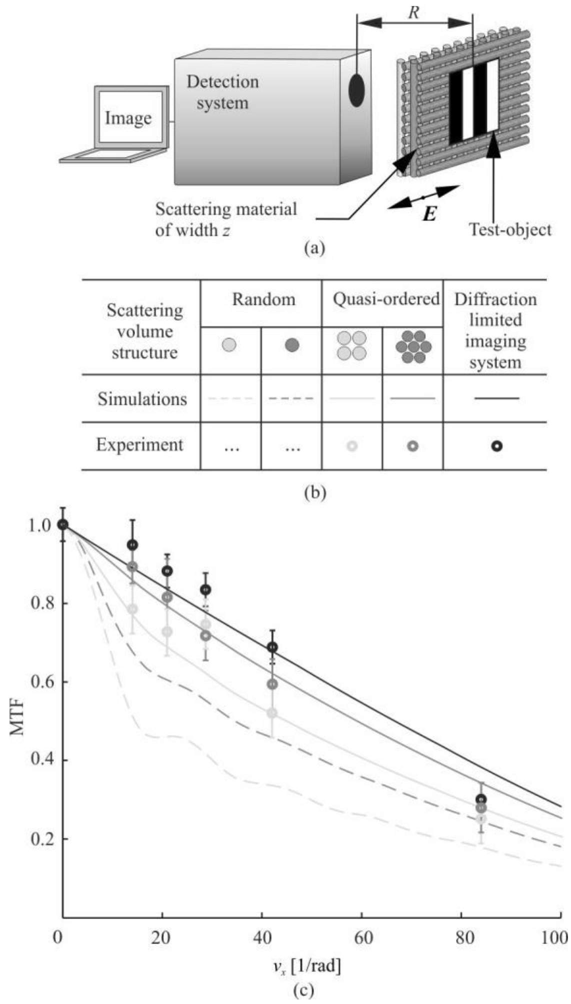

Fig. 1. (a) An experimental scheme for finding MTF using a set of test-objects; (c) and (d) experimental and numerical results, where black color corresponds to measurement without scattering layer.

We also calculated the MTF in case of random distribution of particles in the scattering materials and in case of quasi-ordering.

According to the numerical simulations [7], it is possible to determine particular combination of wavelength, particle system parameters, local period and dielectric parameters, for which imaging contrast of a remote object (and the corresponding MTF) would increase. On the contrary, almost opaque media could be achieved.

The demonstrated analysis could be effectively used for finding optimal wavelengths for imaging applications.

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Generation of vortex beamlet lattices via diffraction of Bessel vortex beams on 2D hole arrays: analytical and numerical calculations and comparison with experiments

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The Novosibirsk Free Electron Laser (NovoFEL) [1] is a source of monochromatic and frequency-tunable terahertz radiation of high average power. At the entrance to a workstation, the beam of the laser is a Gaussian beam within good accuracy. However, it is necessary to transform the beam mode composition (focusing radiation with a defined intensity distribution). Diffraction optical elements (DOEs) were shown to excel refractive elements in the manipulation of high-power laser radiation in the experiments at the NovoFEL; DOEs can be considered as amplitude-phase masks (APMs) within the framework of physical optics [2-3]. Objects in some experiments, such as terahertz holography [4] and beam diffraction of complex mode composition on lattices [5], are also APMs.

For the experiments, a program in the Matlab environment with an easy-to-use interface has been written to simulate radiation transmission through optical systems consisting of a sequence of amplitude-phase elements. The calculations were performed within the framework of the scalar theory of diffraction. The software calculates the Rayleigh-Sommerfeld integral in the Fresnel approximation [6] using a combination of the impulse response method and the transfer function method, which ensures the solution correctness in the entire Fresnel diffraction region (see eq. (1)) [7].

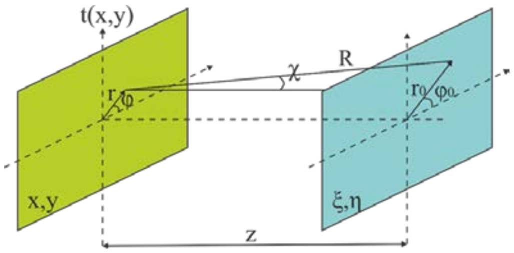

Fig. 1. Calculation geometry. The left rectangular is the amplitude-phase mask plane and the right rectangular is the observation plane.

$$E(z,\xi,\eta)=\frac{1}{i\lambda}\begin{cases}F^{-1}\left\{F\left[u(x,y)\right]F\left[h_f(z,x,y)\right]\right\} & z\geq\dfrac{L\cdot\Delta x}{\lambda}\\ F^{-1}\left\{F\left[u(x,y)\right]\cdot H_f\right\} & z\leq\dfrac{L\cdot\Delta x}{\lambda}\end{cases}\quad(1)$$

where

$$h_f(z,x-\xi,y-\eta)=\frac{\exp(ikz)}{z}\cdot\exp\left(ik\frac{(x-\xi)^2+(y-\eta)^2}{2z}\right)$$

is the impulse response function and its Fourier image is $H_f(\nu_x,\nu_y)=i\lambda\cdot\exp(ikz)\cdot\exp\left[i\pi\lambda z\left(\nu_x^2+\nu_y^2\right)\right]$, which is a transfer function, $u(x,y)=E(0,x,y)\cdot t(x,y)$, F is the Fourier transformation, L is the size of grid, and Δx is the grid spacing.

During a year, the program was widely applied to modeling of beam propagation in different optical systems used in experiments at the NovoFEL such as formation of beams of different mode compositions with DOEs (Hermite-Gaussian and Laguerre-Gaussian beams and Bessel beams with an orbital angular momentum), diffraction of beams on amplitude and phase gratings etc. In all cases, the results of experiments and modeling were in good agreement. Experiments on the diffraction of Bessel beam with an orbital angular momentum on periodic gratings (the quasi-Talbot effect) turned out to be the most interesting among these explorations. They were conducted for the first time.

We have investigated transmission of vortex Bessel beam formed by binary phase axicons through two-dimensional periodic gratings of round holes. It has been found that behind the grating, in the planes corresponding to the planes of self-images of the classical Talbot effect (see eq. (2)), a lattice of vortex ring beams appears, the topological charge of which corresponds to the charge of the incident beam:

$$L_T=\frac{2p^2}{\lambda}\left(N-1+\frac{n}{m}\right)=Z_T\cdot\left(N-1+\frac{n}{m}\right),\qquad(2)$$

where N and $n<m$ are integers and p is the period of the grating.

After the experiments and numerical calculations, it became clear to us that the diffraction patterns observed in the Talbot planes had a beautiful geometry, which suggested existence of a beautiful analytical solution for their description. The problem was also solved analytically. The analytical expression obtained so far for the main Talbot plane is as follows:

$$E(\boldsymbol{x},z_N)=\frac{2\pi^2R^2}{\kappa}\sum_{m,n}\iint\frac{d^2k_\perp}{(2\pi)^2}\exp\left(i\boldsymbol{k}_\perp\cdot\boldsymbol{x}+i\ell\varphi_k\right)\cdot i^{-\ell}\times\delta\left(k_\perp-\kappa\right)\cdot\delta\left(\boldsymbol{x}-\boldsymbol{p}_{mn}-\frac{k_\perp z_N}{k}\right),\quad(3)$$

where $\boldsymbol{x}=\{x,y\}$, $\boldsymbol{p}_{mn}=\{mp,np\}$, R is the hole radius, k is the wavenumber, $z_N=Z_T\cdot N$, ℓ is the orbital angular momentum, and κ is the radial wavenumber.

Hence, it is clear that the image has a form of circles with centers at the points $\boldsymbol{x}=\boldsymbol{p}_{mn}$ and radii $a_N=\dfrac{\kappa\cdot z_N}{k}=\kappa\dfrac{p^2}{\pi}N$. The results of the analytical studies of the problem in more detail will be published elsewhere.

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Diagnostic value of microwave imaging of dielectric tissues properties in patients with Dupuytren disease

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Dupuytren's disease - a pathology of connective tissue, leading to wrinkling of the Palmar aponeurosis and progressive deformation of the fingers, is a fairly common pathology. For example, in Germany about 1.9 million people suffer from Dupuytren's contracture, but in the U.S. 3% of the population has this pathology [1, 2]. In recent years, there has been a tendency to increase the frequency of this pathology. According to the Department of hand surgery in Moscow scientific research Institute of emergency care named after N.V. Sklifosovsky, the number of patients operated for Dupuytren's contracture, is about 20% of the total number of planned operations [3].

To date, the overwhelming majority of the authors consider surgical treatment of Dupuytren's disease to be the most radiacal and effective. Partial or total fasciectomy is considered as a gold standard of surgical treatment in most cases [4, 5]. However, despite the introduction of new technologies of surgical intervention, unsatisfactory treatment outcomes reach 30%, and as the contracture progresses, the results of operations deteriorate [6]. The number of relapses after surgical treatment remains high, which ranging from 26 to 80%, according to some foreign authors [2, 4].

In our opinion, one of the reasons for the poor results of surgical treatment of Dupuytren's contracture is the complexity of determining the boundaries of the lesion of Palmar aponeurosis, which determines the choice of rational surgical tactics. As a rule, these boundaries are determined visually by the surgeon directly during the operation. I. Zh. Osmonaliev et al. (2013) suggest using magnetic resonance imaging for this purpose without using the mode with suppression of the signal from adipose tissue [7]. According to the authors, the use of MRI allows more accurate visualization of the boundaries of the affected aponeurosis in patients with I-III degree of Dupuytren's contracture, and, respectively, to select a minimally invasive access and minimal traumatical method of excision of the affected tissues.

We believe that in modern economic conditions, the use of MRI to assess lesions in Dupuytren's contracture is justified due to the high cost of the survey. That is why the search for other objective methods of diagnosis of the area and boundaries of pathologically altered aponeurosis is very relevant and promising.

In this regard, in recent decades, studies have been conducted on the microwave diagnosis of the structure of biological tissues [8-11]. The method of resonance near-field microwave tomography, which allows to study the spatial distribution of the dielectric permeability and conductivity of living tissues with a resolution significantly lower than the wavelength λ, has broad prospects among non-invasive diagnostic methods. Unlike passive microwave sensing, near-field tomography requires a much smaller sensor (probe), and the resolution increases significantly [8-14].

The advantages of the method are confirmed by experimental studies. Thus, the assessment of skin electrodynamic properties in dermatoses indicated the diagnostic value of their study in microbial eczema and keratodermia [8, 9, 15]. Resonance near-field microwave diagnosis is potentially informative for the diagnosis of organ cancer (superficial or subepithelial localization), in determining the boundaries of the pathological focus [8, 15]. A.V. Arsenyev et al. (2011) investigated the level of functional activity of tissue growth zone in children, on the basis of which the presence of sexual characteristics of this process was established [16]. In addition, near-field microwave sensing makes it possible to quickly diagnose organ viability during transplantation [8]. Thus, with the help of near-field microwave sensing of the tissue structure, it is possible to obtain information about the biological object and the processes occurring in it [17-19]. At the same time, there is no data in the literature on the possibility of using microwave imaging in Dupuytren's contracture.

The aim of this study was to estimate the dielectric properties of fibrously altered tissues in patients with Dupuytren's contracture.

Material and methods

The study included 12 patients (male, mean age 53.9 years) with Dupuytren contracture of II-III degree according to R. Tubiana (1968), treated at the University hospital of the "PRMU" of Ministry of health of Russia. All patients were examined before surgical intervention.

The dielectric properties of the skin and subcutaneous structures were studied in different areas of the hand, including in the area of fibrous (altered and healthy tissues).

The dielectric characteristics of the biological tissues was evaluated by the method of resonance near-field microwave sensing. Near-field microwave sensing of tissues was performed using a special installation created at the Institute of Applied Physics of the Russian Academy of Sciences (Nizhny Novgorod), as well as specialized software that interfaces the installation with a PC and allows to calculate the effective part of the dielectric permittivity [8, 9]. This indicator was recorded and evaluated at depths of 2 to 5 mm using a series of probes.

The results were processed using the program Statistica 6.0.

The results and discussion

The study allowed to establish that in the field of healthy tissues the microwave profile of the skin corresponds to the physiological pattern formed by us on the basis of examination of healthy volunteers [10, 15]. It is revealed that the real part of the permittivity in the intact part of the Palmar aponeurosis increases monotonically with increasing sensing depth (Fig. 1).

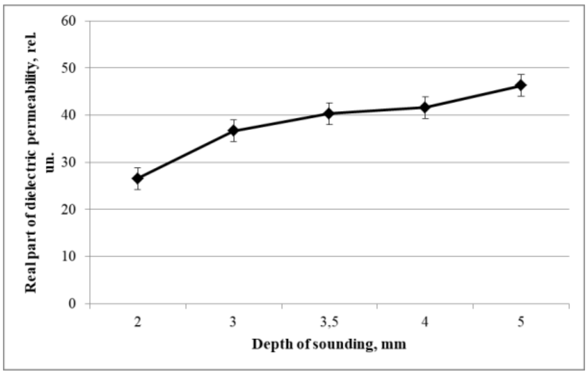

Fig. 1. Dielectric profile of intact area of the hand in patients with Dupuytren contracture

Then the microwave profiles of sub-skin tissues were compared at points 1 and 3 corresponding to intact and fibrous-modified areas (Fig. 2). It is established that fibrosis-changed tissues su-substantially differ in their dielectric parameters from the healthy, which leads to the significant transformation of the microwave profile in the area of measurement and control hardware of the Palmar aponeurosis are relatively to physiological pattern. The data obtained allow the conclusion that fibrosis in the tissue absorb microwave radiation, has extremely low values of the real part of dielectric permittivity. Such shifts are recorded at a depth of 2-3.5 mm, which approximately corresponds to the depth of pathologically altered tissues under Dupuytren's contracture [20, 21]. It should be emphasized that the sounding of deeper layers (4-5 m) does not detect significant deviations from the norm. This indicates the presence of intact morphological structures.

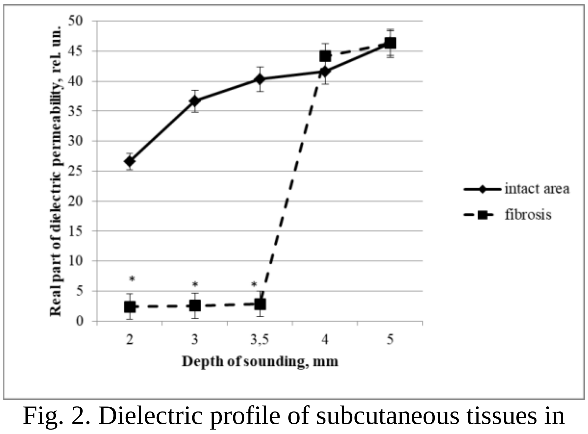

Fig. 2. Dielectric profile of subcutaneous tissues in intact and transformed area of the hand in patients with Dupuytren's contracture ("*" – statistical differences to intact area $p<0.05$)

Conclusion

The conducted studies allowed to form a microwave pattern of the actual part of the dielectric permeability in patients with Dupuytren's contracture in the area of healthy and fibrous-changed tissues, and a sharp decrease in this parameter was found in the zone of the pathological process at depths up to 3.5 mm.at the same time, in the area of healthy tissues, there were no features of dielectric properties compared with healthy volunteers. It is also shown that the fibrous-modified Palmar aponeurosis has a fairly uniform microwave structure, which allows us to count on the possibility of accurate visualization of its boundaries. This is crucial for the planning of surgery in patients with Dupuytren's contract.

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Comparative study of dielectric properties of the skin of human and laboratory animals

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Work on the study of electrical conductivity of tissues, including skin, first appeared about 40 years ago [12]. Since that time, the number of publications, despite their interesting results, is relatively small [7-11].

The skin, despite the superficial localization, being a difficult object for visualization, for a long time remained only the subject of histological examination [2, 5, 7, 9-12]. Existing methods (for example, optical coherence tomography, IR thermography, etc.) allow to study only the surface and the nearest surface structures of the skin [2, 5, 6, 10].

A more extensive methodological apparatus is available for monitoring skin vessels [5], while the deep structure of the latter is difficult for non-invasive study [1, 2, 5]. In this regard, the work on profiling of the skin by its dielectric properties attracts attention [1, 3, 4, 6, 8], but this information is isolated and jerky. This is, in particular, due to the lack of available diagnostic tools for assessing the dielectric characteristics of the skin and other tissues [3, 4].

In this regard, the aim of the study was to study the possibilities of near-field microwave sensing in assessing the structure of human and rat skin.

Material and methods

The study, which included a single microwave sounding, was performed in 20 practically healthy people and 20 healthy mature male Wistar rats.

Near-field microwave sensing of tissues was performed using a special installation created in the Institute of Applied Physics of the RAS (Nizhny Novgorod), as well as specialized software that interfaces the installation with a PC and allows to calculate the real part of the dielectric permeability [3]. The dielectric characteristics of the skin were evaluated at depths of 2 to 5 mm using a series of probes.

Measurement in all examined people was performed on the forearm at a single point, and in animals – at one point, localized in the middle part of the back, on a pre-epilated surface.

The obtained data were processed in the program package Statistica 6.1.

Results and discussion

It was found that the real part of the dielectic permeability of human skin increases monotonously with increasing depth of sounding (Fig. 1), showing a tendency to increase by 1.74 times when comparing the parameter values obtained at depths of 2 and 5 mm ($p<0.05$).

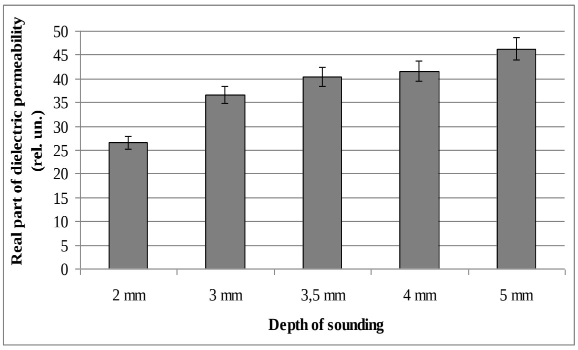

Fig. 1. The profile of dielectric permeability of the skin in healthy people (in rel. un.)

This is due to the fact that the value under consideration is cumulative, and each subsequent value includes the previous as well as the contribution made by tissues located from the previous to the current level of sensing. On the basis of the obtained data, a linear mathematical model of the change in the dielectrical permeability of the skin is constructed, which sufficiently describes its subsurface profile (determination coefficient - 0.94).

The linear regression equation, which allows to predict the value of dielectric permittivity at other sensing depths, is presented in the following form:

$$y = 6{,}4125 \bullet x + 15{,}844 \qquad (1)$$

Analysis of the dielectric properties of rat skin allowed to establish that the permeability of the latter is significantly, almost an order of magnitude lower than in humans, but the nature of the dependence of the considered parameter remains, demonstrating a monotonously increase in the value with a maximum at a depth of 5 mm (fig. 2).

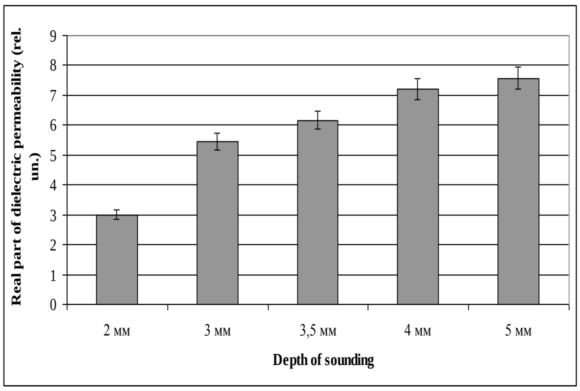

Fig. 2. The profile of dielectric permeability of the skin in healthy rats (in rel. un.)

At the same time, the level of the studied parameter at the minimum and maximum depths differs by 2.55 times ($p<0.01$), which is related to the assessment of deeper structures in rats during microwave profiling by a single date that performs sounding at a depth of 5 mm.

For the microwave profile of the skin of rats, we also formed the linear regression equation, as well as for humans, which fully reflects the experimentally obtained values of the dielectric permittivity (the determination coefficient is 0.91). This equation has the following form:

$$y = 1{,}55 \bullet x + 0{,}455 \quad (2)$$

Conclusion

The conducted studies allowed to establish a picture of the deep distribution of dielectrical permeability of the skin of healthy people and animals (Wistar rats), which can serve as a physiological microwave pattern for the study of subsurface tissues, including various layers of the skin and the nearest subcutaneous structures. It is shown that the real part of the dielectric permittivity at all the studied depths in humans is much higher than in rats, and monotonically increases with an increase in the sensing depth in the range from 2 to 5 mm in increments of 0.5 to 1 mm.

The stability of this pattern precedes the possibility of using the method of microwave profiling of the skin in the assessment of its structure in normal and local changes (benign and malignant neoplasms, burns, etc.), and the obtained equations can serve as a guide for the subsequent study of the dielectric characteristics of human cover tissues and mature rats in different experiments.

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Microwave imaging of skin damage at experimental burns

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The ubiquitous prevalence of thermal injury predetermines not only the search and testing of innovative technologies for the treatment of severely burned, but also the improvement of the diagnostic apparatus of combustiology [1, 2, 4]. Currently, the clinical assessment of the local status has the greatest importance for the considered contingent of victims, including the one associated with the use of a number of empirical algorithms to determine the spatial characteristics of the injury ("rule of nines", etc.) [1, 2]. On the other hand, in combustiology there is a significant number of diagnostic difficulties associated with the specification of the boundaries of burn injury, tissue viability in the near-wound zone, wound uniformity, etc. [1, 2, 4]. Verification of the depth of skin and subcutaneous structures lesions should be singled out as a separate item [1-4]. In order to solve this complex of problems, in addition to the empirical approach prevailing in real clinical practice, the possibilities of thermal IR-imaging were studied [1, 3, 6]. It is shown that this technology is informative in a number of situations, but it allows us to judge only the state of the skin surface and the nearest underlying structures. Modern variants of ultrasound examination, which have high informative value and resolving ability in other pathology, do not allow to achieve the necessary contrast [3] in relation to the thermal injury.

An additional complicating factor in tissue imaging in combustiology is the presence of a physical barrier between the sensor and the surface of the skin (temporary and permanent wound coatings), which is not possible to eliminate for diagnostic manipulations (for example, when using biopo-coatings containing matrix with stem cells).) [1-3]. This is an obstacle for most methods of investigation of subsurface structure and blood tissues, in particular, for ultrasound examination. Therefore, it is necessary to search and test fundamentally different technologies of the assessment of the deep characteristics of the burn wound and the near-wound zone [2-4].

In this aspect, the method of near-field resonance microwave profiling, which has recently appeared in biomedicine and is based on the study of the dielectrical properties of tissues (dielectric permeability and conductivity) is very interesting [5]. Previous studies have shown that this technology is high informative in dermatology, allowing how to carry out primary diagnostics and differential diagnostics of various skin diseases and to monitor the efficacy of treatment, predicting the occurrence of the patient in the remission phase [5]. At the same time in combustiology the considered method was not applied earlier.

The **purpose of this study** is to evaluate the diagnostic capabilities of near-field microwave sensing in the estimation of the deep structure of the skin in the norm and in experimental burn wounds.

Material and methods

The study was performed on 30 male rats of the Wistar line, divided into 2 equal groups. The first group of animals (n=15) was a control group (no manipulations were performed, except for a single microwave sounding). Rats in the second group (n=15) was simulated thermal contact burns on 20% body square percent with our methodology (Peretyagin S.P. et al., 2009) [6]. The dielectrical properties of burn wound tissues were studied immediately after the application of burn and on 1 day after it.

Near-field microwave sensing of tissues was performed using a special device created at the Institute of Applied Physics of the Russian Academy of Sciences (Nizhny Novgorod), as well as specialized software, matching the installation with a PC and allowing the calculation of the real part of the dielectic permeability [5]. Dielectric characteristics of the skin were assessed at depths of 2 to 5 mm using a series of probes. All animals were measured at one point, localized in the middle part of the back, on a pre-epilated surface.

The results were processed using the program Statistica 6.0.

The results and discussion

The conducted research allowed to establish that it is possible to carry out the analysis of dielectric properties of skin of rats by means of the studied hardware-software complex.

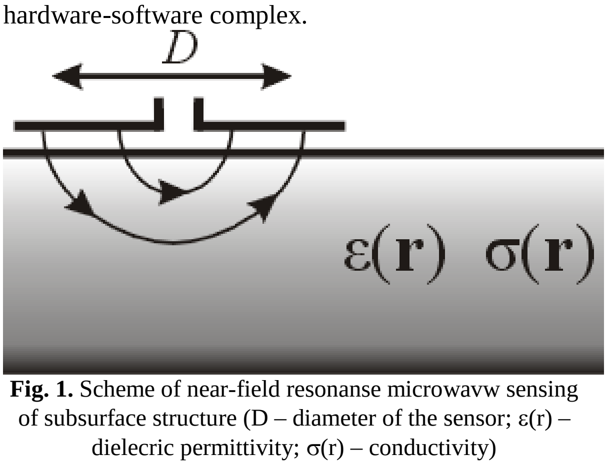

Fig. 1. Scheme of near-field resonanse microwavw sensing of subsurface structure (D – diameter of the sensor; ε(r) – dielecric permittivity; σ(r) – conductivity)

At the same time, it was possible to show that at the studied depths (2-5 mm) the level of dielectric conductivity of subsurface structures is at values less than 9 rel. un., monotonically increasing with increasing depth of sensing.

Given that each value is cumulative, i.e. includes the conductivity of the entire subsurface layer up to the specified depth (Fig. 1), the maximum level of the parameter is recorded at a distance of 5 mm from the surface of the skin. This is reflected in the character of the method of sounding as near-field (Fig. 1).

At the same time, the level of the studied parameter at the minimum and maximum depths differs by 2.55 times (p<0.01), which is associated with the assessment of deeper structures in rats during microwave profiling by one sensor performing sensing at a depth of 5 mm. This is due to the fact that each subsequent value of the dielectric conductivity includes the previous one in conjunction with the contribution made by tissues located from the previous to the current level of sensing [11, 19-21].

Based on the data obtained from intact rats, a linear mathematical model of changes in the dielectric permittivity of animal skin is constructed, which sufficiently describes its subsurface profile (determination coefficient – 0.91). The linear regression equation allows to predict the value of dielectric permittivity at other sensing depths. This model can be used to calculate the physiological level of dielectric conductivity of the subsurface structures of the skin of rats, used as a guide to identify its changes caused by various pathological processes.

The features of the deep structure of the dielectric properties of the skin and subcutaneous tissues in animals with modeled thermal injury (in the form of a thermal burn on the previously epilated surface of the back skin) were also studied. Evaluation of the dielectric permittivity of the subsurface tissues of the experimental burn wound was carried out by us immediately after the injury and on 1 day after its simulation. This allowed to form deep skin profiles by this parameter in the dynamics of the experiment and in comparison with intact biological tissue (Fig. 2).

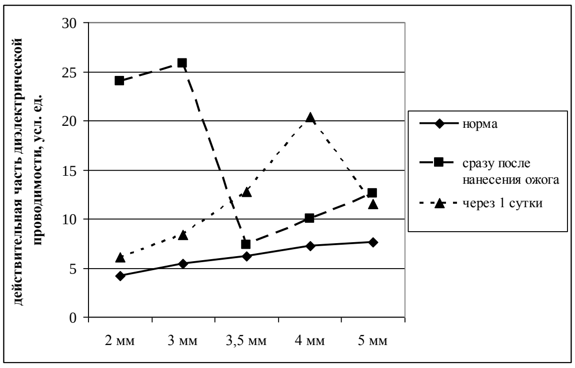

Fig. 2. The profile of dielectric permittivity of rats skin an subcutaneous tissues in normal conditions and after the burn

It was found that the dielectric properties of the burn wound differ significantly from the intact cover tissue. These shifts are characterized by an increase in the real part of the dielectric permittivity of the medium at both observation points. Thus, immediately after the application of thermal trauma, the greatest changes occur in the nearest subsurface layers of the skin (2-3 mm.), in which the figure under consideration repeatedly increases relative to intact rats (7.46 and 9.47 times at the depths of sensing 2 and 3 mm; p<0.05 for both cases), amounting to about 24.0 and 25.8 units, respectively. This may be due to the rapid intensive local heating of the tissues at a shallow depth immediately after exposure, whereas this effect has not yet spread to the deeper layers.

In 1 day after the burn the depth profile of the dielectric conductivity of the skin was significantly transformed (Fig. 3). During this period, there is a deepening of the lesion of subsurface structures, which is accompanied by a decrease in the level of the studied parameter at minimum depths (2-3 mm.) with its increase relative to the intact skin at a distance of 3.5-5 mm below the skin surface (p<0.05 for all cases). At the same time, the maximum dielectric conductivity was recorded at a depth of 4 mm, which in our experiments corresponded to the zone of greatest damage. This indicates a partial cooling of the surface layers of the skin with simultaneous overheating of more proximally lying and, consequently, a shift in the focus of damage to the deeper layers. The presented data indicate the possibility of monitoring the depth of thermal tissue damage, including creating an experimental basis for testing the processes of deepening burn in the post-traumatic period.

Conclusion

The studies have shown that the burn wound tissue shows a higher level of the real part of the dielectric permittivity in comparison with intact skin, and these changes have a temporal dynamics. So, immediately after the burn, the parameter change prevails in the surface layers of biological tissue, and after one day – in the deeper layers.

The stability of this pattern determines the possibility of using the method of microwave profiling of the skin in the assessment of its structure in normal and local changes (benign and malignant tumors, burns, etc.), and the equations can serve as a guide for the subsequent study of the dielectric characteristics of the cover tissues of mature Wistar rats in diverse experiments.

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Subsurface diagnostics of quasi-one-dimensional inhomogeneities using the method of near-field microwave sounding

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Potentialities of the near-field microwave sounding are studied for the case of model media with spatially localized inhomogeneities.

The method of resonance near-field sounding [1-3] is used successfully to study electrodynamic properties of various substances in the microwave range. Depending on the operating frequency, either oscillatory circuits with lumped parameters or distributed resonance systems can be used as measurement sensors. When a sample is introduced into the region occupied by the quasi-static field of a sensor, its resonance frequency and the Q-factor change. These variations can be used to judge about the electric and magnetic properties of the studied object. Using the sensors with different sounding depths, one can study the internal structure of the object without disrupting its integrity.

The near-field measuring system, which we use for diagnostics of inhomogeneous media, was a microwave resonator in the form of a section of a loop line closed on one end. A measuring capacity at the other end of this section is made up by two parallel wires with the radius *r*=0.5 mm, the length d_m=4 cm, and the varying distance *d* between the wires. Magnetic coupling loops were used to excite the resonator and receive its responsse. In this case, the maximum sounding depth was close to *d*. Eight sensors with sounding depths ranging from 5 mm to 25 mm were used to study the internal structure of the media. The eigen frequencies f_0 of the measuring systems were about 550 MHz, and their *Q*-factors, about 150.

The relationship between the resonant frequency *f* of the sensor and the parameters of the inhomogeneous medium is expressed as follows

$$\frac{f-f_0}{f_0}=\frac{d}{l}\left(1-\varepsilon_{\text{int}}\frac{\rho_1}{\rho_2}\right) \qquad (1)$$

where ε_{int} - the integral permittivity of the inhomogeneous medium, ρ_1 and ρ_2 - wave resistances of two-wire lines corresponding to the resonator and the measuring capacitance, l - the length of the resonator. In the derivation of the expression (1) it was assumed that the electrical length of the measuring part is significantly less than the wavelength, $d_m \ll c/(f_0\varepsilon_{\text{int}})$ (*c* – the speed of light in vacuum). In the case of planar media, using the image method, you can obtain the following expression for ε_{int}.

$$\varepsilon_{\text{int}}=(\varepsilon_1+1)\left(2+\left(\frac{2\varepsilon_1}{\varepsilon_1+1}\right)\left(\frac{\varepsilon_1-\varepsilon_2}{\varepsilon_1+\varepsilon_2}\right)\frac{\ln\left(\frac{d^2+(2h)^2}{r^2+(2h)^2}\right)}{\ln\left(\frac{d}{r}\right)}\right)^{-1} \qquad (2)$$

h - depth of inhomogeneity, ε_1 and ε_2 -dielectric permeability of the medium and inhomogeneity, respectively.

The medium studied in the experiments, in which the method of near-field microwave sounding was tested, was organic glass having the dielectric permittivity ε_1=3.5 with the rectangular inclusions of glass having the dielectric permittivity ε_2=7.8, which were situated at the depths h=4 and 5.5 mm. The length and thickness of the inhomogeneity were equal to L_n=10.5 cm and h_n=7 cm, respectively.

To spot the inhomogeneities, a probe with a sounding depth of 10 mm moved parallel to the flat surface of the organic glass. The value of the shift of the resonance frequency Δf was registered depending on the position *x* of the sensor (see Fig.1).

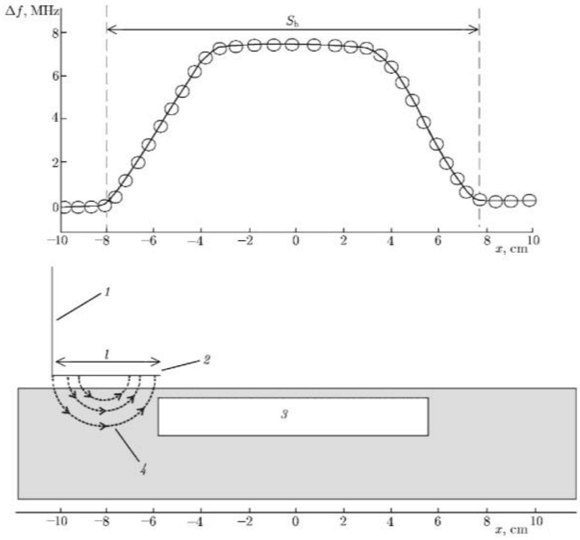

Fig. 1. Shift of the resonance frequency Δf of the sensor with a sounding depth of 10 mm as a function of the probe coordinate x for the case of scanning along the plane surface of the medium with a rectangular inhomogeneity.

The length of inhomogeneities is equal to the difference between the length s of the "swell" in the plot of the resonance frequency and the length d of the wires of the measuring capacity.

Further, the medium was studied using sensors with different sounding depths. The resonance frequency of the measuring systems was registered as the systems contacted the surface of the medium near the center of the inhomogeneity. Then, the dielectric permittivity ε_{ex} of the medium was determined for each probe using Eq. (1).

$$F(\varepsilon_1,\varepsilon_2,h)=\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\varepsilon^{ex}(d_i)-\varepsilon_{\text{int}}(\varepsilon_1,\varepsilon_2,h,d_i)\right)^2} \qquad (3)$$

To measure the medium parameters, we minimized function (3) being the r.m.s. deviation between $\varepsilon_{int}(\varepsilon_1, \varepsilon_2, h, d)$ for the plane-layered medium and the experimentally found values of the dielectric permittivity ε_{ex}. Table shows the actual and experimental values of the electrodynamic and geometric parameters of the studied media.

This paper deals with testing of the method of the near-field microwave sounding. The algorithm of solving of the inverse problem is presented, and the geometric and electrodynamic parameters of rectangular inhomogeneities are determined with good accuracy.

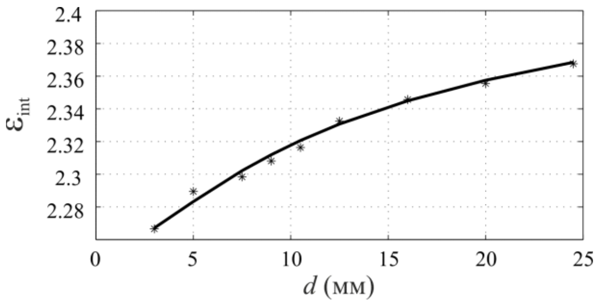

Fig. 2. Integral dielectric permittivity $\varepsilon_{\rm int}$ as a function of the distance *d* between the wires of the sensor measuring head in the case of studying an inhomogeneity in the form of a rectangular parallelepiped. The asterisks mark the experimental data, and the solid curve represents the theoretical dependence that corresponds to Eq. (2) for the found values of ε_1, ε_2 and h.

Model media 1	ε_1	ε_2	*h*	L_n
Experiment	3.5	7.3	5.0	11.4
Real value	3.5	7.8	5.5	10.5
Model media 2	ε_1	ε_2	*h*	L_n
Experiment	3.5	7.6	3.6	11.4
Real value	3.5	7.8	4.0	10.5

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Investigation of electrodynamics parameters of biological tissues

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Pathological and physiological processes in living tissues are usually accompanied by variation of their electrodynamic parameters; hence study of dielectric permittivity and conductivity of bio-objects is of considerable interest for various medical applications.

Diagnostics of skin pathologies without using the hystomorphologic method is required in dermatology. Tissue sampling (biopsy) refers to minor operations and is often undesirable for patients with abnormality in carbohydrate metabolism, vascular pathology, and eruption on unclothed parts of the body (face, neck, and hands).

The estimation of viability of organs in vivo in the case of acute pathology and organs conserved for their further transplantation is necessary in surgery. The processes of tissue ischemia and reperfusion complications are the result of violation of the fine cellular mechanisms, diagnostics of which cannot be carried out by the known diagnostic techniques (X-ray, ultrasound). These processes can be recognized only by means of biopsy with further optical or electron microscopic analysis; this procedure is time-consuming, whereas a clinician does not have much time at his disposal.

The aim of the study is to consider the opportunities of resonance near-field microwave sounding for estimation of viability of parenchymal organs in critical states, determination of pathologic processes, differential diagnostics of various dermatoses, and control of medical maintenance.

The method of resonance near-field microwave probing can be explained as follows. The area of a medium located in the near field of a probing electrically small antenna affects its impedance. This feature enables one to provide high spatial resolution. If the antenna is connected to the resonance system as a load, the resonance frequency shift and the Q-factor variation can be used to estimate the electromagnetic parameters of the medium and then the state of the examined object.

Diagnostic probes for passive measurements of the electrodynamic features of parenchymal organs and sensors for investigation of skin of dermatologic patients have been developed. A high-Q microwave resonator placed on a segment of the coaxial line is employed as a resonance system. The eigen frequencies of the sensors are $\omega_0 \sim 2\pi \cdot 800$ MHz and the Q-factor is Q_0 ~150. The spatial resolution and the sensitivity are determined by the design and sizes of the electrically small antenna.

If Z_0 is the internal impedance of the antenna, Z_{medium} is the impedance of the antenna contacting with the medium, and $Z_{medium} < \rho$ (ρ is the wave resistance of the coaxial resonator), according to [1] one can obtain the equation of the resonance curve $U_{res}(\omega)$ of the sensor

$$U_{res}(\omega) = U_0 \left[16 Q_0^2 \left(\frac{\omega - \omega_0}{\omega_0} + \frac{1}{\pi\rho} \mathrm{Im}(\delta Z_x) \right)^2 + \right.$$

$$\left. + \left(1 + \frac{4}{\pi} \frac{Q_0}{\rho} \mathrm{Re}(\delta Z_x) \right)^2 \right]^{-\frac{1}{2}}$$

$\delta Z_x = Z_0 - Z_{medium}$, U_0 is the signal amplitude in the resonance curve maximum.

From the equation $U_{res}(\omega)$ one can easily obtain the relation between the resonance characteristics of the sensor and the impedance features of the electrically small antenna

$$\omega_{res} - \omega_0 = -\frac{1}{\pi} \frac{\omega_0}{\rho} \mathrm{Im}(\delta Z_x)$$

$$\max(U_{res}) = U_0 \left(1 + \frac{4}{\pi} \frac{Q_0}{\rho} \mathrm{Re}(\delta Z_x) \right)^{-1}$$

Electrodynamic characteristics of skin of 32 cases of psoriasis, 10 cases of atopic dermatitis, and 13 cases of lichen acuminatus (LA) were studied at the Research Institute of Dermatology and Venereology (the city of Nizhny Novgorod).

It is stated that the dielectric permittivity and conductivity of skin of dermatologic patients (cases of psoriasis, atopic dermatosis, and lichen acuminatus) are lower than those of healthy skin. The patients were examined before treatment, in the course of treatment, and after it. As the patients recovered, the dielectric permittivity and conductivity of tissues in the area of the focus of disease in all three groups of patients approximated the values of healthy skin.

In the exacerbation stage, the difference between healthy and damaged skin were more distinct in the case of psoriasis. In the regress stage, the dielectric permittivity and conductivity of tissues in the area of psoriatic focuses of disease were analogous to ε and σ of tissues in the case of atopic dermatitis. Hence in the cases of psoriasis and atopic dermatitis, the method is diagnostically significant only when a disease is active.

When studying the electrodynamic characteristics of skin in the case of lichen acuminatus, it was found out that if the dielectric permittivities of tissues in the case of psoriasis and in the case of LA coincided, the conductivities in these cases differed by factor of 2.

This permits drawing a conclusion on the possibility of diagnostics in the cases of psoriasis and LA at arbitrary stages of disease.

Differential diagnostics of pathologic processes in parenchymal organs is carried out. It is shown that the measuring systems are sensitive to physiological and pathological properties of tissues. The possibility to determine tumor focuses of disease in an organ and the limits of their growth is demonstrated. Study of a remote material (fig. 1) confirmed high accuracy and sensitivity of the measuring complex. The difference in sensor indications in measurement of various types of tissues is well seen in fig. 2.

It should be noted that near-field systems are sensitive to arbitrary, even slight, variations of blood flow in tissues abounding with blood vessels.

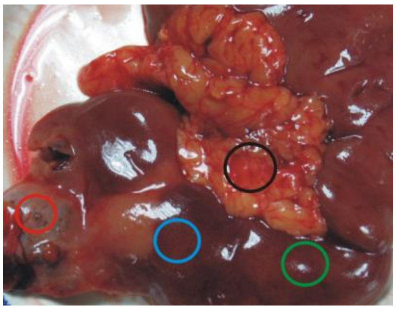

Fig. 1. Examined object (kidney). Circles show the measuring areas

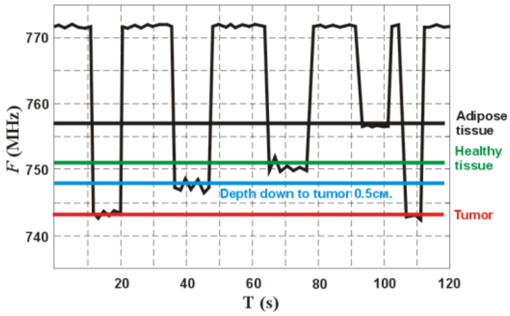

Fig. 2. Resonance frequency shift of sensor depending on the features of an examined tissue.

Electrodynamic characteristics of parenchyma of kidneys under the conditions of thermal and cold ischemia are measured in time dynamics. Laboratory animals (rabbits) were used in the studies. The process of multiorgan sampling for transplantation was simulated completely. Kidneys were irrigated with a cooled solution of kustodiol (additive) through the aorta and appropriate arteries until blood was fully eliminated from the organ. Measurement results of the resonance frequency of sensor (dielectric permittivity) on time are given in fig. 3. The results show a difference between cold and thermal ischemia of organs; the signal frequency variation depends directly on the rate of ischemic damage.

Besides the probe contacting with the examined tissue, a sensor based on the resonance contact sensor was fabricated and tested; it responded to small additives occurring as a result of diffluence in the conserving liquid irrigating the organ prepared to transplantation and being in the critical state. Additive sampling was made in definite periods. The result obtained unambiguously demonstrates the relation between the electrodynamic characteristics of kustodiol varying in the experiment, as diffluence products accumulate in it (fig. 4). Having a set of gage curves, one can carry out express diagnostics of viability of an organ during several seconds.

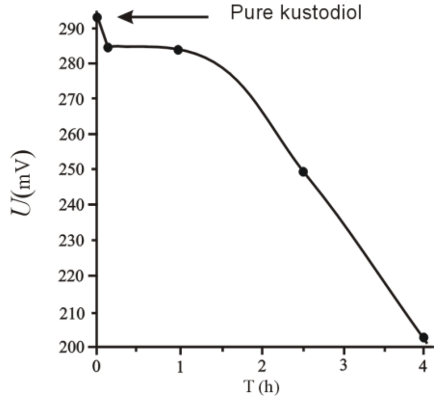

Fig. 3. Variation of the signal amplitude of sensor at the resonance frequency on pump time. The examined liquid is “kustodiol”. (Thermal ischemia)

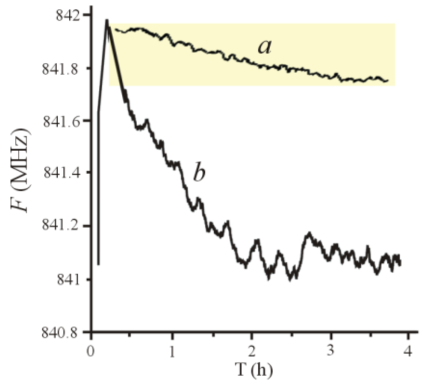

Fig. 4. Variation of the resonance frequency of sensor in time; the sensor are in contact with parenchyma of a kidney (a) cold ischemia, (b) thermal ischemia.

When comparing measurements of the electrodynamic parameters of the parenchimatous tissue and the additive, it is seen that the occurrence of diffluence products in kustodiol slightly “delays”, which agrees with recent publications on results of marginal (cadaveric) transplantations of kidneys [2].

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