Near-Field Microwave Tomography of Biological Tissues: Future Perspectives

Andrew K. Martusevich,[a,b,]* Vladimir V. Nazarov,[a,c] Alexandra V. Surovegina,[a,b] & Alexander V. Novikov[a]

[a]Privolzhsky Research Medical University, Nizhny Novgorod 603950, Russia; [b]Nizhny Novgorod State Agricultural Academy, Nizhny Novgorod 603109, Russia; [c]Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod 603950, Russia

*Address all correspondence to: Andrew K. Martusevich, Privolzhsky Research Medical University, Nizhny Novgorod 603950, Russia; Tel.: +7-909-144-91-82, E-mail: cryst-mart@yandex.ru

ABSTRACT: This overview shows the mapping of specific visualization techniques, depth assessment of the structure of the underlying tissues and used wavelengths of radiation. Medical imaging is currently one of the most dynamically developing areas of medical science. The main aim of the review is a systematization of information on the current status of the microwave imaging of biological objects, primarily of body tissues. The main options of microwave sensing of biological objects are analyzed. Two basic techniques for sensing differing evaluation parameters are characterized. They are microwave thermometry (passive) and near-field resonance imaging. The physical principles of microwave sensing application are discussed. It is shown that the resonant near-field microwave tomography allows visualization of the structure of biological tissues on the basis of the spatial distribution of their electrodynamic characteristics - permittivity and conductivity. Potential areas for this method in dermatology, including dermatooncology, are shown. The known results of applying the method to patients with dermatoses are given. The informativeness of the technology in the early diagnosis of melanoma is shown. The prospects of microwave diagnostics in combustiology, reconstructive and plastic surgery are demonstrated. Thus, microwave sensing is a modern, dynamically developing method of biophysical assessment of body tissues. There is a strong indication of the feasibility of application of microwave sensing in combustiology (in different periods of burn disease), as well as in reconstructive surgery. Further research in this and other areas of biomedicine will significantly expand the range of possibilities of modern technologies of visualization.

KEY WORDS: microwave probing, skin, wound, burn

I. INTRODUCTION

Medical imaging is currently one of the most dynamically developing areas of medical science.[1–4] Dozens of different imaging methods based on a wide range of physical principles are proposed, studied and tested, and almost all wavelength ranges are used to solve biomedical problems: from X-ray to microwave radiation.[1,5–12] At the same time, the optical wave range is studied in the most in-depth way.

Within the framework of optical imaging, a comparison of specific imaging methods, the depth of assessment of the structure of the underlying tissues achieved with their help, and the radiation wavelengths required for their implementation are shown (Table 1).[7,13,14] Among them, in recent years, optical coherence tomography has become widely used, which has found applications in dermatology, oncology and other areas of biomedicine.[1,2] At the same time, the diagnostic value of this method remains a subject of discussion even now.

Technologies based on the use of luminescence and fluorescence, including those involving the introduction of probes, are actively developing. In particular, this principle is used for fluorescence microscopy, which makes it possible to obtain high-quality images of the tissue structure, but the penetration depth achieved is relatively small (up to 200 μm).[7,14] Conversely, an improved version of the method, embodied in the form of multiphoton confocal laser scanning microscopy, allows you to visualize not only individual cell structures, but also macromolecules inside them.

A special aspect that limits the applicability of biophysical diagnostic and therapeutic technologies based on the effects of radiation is their safety for the patient and service personnel. In this regard, it

TABLE 1: Methods of bioimaging

Method of bioimaging	Depth of investigation	Wavelength
Optic sensing		
Microscopy	100–200 μm	400–1200 nm
Optical coherence tomography	1–2 mm	600–1200 nm
Optical acoustic tomography	2–20 mm	600–1200 nm
Optical diffusion tomography	1 mm–10 cm	700–950 nm
Microwave sensing		
Microwave bioimaging	1–30 mm	20–50 cm

should be noted that a number of radiations are classified as ionizing (in particular, gamma and X-ray radiation), and therefore the issue of developing safe methods of diagnosis and treatment remains relevant. These include electromagnetic radiation of the microwave range, the possibilities of which for biology and medicine are just beginning to open up.[7,15–20] On this basis, the purpose of the review is to systematize information about the current state of microwave imaging of biological objects, primarily body tissues.

II. OPTIONS FOR MICROWAVE SENSING OF BIOLOGICAL OBJECTS

The analysis of the specialized literature on the methodology and methodological apparatus of microwave imaging implemented in biomedicine allows us to distinguish two main sensing techniques that differ in the estimated parameters: microwave thermometry (passive) and near-field resonance tomography.[15–17,21]

In the framework of microwave thermometry (radiometry), the volume dynamics of the subsurface temperature distribution is recorded by the trapping device.[5,18,22–24] At the same time, it is known that in a number of pathological conditions (for example, in oncomammology), there is a significant local hyperthermia, which will be detected using a microwave sensor.[18,25]

On the contrary, in recent decades, near-field resonant microwave tomography has been actively developed, which makes it possible to visualize the structure of biological tissues based on the spatial distribution of their electrodynamic characteristics – dielectric permittivity (ε) and conductivity (σ),[18,21,26–29] describing the type and structural features of the biological object.[21,27,30,31] The possibility of using such a variant of tomography for diagnostic purposes is due to the fact that during the formation of pathological changes in biological tissues, there is a distinct change in their electrodynamic characteristics.[21,22,27,30–34] The physical principles of the method will be discussed in more detail in the next section of the review.

Currently, work is underway to improve the characteristics of microwave diagnostics in the following directions: the development of new algorithms for processing the received microwave signal and the development of new geometric designs of emitting and receiving antennas, the development and creation of new contrast agents, the introduction of the possibility of using data from other diagnostic methods as preliminary information.

A wireless interrogation system to acquire sensing data in the far field region of wireless communication was developed in Yao et al.[35] using reactive impedance surface ground based patch antennas. To provide the required features, a number of ultra-wide-band (UWB) antennas have been proposed: planar UWB antennas,[36] square monopole antennas,[37] square patch antennas,[38] hook-shaped monopole antennas,[39] tapered slot antennas,[40] metamaterial-based UWB antennas,[41,42] flexible coplanar waveguide fed fishtail antennas,[43] semi-circular antennas,[44] different types of Vivaldi antennas,[45,46] and many more. A novel antenna miniaturization technique was introduced in Mosallaei and Sarabandi[47] using reactive impedance surface as a substrate, which can be used as a perfect electric conductor as well as perfect magnetic conductor surface to enhance the bandwidth and radiation performance.

The variety of antenna systems currently used for microwave imaging of biological tissues is presented in Table 2.[48]

III. PHYSICAL PRINCIPLES OF MICROWAVE NEAR-FIELD TOMOGRAPHY

The absolute majority of work in the field of microwave sensing of biological objects is associated with the solution of the wave problem when radiation passes through the studied biological medium or reflected from its elements (from the potential foci of the pathological process; Fig. 1).[49] A specific feature of the diagnostic technology we are developing is the study of the dielectric parameters of an object through scanning it with the near field of the sensor.

As mentioned above, near-field resonant microwave diagnostics is based on the measurement of the electrodynamic characteristics of biological tissues. Work in this direction from a biomedical perspective is relatively recent, but the physical principles underlying near-field microwave tomography have been studied much more fully. Thus, the fundamental basis of the method is the measurement of the impedances located on the surface of the biological object of a system of electrically small antennas with different localization scales of the probing electric field.[16,18,21,22] Based on the values of the impedances (active and reactive resistance) of the antennas, the spatial distribution of the permittivity and electrical conductivity of the tissues is reconstructed on the basis of a special mathematical apparatus.[5,16,21]

The measurement of the antenna impedance is implemented in a special resonant sensor, schematically shown in Figs. 2 and 3. The sensor is a microwave resonator in the form of a segment of a transmission line (coaxial, two-wire, or strip).[21,30,31] At one end of this segment there is a probing near-field antenna (measuring capacity), at the opposite end there is a magnetic frame. The resonator is excited and its response is received by means of magnetic coupling loops located near the magnetic frame of the resonator. All elements of the resonant system, with the exception of the measuring tank, are located in a metal cylindrical housing. The natural resonant frequency of the sensor, as a rule, is in the range of 600–800 MHz, the characteristic Q-factor is 150.

When the near-field antenna contacts the surface of the biological object, changes occur in the resonant frequency of the sensor and the amplitude of the signal at the resonance (Fig. 4), the values of which determine the antenna impedance.

A diagram illustrating the deep probing of biological tissues under near-field microwave imaging is presented in Fig. 5. Near-field antenna located on the surface of the studied object, its quasi-static electric field penetrates the medium to a depth defined by the antenna design and the size of the aperture (D). As the aperture D increases, the depth of penetration of the electric field into the medium will increase.[30,31,50,51]

The study of heterogeneous biological environments is carried out as follows. First, the measurements are carried out by the sensor with the lowest value of D_1 and, accordingly, with the lowest sounding depth (h_1), the measurement results reflect the integral properties of the medium in the near-surface layer with a thickness of h_1. For a sensor with a depth of sensing integral properties of the medium in the near-surface layer with a greater thickness, etc. Knowing the responses of measuring systems with different sounding depths, it is possible to restore the deep structure of an inhomogeneous medium. For tomography of a three-dimensional inhomogeneous medium based on the methods of one-dimensional subsurface diagnostics, the measurements should be supplemented by two-dimensional scanning along the object surface.[16,21]

In the currently developed near-field diagnostic systems, the key ratio probe aperture size (D)/wavelength of the probing microwave signal (λ) reaches the level of 10^{-5} to 10^{-6}, which, compared with wave methods, makes it possible to study the state and structural features of tissues by their electrodynamic properties with a subwavelength spatial resolution (significantly less than the wavelength λ).

TABLE 2: Various types of antenna systems for microwave imaging of biological tissues (adapted from Alani et al.[48])

Origin	Imaging domain	Antenna configuration	Targets	Results
Dartmouth College	Cylindrical tank (agar gel, corn syrup, water mixer)	16 antennas mechanical scanning	Detecting malignant tumors	2D and 3D images
University of Bristol	Acrylonitrile butadiene styrene plastic half sphere	UMB radar	Measure the symptomatic patients	First real breast phantom but limitations in terms of resolution and clutter rejection
Carolinas Medical Center	Metallic tank 21.5 cm in diameter	24 waveguide antennas	Detection of physiological activity of soft tissues	2D and 3D tomographic images of swine torso obtained
University of Calgary	Tank with canola oil	Single balanced antipodal antenna with mechanical scanning	Pilot clinical experiment	Consistent imaging results
University of Manitoba	Plexiglass tank with canola oil	Single Vivaldi antenna	Pre-clinical UWB prototype	Improvements to quantitative dielectric image
University Rovira	Water filled cylindrical glass tank	UWB disc monopole antenna	Working prototype for microwave imaging	Tumor position was detected
University of Queensland	Plastic container filled with canola oil	12 UWB antennas	UWB biomedical imaging	Mutual coupling and fidelity
McGill University	Hemispherical ceramic (Al_2O_3) radome	16 elements antenna array	Clinical testing	First study of microwave time domain with actual volunteers
Politecnico di Torino	Metallic cylinder	Monopole 8 element antenna array	Design and construction of imaging prototype	2D imaging at MiMed cost meeting
Duke University	Rectangular tub filled with fluid	Two dipole antennas	3D imaging system prototype	5 mm diameter dielectric objects detected
Toyohashi University of Technology	Rectangular tub with cooking oil	UWB Vivaldi antennas	Breast cancer tumor detection	9 mm metallic ball detected
Technical University of Denmark	Water filled spheres	32 monopole antennas	20 to 40 mm target objects detection	3D images are obtained with consuming more than 100 min
McMaster University	Glycerin based flat artificial phantom	2 TEM horn antenna	3D model and phantom analysis where antenna directly contacted images body	Image de-blurred using blind deconvolution algorithm

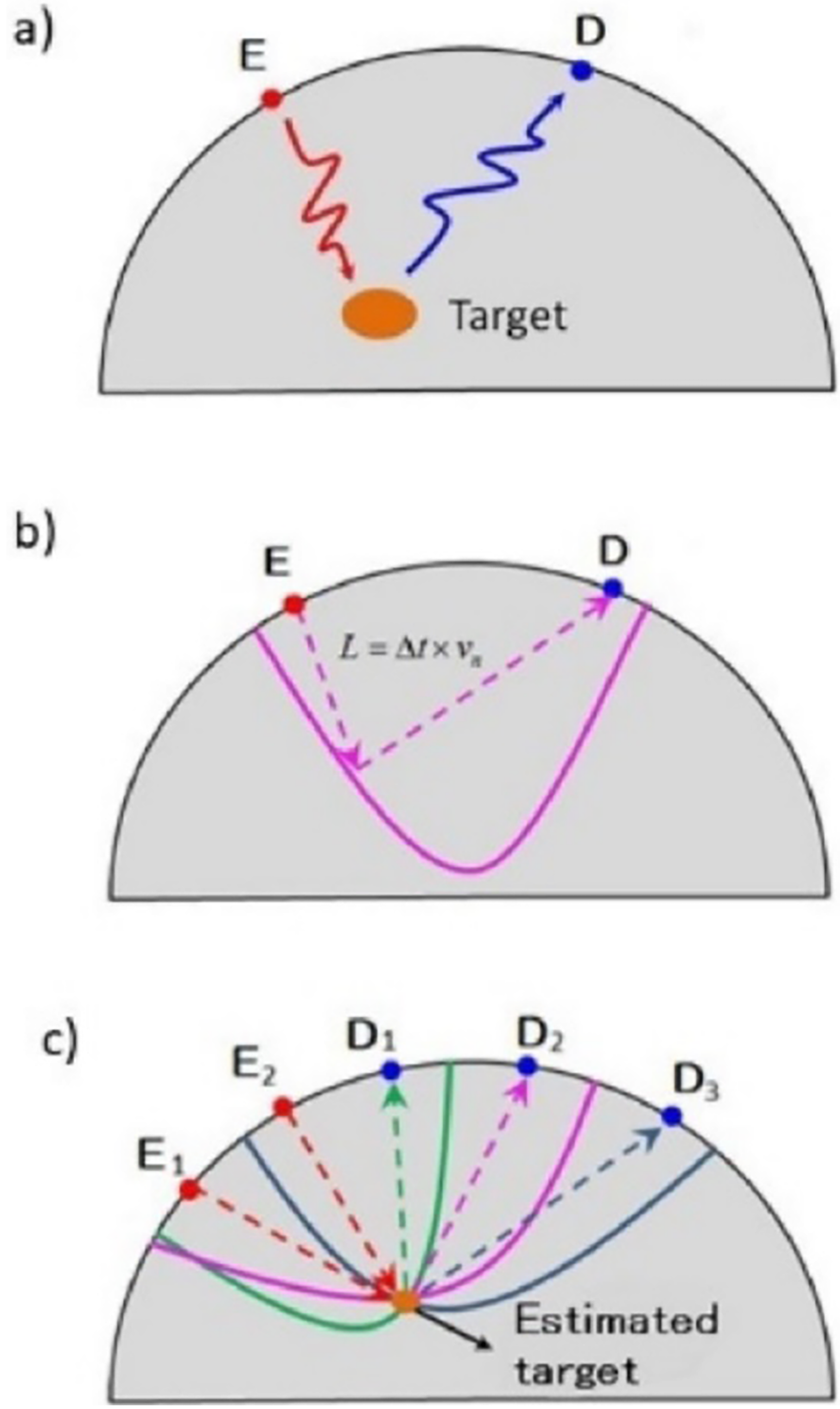

FIG. 1: Principles of microwave radar-based imaging technology. Figure reproduced from (Adachi et al.) under a Creative Commons license.[49]

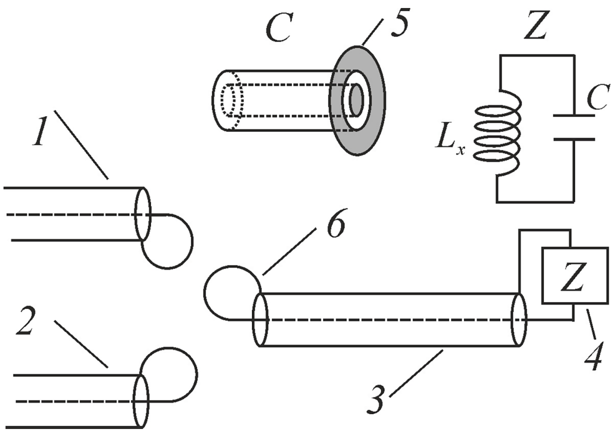

FIG. 2: Electrodynamic model of resonance near-field measuring system: (1) exiting line; (2) receiving line; (3) resonator; (4) load of resonator; (5) near-field antenna as cylindrical capacitor; and (6) magnetic loop of resonator

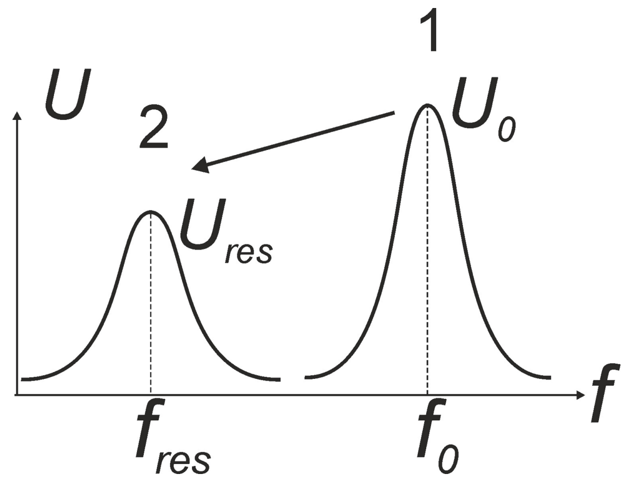

FIG. 4: Resonance characteristic of measurement system: (1) without contact bio object and (2) with contact bio object

FIG. 3: Measurement system and replaceable applicators with various depth of sounding

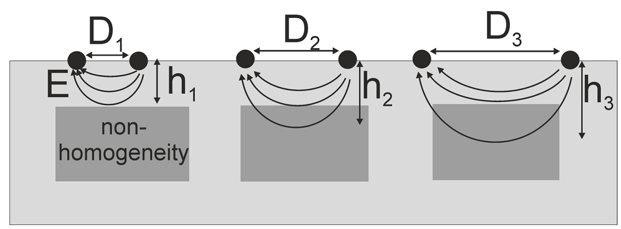

FIG. 5: Explanation of depth's sounding by method of near-field resonance tomography

Applied in near-field microwave imaging of the skin as a probe of element (measuring capacity) used regional capacity cylindrical capacitor, the external cover of which ends with a metal flange (Fig. 2). This configuration allows the antenna to realize the depth sensing required for the study of the structural layers of the skin. As shown in Fig. 2, in such an antenna there are 3 main elements located concentrically from the inside to the outside: a central conductor, a fluoroplast insulator and an external capacitor plate with a round metal flange. Figure 5 shows the distribution of the probing electric field.

Thus, the near-field resonant microwave sounding, due to its physical principles, makes it possible to vary the depth and surface area of the study of biological objects, using as diagnostic criteria the electrodynamic characteristics of the medium and its dielectric permittivity and conductivity.

IV. APPLICATION OF MICROWAVE IMAGING IN DERMATOLOGY, INCLUDING IN DERMATO-ONCOLOGY

The most accessible and easiest biological tissue for conducting a microwave study is the skin. That is why the first attempts to clinically test the method of microwave sensing were made in dermatology.

The first works in this direction were carried out on the basis of the Nizhny Novgorod Research Institute of Skin and Venereology. Panteleeva et al. based on a comparative assessment of the dielectric permittivity and conductivity of the skin in the area of the palms and feet demonstrated the differential diagnostic value of the method of microwave diagnostics in psoriasis, eczema and keratodermia.[52] It should be emphasized that the authors were able to show not only the presence of significant differences in the electrodynamic characteristics of the skin of patients with these dermatological diseases, but also the temporal dynamics of the parameters, their variability during periods of exacerbation and remission of pathology. It is established that the effective treatment of the considered contingent of patients contributes to the normalization of the indicators of ε and σ.

Kostrov et al. showed a marked decrease in both the dielectric constant and the skin conductivity in patients with psoriasis, atopic dermatitis and lichen planus in the acute phase.[17] In this case, as in the previously mentioned study, the successful suppression of the activity of the pathological process ensured the optimization of the level of the indicator parameters of the microwave sensing. In addition, this publication demonstrates the heterogeneity of the considered pathology in terms of electrodynamic parameters: in the acute stage, the maximum deviations from the physiological values were observed in patients with psoriasis, while in the period of remission, the shifts ε and σ in the studied diseases were smoothed out until the statistical significance of the differences disappeared. Based on this, the authors conclude that the differential diagnostic value of assessing the dielectric permittivity of the skin only in the active phase of the considered dermatoses. At the same time, the conductivity of the skin allows you to clearly distinguish between diseases in these conditions.

In another work of the team, the specificity of changes in ε and σ was confirmed in microbial eczema compared with keratoderma.[31]

Interestingly, the depth of occurrence of pathological foci in these diseases of the dermatological profile allowed using small-diameter sensors with a depth of 0.2–0.3 mm for microwave research. In addition, the microwave imaging allowed us to clarify the boundaries of the pathologically altered skin area.[53,54]

A separate segment of the application of microwave sensing is dermato-oncology, in particular, the possibility of diagnosing melanoma using this method.[3,17,21,24,30,50] The most accurate method of verification is the morphological assessment of biopsies, but its implementation is difficult both because of the invasiveness of the procedure, and the high risk of tumor metastasis induced by this manipulation.[3,30,33,55] This determines the urgent need to search for informative, non-invasive and non-destructive methods for the diagnosis of melanoma and its differentiation in relation to clinically similar pathology.[3,28,31,34] Taking this into account, a pilot study was carried out aimed at a comparative analysis of the electrodynamic characteristics of intact skin, pigmented nevus and melanoma.[17,30] At the same time, the authors used a large sounding depth of 1.1 mm. It was found that the estimated parameters of microwave imaging under consideration do not show significant differences between intact skin and pigmented nevus, whereas in the case of melanoma, a pronounced decrease in the dielectric constant and conductivity was observed by two times relative to healthy areas, and in keratoma – by 1.3 times.

Also interesting data were obtained from the microwave analysis of the deep structure of healthy skin.[18.25–20,53,56] On its basis, it is shown that as the depth of probing increases, an increase in the values of the indicators ε and σ is recorded compared with the upper (subsurface) layers of the skin. In general, despite the preliminary nature of the available research results, we can talk about the prospects of the method of microwave sensing in dermatology.

V. PROSPECTS OF MICROWAVE DIAGNOSTICS IN COMBUSTIOLOGY AND PLASTIC AND RECONSTRUCTIVE SURGERY

Dermatology and dermato-oncology are closely related to other areas of medicine, the subject of which is the skin. In this regard, it is of scientific and practical interest to consider the possibilities of microwave imaging in combustiology, treatment of the consequences of burns and reconstructive plastic surgery.[7,13,57–59] It is known that one of the most important tasks solved by a surgeon during the initial examination of a patient with a burn is to clarify the depth of the lesion and its boundaries, as well as the state of the parawound and marginal zones.[10,13,32,39,60] This information is the key to the correct choice of treatment tactics and its success, as well as the effectiveness of subsequent rehabilitation measures.[7,57–61] In the condition of acute burn injury, alternative non-invasive rapid methods of assessing the condition of the wound are necessary. In recent decades, infrared thermography has been actively tested to solve this problem,[62–64] but despite its certain diagnostic value, it allows us to obtain information only about the surface temperature of the skin area. At the same time, the analysis of the depth temperature, physical and chemical parameters of the skin in the area of the wound and the parawound zone remains difficult. It is this aspect of the problem that can be studied using microwave sensing, the design features of which allow for non-invasive examination and accurate assessment of the electrodynamic characteristics of the subsurface structures of the skin.[54,65]

The second, but no less significant area of potential application of microwave sensing in patients with thermal trauma is the monitoring of the state of the wound in the dynamics of the treatment. It should be emphasized that microwave diagnostics is possible without removing temporary or permanent wound coverings, including using cellular technologies, which is an indisputable advantage of this diagnostic technique.[13,32,60] This allows us to identify objective instrumental criteria for the condition of a burn wound in its thickness, without resorting to invasive procedures.

A special area for the possible application of microwave sensing is the treatment of the consequences of burns (post-burn scars) at various stages of their formation, as well as reconstructive plastic surgery.[7,10,13,32,57,59] In this regard, the considered diagnostic method can make it possible to predict the formation of pathological scars, taking into account their histological type, which, in turn, can optimize the treatment tactics of this condition of patients and assess the prospects for the recurrence of the pathological process.

In relation to reconstructive plastic interventions, it is advisable to perform a microwave assessment of the preoperative condition of the skin in the area of the intended surgical manipulation and postoperative monitoring of reparative and regenerative processes.

In general, integrating the research data in the field of microwave sensing of biological tissues, it is possible to identify a number of main areas that are logically grouped by localization (Table 3). The most significant among them are the mammary gland, skin, brain and limbs. It should be noted that the range of studied organs and tissues, for which the possibilities of the diagnostic technology under consideration are shown, are constantly expanding.

VI. CONCLUSIONS

Thus, microwave sensing is a modern, dynamically developing method of biophysical assessment of the state of body tissues located subsurface. The diagnostic technology created on the basis of this method has a clear fundamental justification, its physical principles are well studied. Conversely, the biomedical aspects of the practical application of microwave imaging still require careful development. Currently, the specialized literature provides information about the diagnostic informativeness of the method under consideration in the dermatological and dermato-oncological pathology, but these data need to be confirmed and clarified. In addition, there are strong indications about the feasibility of using microwave sensing in combustiology (in different periods of burn disease), as well as in reconstructive plastic surgery. Further research in this and other areas of biomedicine will, in our opinion, significantly expand the range of possibilities of modern imaging technologies.

ACKNOWLEDGMENT

This study received no financial support.

TABLE 3: Microwave sensing in medical diagnostics

Organ	Disease	Used frequencies	Refs.
Mammary glands	Breast cancer	Maximal range: 300 MHz to 30 GHz (most frequently, 1–4 GHz)	18,48,49
	Breast skin cancer	3.1–10.6 GHz	24,66,67
Skin	Melanoma	700–900 MHz	30
		90–104 GHz	68
	Another skin cancer	300–6000 MHz	24,69
		42–70 GHz	55,70
	Burns	500–750 MHz	60
		26.5–40 GHz	71
	Cosmetology	500–700 MHz	50,54
	Dermatoses	540–760 MHz	52
Brain	Stroke	900–4000 MHz	72–74
	Cerebral oedema	1.1–2.4 GHz	11
	Hematoma	100–3000 GHz	75,76
	Tumor	7.3 GHz	77
Extremities	Traumas and orthopedics pathology	2–5 GHz	20
	Hand surgery (for example, Dupuytren's disease)	540–720 MHz	51
Bones	Osteoporosis	600–1900 MHz	78,79
Lungs	Tumors	1.5–3.0 GHz	80
	Pulmonary oedema	~ 1 GHz	34
Heart	Structural analysis, ischemia detection	2.5–7.0 GHz	81,82

REFERENCES

1. Gladkova ND, Sergeev AM. Manual of optical coherence tomography. Moscow: Fizmatlit; 2007.
2. Gladkova ND, Fomina YuV, Urutina MN. The possibilities of the optical coherence tomography method in dentistry: A methodological guide. Nizhny Novgorod: Nizhny Novgorod State Medical Academy; 2005.
3. Demidov LV, Sokolov DV, Bulycheva IV, Shashkov BV, Makhson AN. Improving methods for diagnosing skin melanoma. Bulletin of the N.N. Blokhin Russian Research Center of the Russian Academy of Medical Sciences. 2007;18(1):36–41.
4. Stuchly MA. Applications of time-varying magnetic fields in medicine. Crit Rev BIomed. Eng. 1990;18(2): 89–124.
5. Gaikovich KP. Subsurface near-field scanning tomography. Phys Rev Lett. 2007;98(18):183902.
6. Lazebnik M, Madsen EL, Frank GR, Hagness SC. Tissue-mimicking phantom materials for narrowband and ultrawideband microwave applications. Phys Med Biol. 2005;50(18):4245–58.
7. Martusevich AK, Kostrov AV. Biomedical applications of microwave radiation: Innovative approaches. EPJ Web of Conferences. 2018;195:00003
8. Naito S, Hoshi M, Mashimo S. In vivo dielectric analysis of free water content of biomaterials by time domain reflectometry. Anal Biochem. 1997;251(2):163–72.
9. Petrosyan VI. Resonant radiation of water in the radio range. JTP Lett. 2005;31(23):29–33.
10. Schertlen R, Pivit F, Wiesbeck W. Wound diagnostics with microwaves. Biomed Tech. 2002;47(Suppl 1):672–3.
11. Semenov S. Microwave tomography: Review of the progress towards clinical applications. Philos Trans A Math Phys Eng Sci. 2009;367(1900):3021–42.
12. Zaman A, Rezaeieh SA, Abbosh AM. Lung cancer detection using frequency-domain microwave imaging. Electron Lett. 2015;51(10):740–1.
13. Galka AG, Martusevich AK, Yanin DV, Kostrov AV. Resonansce near-field microwave probing of burn wound. J Commun Technol Electron. 2020;65(9):1038–45.
14. Turchin IV. Methods of optical biomedical visualization: From subcellular structures to tissues and organs. Uspekhi fizicheskikh nauk. 2016;186(5):550–67.
15. Arsenyev AV, Volchenko AN, Likhacheva LV, Pechersky VI. Application of the RF-near-field sounding method in

the diagnostics of biological objects. Sci Tech Bull Inform Technol Mechan Opt. 2011;2:154–7.
16. Gaikovich KP. Scanning near-field electromagnetic tomography. Phys Rev Lett. 2007;98(18):183902.
17. Kostrov AV, Strikovsky AV, Yanin DV, Zagainov VE, Plotnikov AF. Research of electrodynamic parameters of biological tissues. Almanac Clin Med. 2008;17:96–9.
18. Li X, Bond EJ, van Veen B, Hagness S. An overview of ultra-wideband microwave imaging via space-time beamforming for early-stage breast-cancer detection. IEEE Antennas Propagat Mag. 2005;47(1):19–34.
19. Reznik AN, Yurasova NV. Near-field microwave tomography of biological media. J Tech Phys. 2004;74(4):108–16.
20. Semenov S, Kellam J, Althausen P, Williams T, Abubakar A, Bulyshev A. Microwave tomography for functional imaging of extremity soft tissues: Feasibility assessment. Phys Med Biol. 2007;52(18):5705–19.
21. Kostrov AV, Smirnov AI, Yanin DV, Strikovsky, Panteleeva GA. Resonant near-field microwave diagnostics of inhomogeneous media. Izvestiya RAS. A series of physical. 2005;69(12):1716–20.
22. Reznik AN, Yurasova NV. Detection of contrast formations inside biological media using near-field microwave diagnostics. J Tech Phys. 2006;76(1):90–104.
23. Bennett D, Li W, Taylor Z, Grundfest W, Brown E. Stratified media model for terahertz reflectometry of the skin. IEEE Sensors J. 2011;11(5):1253–62.
24. Mehta P, Chand K, Narayanswamy D, Beetner DG, Zoughi R, Stoecker WV. Microwave reflectometry as a novel diagnostic tool for detection of skin cancers. IEEE Trans Instrum Meas. 2006;55(4):1309–6.
25. Sunaga T, Ikehira H, Furukawa S, Shinkai H, Kobayashi H, Matsumoto Y, Yoshitomi E, Obata T, Tanada S, Murata H, Sasaki Y. Measurement of the electrical properties of human skin and the variation among subjects with certain skin conditions. Phys Med Biol. 2002;47(1):N11–5.
26. Baloshin YuA, Sorokin AA, Volchenko AN. Electrodynamic model of RF-near-field sounding of physical objects. Izvestiya VUZov. Instrumentation. 2011;12:68–73.
27. Foster KR, Schwan HP. Dielectric-properties of tissue and biological-materials – A critical review. Crit Rev Biomed. Eng. 1989;17(1):25–104.
28. Raicu V, Kitagawa N, Irimajiri A. A quantitative approach to the dielectric properties of the skin. Phys Med Biol. 2000;45(2):L1–4.
29. Alanen E, Lahtinen T, Nuutinen J. Penetration of electromagnetic fields of an open-ended coaxial probe between 1 MHz and 1 GHz in dielectric skin measurements. Phys Med Biol. 1999;44(7):N169–76.
30. Yanin DV, Galka AG, Smirnov AI, Kostrov AV, Strikovsky AV, Orlinskaya NYu, Epishkina AA, Grebenkin EV. Noninvasive diagnosis of melanoma and other skin neoplasms by resonant near-field microwave sensing. J Radio Electron. 2015;1:20.
31. Yanin DV, Galka AG, Smirnov AI, Kostrov AV, Strikovsky AV. The resonant near-field microwave diagnostics of inhomogeneous media. Adv Appl Physics. 2014;2(6):555–70.
32. Hayashi Y, Miura N. Shinyashiki N, Yagihara S. Free water content and monitoring of healing processes of skin burns studied by microwave dielectric spectroscopy in vivo. Phys Med Biol. 2005;50(4):N8–14.
33. Caratelli D, Massaro A, Cingolani R, Yarovoy A. Accurate time-domain modeling of reconfigurable antenna sensors for noninvasive melanoma skin cancer detection. IEEE Sensors J. 2012;12(3):635–43.
34. Rezaeieh SA. Feasibility of using wideband microwave system for non-invasive detection and monitoring of pulmonary oedema. Sci Rep. 2015;5:231–6.
35. Yao J, Tchafa FM, Jain A, Tjuatja S, Huang H. Far-field interrogation of microstrip patch antenna for temperature sensing without electronics. IEEE Sens J. 2016;16:7053–60.
36. Abbosh A. Miniaturization of planar ultrawideband antenna via corrugation. IEEE Antennas Wirel Propag Lett 2008;7:685–8.
37. Ojaroudi M, Ghobadi C, Nourinia J. Small square monopole antenna with inverted t-shaped notch in the ground plane for UWB application. IEEE Antennas Wirel Propag Lett. 2009;8:728–31.
38. Lakrit S, Ammor H, Terhzaz J, Tribak A. Realization and measurements of a miniature square patch antenna for ultra wideband applications. Int J. Microw Opt Technol. 2015;10:307–13.
39. Liu H-W, Yang C-F. Miniature hook-shaped monopole antenna for UWB applications. Electron Lett. 2010;46:265–6.
40. Azim R, Islam MT, Misran N. Compact tapered-shape slot antenna for UWB applications. IEEE Antennas Wirel Propag Lett. 2011;10:1190–3.
41. Li L-W, Li Y-N, Yeo TS, Mosig JR, Martin OJ. A broadband and high-gain metamaterial microstrip antenna. Appl Phys Lett. 2010;96:164101.
42. Pandey G, Singh H, Bharti P, Meshram M. Metamaterial-based UWB antenna. Electron Lett. 2014;50:1266–8.
43. Liu H, Zhu S, Wen P, Xiao X, Che W, Guan X. Flexible cpw-fed fishtail-shaped antenna for dual-band applications. IEEE Antennas Wirel Propag Lett. 2014;13:770–3.
44. Samsuzzaman M, Islam MT. A semicircular shaped super wideband patch antenna with high bandwidth dimension ratio. Microw Opt Technol Lett. 2015;57:445–52.
45. Natarajan R, George JV, Kanagasabai M, Shrivastav AK. A compact antipodal vivaldi antenna for UWB applications. IEEE Antennas Wirel Propag Lett. 2015;14:1557–60.
46. Mahmud M, Islam MT, Samsuzzaman M, Kibria S, Misran N. Design and parametric investigation of directional antenna for microwave imaging application. IET Microw Antennas Propag. 2016;11:770–8.
47. Mosallaei H, Sarabandi K. Antenna miniaturization and

bandwidth enhancement using a reactive impedance substrate. IEEE Trans Antennas Propag. 2004;52:2403–14.
48. Alani S, Zakaria Z, Saeidi T, Ahmad A, Imran MA, Abbasi QH. Microwave imaging of breast skin utilizing elliptical uwb antenna and reverse problems algorithm. Micromachines. 2021;12:647.
49. Adachi M, Nakagawa T, Fujioka T, Mori M, Kubota K, Oda G, Kikkawa T. Feasibility of portable microwave imaging device for breast cancer detection. Diagnostics. 2022;12:27.
50. Martusevich AK, Galka AG, Krasnova SY, Soloveva AG, Kostrov AV. Near-field microwave sensing of human skin: Physiological pattern. Archiv Euromedica. 2018;8(2): 120.
51. Martusevich AK, Krasnova SY, Petrov SV, Galka AG, Petrov MS, Novikov AV. Application of near-field microwave probing in diagnosing Dupuytren's disease. Sovremennye Tehnologii v Medicine. 2019;11(4):106–10.
52. Panteleeva GA, Davoyan ZV, Yanin DV, Kostrov AV. Resonant near-field microwave diagnostics of dermatoses with palmar-plantar localization. Abstr. of scientific papers of the 3rd Congress of Dermatovenerologists. Kazan, 2009. p. 51.
53. Martusevich AK, Golygina ES, Anuchin AA, Galka AG, Tuzhilkin AN, Fedotova AF, Epishkina AA. Microwave detection of skin dielectric properties in some laboratory animals. Archiv Euromedica. 2020;10(1):46.
54. Martusevich AK, Epishkina AA, Golygina ES, Tuzhilkin AN, Fedotova AS, Galka AG. Near-field resonance microwave sounding to study dielectric properties of different skin areas (experimental study). Sovremennye Tehnologii v Medicine. 2020; 12(5):57–61.
55. Philipsen PA, Knudsen L, Gniadecka M, Ravnbak MH, Wulf HC. Diagnosis of malignant melanoma and basal cell carcinoma by in vivo NIR-FT Raman spectroscopy is independent of skin pigmentation. Photochem Photobiol Sci. 2013;12(5):770–6.
56. Gabriel C, Gabriel S, Corthout E. The dielectric properties of biological tissues: I. Literature survey. Phys Med Biol. 1996;41(11):2231.
57. Arai T. Burns. Nihon Rinsho. 2016;74(20):231–5.
58. Daigeler A, Kapalschinski N, Lehnhardt M. Therapy of burns. Chirurg. 2015;86(4):389–401 (in German).
59. Tan Q, Xu P. Repair of skin and soft tissue defects around the knee joint. Zhonghua Shao Shang Za Zhi. 2015;31(5):321–4.
60. Martusevich AK, Krasnova SYu, Galka AG, Peretyagin PV, Kostrov AV. Resonance near-field microwave probing as a method for exploration of deep burn wound structures in experiment. Sovremennye Tehnologii v Medicine 2018;10(3):125–9.
61. Tamura T, Tenhunen M, Lahtinen T, Repo T, Schwan HP. Modelling of the dielectric properties of normal and irradiated skin. Phys Med Biol. 1994;39(6):927–36.
62. Kolesov SN, Volovik MG. Modern methodology of thermal imaging studies and thermal imaging medical equipment. Opt J. 2013;80(6):59–67.
63. Volovik MG, Kolesov SN. Substantiation of the choice of functional samples in medical thermal imaging (on the example of an alcohol sample). Opt J. 2015;82(7): 62–74.
64. Hammody Z, Argov S, Sahu RK, Cagnano E, Moreh R, Mordechai S. Distinction of malignant melanoma and epidermis using IR micro-spectroscopy and statistical methods. Analyst. 2008;133(3):372–8.
65. Martusevich AK, Galka AG, Krasnova SYu, Golygina ES. The influence of reactive oxygen species and NO on oxidative metabolism and dielectric properties of living tissue. J Integr OMICS. 2020;10(2):39–42.
66. Shao W, McCollough T. Advances in microwave near-field imaging: Prototypes, systems, and applications. IEEE Microw Mag. 2020;21(5):94–19.
67. Song H, Sasada S, Kadoya T, Okada M, Arihiro K, Xiao X, Kikkawa T. Detectability of breast tumor by a hand-held impulse-radar detector: Performance evaluation and pilot clinical study. Sci Rep. 2017;7(1):16353.
68. Topfer F, Dudorov S, Oberhammer J. Millimeter-wave near-field probe designed for high- resolution skin cancer diagnosis. IEEE Trans Microw Theory Techn. 2015;63(6):2050–9.
69. Chand K, Mehta P, Beetner DG, Zoughi R, Stoecker WV. Microwave reflectometry as a novel diagnostic method for detection of skin cancers. Proc. IEEE Instrumentation and Measurement Technology Conf. 2005:1425–8.
70. Taeb A, Gigoyan S, Safavi-Naeini S. Millimetre-wave waveguide reflectometers for early detection of skin cancer. IET Microw Antennas Propag. 2013;7(14):1182–6.
71. Gao Y, Zoughi R. Millimeter wave reflectometry and imaging for noninvasive diagnosis of skin burn injuries. IEEE Trans Instrum Meas. 2017;66(1):77–84.
72. Ireland D, Bialkowski K, Abbosh A. Microwave imaging for brain stroke detection using Born iterative method. IET Microw Antennas Propag. 2013;7(11):909–15.
73. Mohammed BJ, Abbosh AM, Mustafa S, Ireland D. Microwave system for head imaging. IEEE Trans Instrum Meas. 2014;63(1):117–23.
74. Mustafa S, Mohammed B, Abbosh A. Novel preprocessing techniques for accurate microwave imaging of human brain. IEEE Antennas Wireless Propag Lett. 2013;12:460–3.
75. Candefjord S, Winges J, Malik AA, Yu Y, Rylander T, McKelvey T, Fhager A, Elam M, Persson M. Microwave technology for detecting traumatic intracranial bleedings: Tests on phantom of subdural hematoma and numerical simulations. Med Biol Eng Comput. 2017;55(8): 1177–88.
76. Ljungqvist J, Candefjord S, Persson M, Jönsson L, Skoglund T, Elam M. Clinical evaluation of a microwave-based device for detection of traumatic intracranial hemorrhage. J Neurotrauma. 2017;34(13):2176–82.

77. Inum R, Rana MM, Shushama KN, Quader MA. EBG based microstrip patch antenna for brain tumor detection via scattering parameters in microwave imaging system. Int J Biomed Imaging. 2018;2018:8241438.
78. Amin B, Shahzad A, Farina L, Parle E, McNamara L, O'Halloran M, Elahi MA. Dielectric characterization of diseased human trabecular bones at microwave frequency. Med Eng Phys. 2020;78:21–8.
79. Alkhodari M, Zakaria A, Qaddoumi N. Monitoring bone density using microwave tomography of human legs: A numerical feasibility study. Sensors. 2021;21(21):7078.
80. Zamani A, Rezaeieh SA, Abbosh AM. Lung cancer detection using frequency-domain microwave imaging. Electron Lett. 2015;51(10):740–1.
81. Ištuk N, Porter E, O'Loughlin D, McDermott B, Santorelli A, Abedi S, Joachimowicz N, Roussel H, O'Halloran M. Dielectric properties of ovine heart at microwave frequencies. Diagnostics. 2021;11(3):531.
82. Semenov SY, Svenson RH, Posukh VG, Nazarov AG, Sizov YE, Bulyshev AE, Souvorov AE, Chen W, Kasell J, Tatsis GP. Dielectrical spectroscopy of canine myocardium during acute ischemia and hypoxia at frequency spectrum from 100 kHz to 6 GHz. IEEE Trans Med Imaging. 2002;21(6):703–7.