



# Passive microwave radiometry in biomedical studies

Igor Goryanin<sup>1,2,3</sup>, Sergey Karbainov<sup>4</sup>, Oleg Shevelev<sup>5</sup>, Alexander Tarakanov<sup>6</sup>, Keith Redpath<sup>7,8</sup>, Sergey Vesnin<sup>8,9</sup> and Yuri Ivanov<sup>10,11</sup>



<sup>1</sup> University of Edinburgh, UK

<sup>2</sup> Okinawa Institute Science and Technology, Okinawa, Japan

<sup>3</sup> Tianjin Institute of Industrial Biotechnology, Tianjin, China

<sup>4</sup> ARAGON GROUP INC

<sup>5</sup> Peoples' Friendship University of Russia, Moscow, Russia

<sup>6</sup> Rostov State Medical University, Russia

<sup>7</sup> Manus Neurodynamica, Edinburgh, UK

<sup>8</sup> Medical Microwave Radiometry (MMWR), Edinburgh, UK

<sup>9</sup> Bauman Moscow State Technical University (BMSTU), Moscow, Russia

<sup>10</sup> Institute of Biomedical Chemistry (IBMC), Moscow, Russia

<sup>11</sup> Joint Institute for High Temperatures of the RAS, Moscow, Russia

**Passive microwave radiometry (MWR) measures natural emissions in the range 1–10 GHz from proteins, cells, organs and the whole human body. The intensity of intrinsic emission is determined by biochemical and biophysical processes. The nature of this process is still not very well known. Infrared thermography (IRT) can detect emission several microns deep (skin temperature), whereas MWR allows detection of thermal abnormalities down to several centimeters (internal or deep temperature). MWR is noninvasive and inexpensive. It requires neither fluorescent nor radioactive labels, nor ionizing or other radiation. MWR can be used in early drug discovery as well as preclinical and clinical studies.**

## Introduction

The first microwave radiometers were launched on satellites in the 1970s to measure sea surface temperature [1], among other applications for climate and weather remote monitoring. In 1975, Barrett and Myers [2] showed that using a microwave radiometer to identify temperature abnormalities of internal tissue noninvasively could help to detect breast cancer. Subsequently, several studies have confirmed the effectiveness of microwave radiometry in revealing tissue pathologies [3–7]. The term ‘internal temperature’ is more commonly used by medical professionals in the medical literature, whereas physicists use ‘brightness’ temperature. Bones, fatty tissue, breast tissue and other organs have a different depth of measurement. Muscles and skin have a high moisture content and a shallower depth.

Currently, in biomedicine, infrared radiation (IR) and microwave radiation are being used for temperature measurements. The main difference between them is the ability to measure either the skin temperature (IR can penetrate only several millimeters deep) or internal tissue temperature (microwaves can record to a depth of 2–6 cm). In recent years, there has been growing interest in microwave radiometry (MWR; see [Glossary](#)) technology. There are multiple medical applications targeting the breast [8], brain [9–15], carotid artery [16–20], brown adipose tissue (BAT) activity [21], rheumatoid arthritis [22], joints [23], synovial inflammation [24], veins [25], vesicoureteral reflux [26], the urogenital system [27], back pain [28,29] and diabetic foot [30]. Use of this method in preclinical research has been demonstrated in mice [31]. So far, everyone is convinced that all the heated bodies, and really all the bodies that surround us, emit electromagnetic waves in the microwave range. So, everything around us emits a noise signal where power is proportional

Corresponding author: Goryanin, I. ([goryanin@inf.ed.ac.uk](mailto:goryanin@inf.ed.ac.uk))

## GLOSSARY

**Passive medical microwave radiometry** a method of measuring the intensity of intrinsic electromagnetic emission from biological objects in 1–10 GHz range (organs, tissues, cells, enzymes and other proteins).

**Internal (deep) temperature** microwave emission power (W) from human body or other biological objects converted to temperature in degrees using Planck's equation.

**Skin temperature** temperature of the human body measured in infrared spectrum.

**Thermal asymmetry** a deep or skin temperature difference between left and right organs (breast, kidney, lungs, legs, arms or tissues of organs on left and right side of the human body or specific tissue or organ).

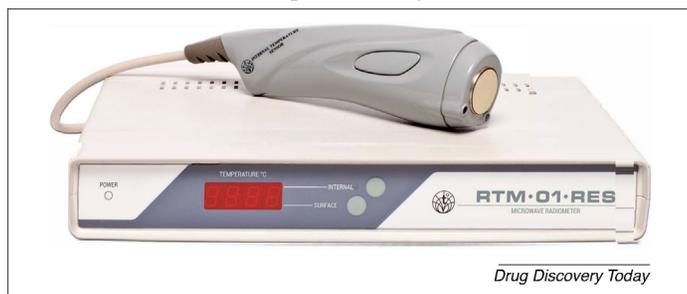
to the temperature. In the microwave range, the power of thermal radiation is linearly correlated to body temperature (Eq. 1).

$$P = k \times T_{br} \times \Delta f \quad (\text{Eq.1})$$

where P is noise power at the output antenna;  $T_{br}$  is brightness temperature; k is the Boltzmann constant; and  $\Delta f$  is receiver bandwidth. However, recent studies show that, in many cases, non-thermal radiation of living systems in the microwave range also takes place. To better understand the nature of the phenomena several *in vitro* experiments on cell lines [32], enzymes [33,34] and proteins [35,37] were performed. Commercially available equipment: RTM-01-RES (<http://www.mmwr.co.uk>) (Fig. 1), has been developed for early diagnosis of cancer and other diseases [8,9,28]. Technical details about different types of sensors and antennae have been reported [38–46].

### Breast tissue

Breast cancer diagnostics is the most explored application of MWR technology – by visualization and analysis of left and right breast deep and skin temperature (Fig. 2). Nine points on each breast, two axillary points and two reference points should be measured. Each measurement takes 5–7 s (Fig. 3). Microwave emission asymmetry between the left and right breast, and difference between skin (infrared) and internal (microwave) temperature, is used for diagnostics. Thermal asymmetry  $<0.5^\circ\text{C}$  indicates a normal state. Larger values could indicate pathology and increases  $>1^\circ\text{C}$  could indicate malignant tumors. Hot areas of a breast could indicate inflammation or acute or chronic malignant growth, whereas cold areas of the breast could be caused by adipose involution, local anemia, scars and fibrosis, lipoma or a cyst.



**FIGURE 1**

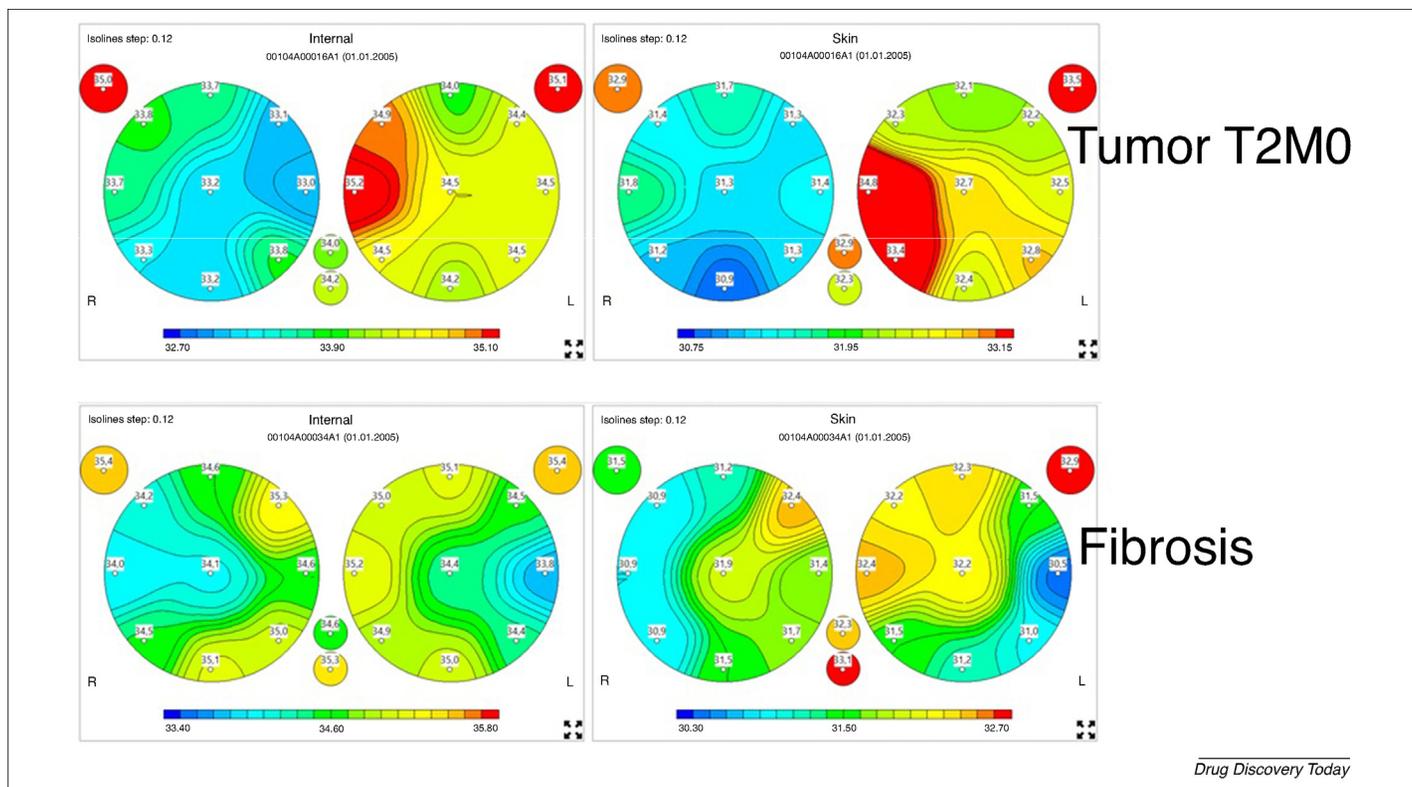
The RTM-01-RES device. The device and antenna for human body deep and skin temperature measurements.

The method has  $\sim 92 \pm 5\%$  sensitivity and  $\sim 80 \pm 5\%$  specificity for breast cancer detection [8]. This effect could be explained by the Warburg effect and/or other changes in metabolic and signaling pathways [47–49]. By measuring the temperature of specific areas of breast tissue, MWR has a potential role in diagnosis, prognosis and monitoring that has not been widely explored. The technology is safe, easy to apply and is painless. There are already good diagnostic tools for breast lumps. MWR has the added potential to provide more than just a diagnosis and it should be able to provide information on the rate of vascularity of cancer and correlate the rate of proliferation. Changes in internal temperature in a cancer should occur early in treatment, before clinical signs of response are apparent. If we can show that this device can successfully predict response, this will allow early prediction of response in individual patients and would have enormous clinical benefit. Deep tumor temperature changes could be used as an indicator of aggressiveness, precede structural changes and correlate with microvessel density.

### Brain

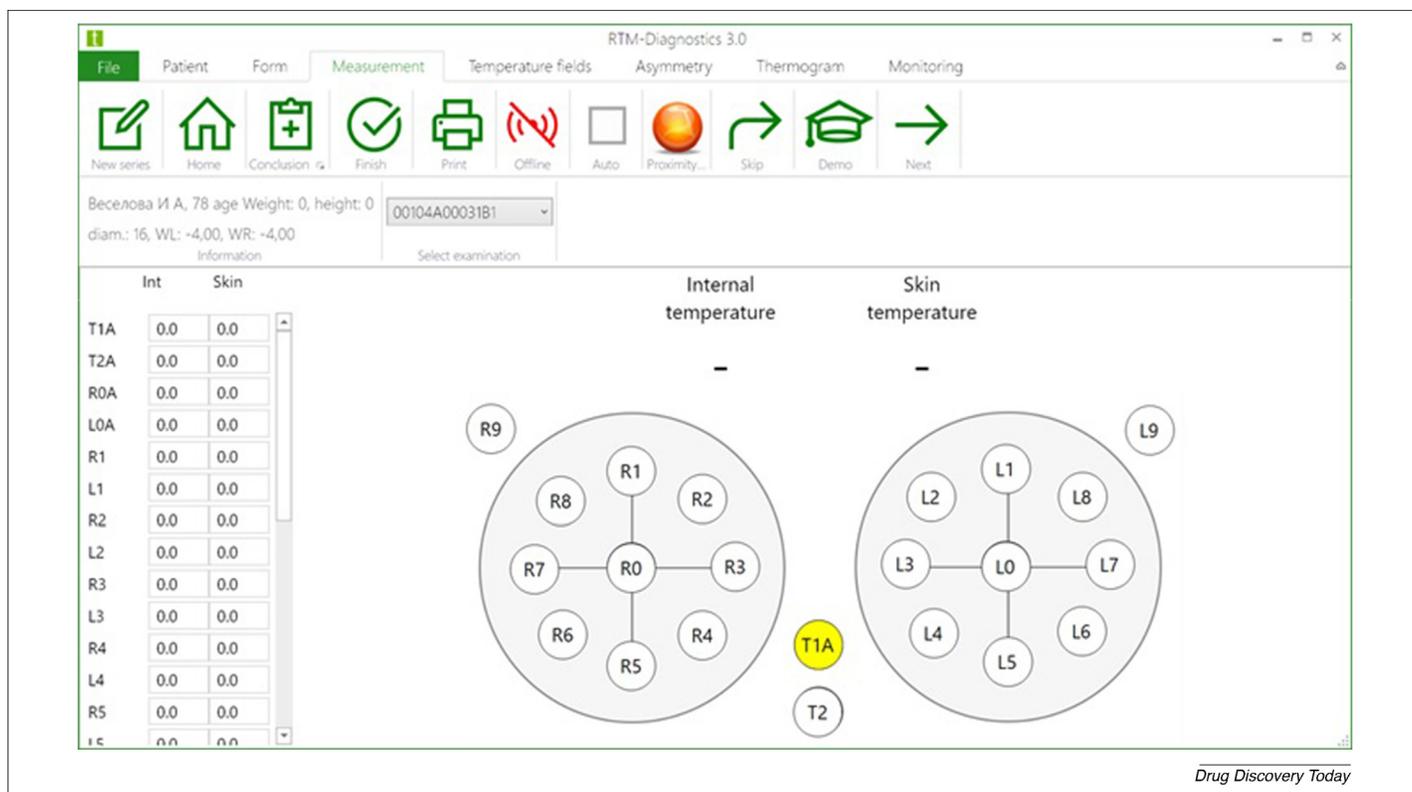
The level of intrinsic radiation of tissues in the microwave range is only  $10^{-12}$  W; and processing such a weak signal is rather complicated. Nevertheless, use of MWR has made it possible to show that regions with thermal anomalies are formed over some areas of the brain in patients with traumatic brain injuries (TBIs). It can also be used to detect regions with a growing tumor and complications after stroke during the process of therapeutic hypothermia [10,11]. Validation of MWR has been performed in animal experiments, in which implanted induction heat sensors were compared with MWR values. In addition, in neurosurgical patients with implanted thermal sensors, recorded temperatures were compared with MRI data. A satisfactory agreement of the data ( $\pm 0.23^\circ\text{C}$ ) was obtained, which made it possible to conduct a large study of temperature heterogeneity of the brain in healthy individuals, athletes with lung trachea arthrosis and patients with ischemic stroke [9]. Subsequently, a large study of the temperature heterogeneity of the brain in healthy individuals and patients with ischemic stroke was carried out [10]. The results of measuring temperature in stroke patients using magnetic resonance spectroscopy were controversial [50]. Several mechanisms of microwave emission and temperature increase in some areas after brain damage have been proposed. According to current thinking, in concussion or other damage to the brain a rapid internal induction of immune factors occurs. Thus, a neurometabolic cascade develops, which causes the clinical manifestations [10].

Another hypothesis is that microwave emission is caused by albumin and other protein denaturation [35]. Hypoalbuminemia in acute stroke patients is associated with increased mortality and morbidity. A study of 750 patients with acute cerebral infarction found hypoalbuminemia, defined as serum albumin level  $<35$  g/l, in 45.5% of patients. The authors found that low serum albumin was associated with poor prognosis in acute ischemic stroke patients and concluded that serum albumin could be used as a rapid, simple and inexpensive treatment. Currently, the albumin decrease index (ADI) is measured using electrophoresis, which is time and labor intensive. Using MWR to monitor albumin denaturation in damaged brain *in vivo* would allow doctors to assess ADI instantly and to choose appropriate therapies. MWR can also be



**FIGURE 2**

Visualization of microwave emission using RTM-01-RES. Deep and skin temperature field. Red color indicates increase of temperature (tumor was confirmed by biopsy in right breast). Green color indicates normal state. Blue color indicates deep temperature decrease as a result of clinically confirmed fibrosis.



**FIGURE 3**

Specialized software. Eight points on the left breast (L1–L8) and eight points on the right breast (R1–R8), and four reference points to measure (L9, R9, T1A, T2).

Drug Discovery Today

Drug Discovery Today

used to monitor albumin degradation after therapeutic intervention [51–53]. Overall, MWR could be used to monitor the course of therapy, determine the extent of brain damage, calculate optimal dosage and type of therapeutic intervention and monitor hypothermia and hyperthermia therapies.

### Noninvasive carotid artery

Atherosclerosis of the internal carotid artery is an important cause of disabling ischemic stroke and therefore constitutes a major medical, social and economic issue; although advances in vascular imaging modalities allow to stratify patients based on ‘high risk’ indications and there is increasing evidence that inflammation is a key factor in the initiation, progression and destabilization of plaques. MWR is used to measure the level of inflammation in carotid arteries [16,17]. In a recent study [18], 300 patients from three centers with significant coronary artery disease were included in this study. Both carotid arteries were measured using ultrasound and MWR for at least 2 years. Temperature difference ( $\Delta T$ ) was defined as maximal minus minimal deep temperature along each carotid artery. Fatty plaques exhibited higher internal temperature heterogeneity compared with mixed and calcified plaques. In recent publications [19,20] it was shown that MWR could contribute significantly to primary and secondary prevention of stroke.

### Back pain

Pain is highly subjective in nature. The measurement of intensity is primarily dependent on patient sensation. The correlation between the pain syndrome and the results of MWR was reported in the diagnosis of muscular-joint disorders of cervicogenic headache [29]. In the area of the projection of back pain, the temperature of deep structures, in comparison with other areas, could be elevated, reduced or normal. So, back pain syndromes can be assessed by MWR. This enables more-precise diagnosis including localization of pain and discrimination of its intensity. It was shown that temperature increases with low-back pain (LBP) severity and MWR allows the objective assessment of the magnitude of clinical symptoms [28]. Recently, clinical studies of 48 LBP patients showed that internal temperature is highest in patients with LBP who report the most severe pain and in whom MWR was performed within the first week after the patient experienced an exacerbation. It was shown that MWR allows an objective assessment of the magnitude of clinical symptoms in patients with LBP and that the method shows promise for measuring the severity of pain and for predicting the duration of exacerbation and time for recovery [28].

### Venous thrombosis

There are multiple publications and patents on this disease [25]. The MWR measurements are conducted at 12 points for >100 patients. The temperature is sequentially measured at symmetrical points on the posterior surface of the legs of the patient in the supine position and standing with a surface infrared sensor and a deep microwave sensor. The diagnosis is made on the following criteria: the axial gradient of deep temperatures is reduced in a standing position and is absent in a prone position; decrease and absence of an axial gradient of deep temperatures associated with an increase in deep temperature along the medial surface of the

lower leg in the middle and lower third sensitivity 100% and specificity 81.3% [25]. It was shown that MWR can be used for early-stage diagnosis of acute thrombosis and to observe the dynamics of the inflammatory process.

### Diabetic foot

Diagnosis of vascular involvement in diabetic foot ulceration (DFU) remains challenging. A proof-of-concept, multicenter feasibility study of MWR for noninvasive differential diagnosis of arterial disease in diabetic patients with suspected critical limb ischemia (CLI) in subjects with DFU was carried out. Eighty participants [30] were divided into four groups (group N: normal control subjects; group DN: participants with diabetes and verified neuropathic ulcers without vascular involvement; group DC: participants with diabetes and CLI and group NDC: participants with CLI without diabetes). Vascular disease was confirmed with angiography. The mean deep tissue temperatures at various predetermined foot sites were measured. Temperatures recorded in the vicinity of the foot ulcers of participants with diabetes and CLI were similar to those with CLI without diabetes but significantly lower than in subjects with neuropathic ulcers without vascular involvement and normal controls (group DC:  $29.30 \pm 1.89$  °C vs group NDC:  $29.18 \pm 1.78$  °C vs group N:  $33.01 \pm 0.45$  °C vs group DN:  $33.39 \pm 1.37$  °C). According to receiver operating characteristic (ROC) analysis, cut-off temperature value to diagnose CLI was 31.8 °C, with a sensitivity of 100% and specificity of 88.37%. Tissue temperatures in the vicinity of the ulcers were significantly lower in participants with CLI, with or without diabetes, compared with nonischemic controls.

### Brown adipose tissue

Recently, MWR technology was used to monitor BAT activity and identify therapies for diabetes, metabolic syndrome, obesity and aging [54,55]. It was shown that activation of BAT is a powerful remedy to ameliorate hyperlipidemia and protect from atherosclerosis [56]; and that brown fat activation reduces triglyceride and low-density lipoprotein (LDL) levels and attenuates diet-induced atherosclerosis progression. The mean radiometry result collected during BAT maximization was  $33.2 \pm 1.5$  °C at points designated as active and  $32.7 \pm 1.3$  °C at points designated as inactive. It was shown that MWR could be used to detect active BAT without a radiotracer injection, and noninvasively [21].

### Urology

MWR was used to determine the microwave emission at nine points for the left and right kidney in the upper, intermediate and lower segments, which increases the sensitivity diagnosis of pathology [27]. First, MWR tests were performed in 30 healthy individuals and then in 86 patients with acute pyelonephritis. Healthy volunteers demonstrated the absence of thermal asymmetry, the temperatures of the kidneys differ with  $34 \pm <0.3$  °C. This temperature was considered as the physiological normal. In acute nonobstructive pyelonephritis, the thermal asymmetry average is 0.9 °C; or 1.5 °C among patients with acute obstructive pyelonephritis. These data provide evidence of MWR value at the early stages of the inflammatory process in renal tissue, when ultrasound has not yet detected structural changes in the renal parenchyma (only 64%). There were similar results in studies of 93

patients with acute nonobstructive pyelonephritis: 55 with acute obstructive, 19 with acute purulent and 140 without urological disease. The increase in deep temperature in acute purulent obstructive pyelonephritis was  $>1.3^{\circ}\text{C}$  and in acute obstructive pyelonephritis it was  $0.9\text{--}1.3^{\circ}\text{C}$ . In healthy individuals the difference between the kidneys was  $<0.3^{\circ}\text{C}$ . For prostate mean temperatures in the suprapubic area in patients with acute prostatitis it was  $37.1 \pm 0.2^{\circ}\text{C}$ , for prostate abscess it was  $38.0 \pm 0.3^{\circ}\text{C}$  and for prostate cancer it was  $36.4 \pm 0.2^{\circ}\text{C}$ . Healthy individuals in the older age group have decreased deep temperature in the perineal area from  $36.4 \pm 0.2^{\circ}\text{C}$  (age 18–25 years) to  $36.0 \pm 0.2^{\circ}\text{C}$  (age 66–75 years). Studies show that MWR could be used for diagnostics in different forms of acute pyelonephritis, renal colic and acute inflammatory diseases of the prostate [27].

### Whole-body scan

The biological aging markers [57] were revealed in the form of MWR thermal asymmetry in the projection zones of the following organs: the thyroid gland eight points; the liver 18 points; the kidneys nine points on each side; the spine (along the median and paravertebral lines in the cervical and thoracolumbar sections) 48 points; knee and hip joints nine points on each side. An average temperature was obtained for each zone. The average deep temperature, taken as a standard, was compared with the temperature at each point in the zone. When the value of the indicator was  $0.6\text{--}1.0^{\circ}\text{C}$  a dysfunctional type of thermal asymmetry was determined. The method enables identification of individuals with an accelerated rate of aging and the individualization of therapeutic measures in this group of patients.

### Preclinical applications

A special antenna was designed for preclinical studies to acquire fundamentally new information about the processes of metabolism, perfusion (microcirculation) and cellular kinetics in malignancies in animal models [31].

### Cell line applications

Microwave emission (brightness temperature) of a suspension of cells of follicular carcinoma of the thyroid gland during necrosis was monitored. It was shown that, when necrosis occurs in a cell suspension, the microwave emission increases, whereas the IR temperature does not change in the infrared range [32]. It was shown that cell necrosis could lead to a non-equilibrium state of the medium, expressed in a change in the microwave emission ratio. The authors hypothesized that the effect can be associated with the restructuring of the intracellular and intercellular cells. Cell necrosis in the microwave and infrared range can be monitored and used to control the dynamics of necrosis.

### In vitro applications

Using smaller microwave antennae with the USB powered sensor RTM-01-RES and a specialized antenna (Fig. 4), a microwave emission change of  $1.5\text{--}2^{\circ}\text{C}$  for aqueous albumin solution was found during its thermal denaturation. In addition, protein denaturation kinetics were determined [33]. The same phenomena were observed during chemical denaturation of egg white, which is well-known to contain 10% protein including albumin. The  $2^{\circ}\text{C}$  increase of microwave emission was observed during the first 20 s



FIGURE 4

Microwave passive antennae (disk and wire) for *in vitro* and cell culture experiments. The microwave sensor with USB connection to a laptop.

after alcohol addition, whereas infrared temperature rose much slower, taking minutes [36].

Microwave emission has been observed as well – in the process of hydroxylation of enzyme CYP102 A1 [34]. The  $0.5\text{--}2^{\circ}\text{C}$  increase within 10–20 s in multi-pulse mode follows the addition of co-substrate NADPH (0.2 mM) to the system containing lauric acid (0.5 mM), and enzyme  $10^{-10}$  to  $10^{-8}$  M. A single-pulse mode (synchronized pulse radiation) at  $10^{-6}$  M concentration of enzyme was observed. This effect could be explained using biomaser hypothesis. Also, the synchronized pulsed radiation could indicate the generation of qubits in a biological system [34]. The similar  $0.5^{\circ}\text{C}$  microwave emission increase in passive mode and  $2^{\circ}\text{C}$  in excitation mode was observed in a solution of horseradish peroxidase (HRP). Luminol ( $10^{-3}$  M) was added to the solution of HRP ( $10^{-6}$  M) and oxidization of the  $\text{H}_2\text{O}_2$  substrate ( $10^{-4}$  M) within 20 s in excitation mode has been observed [33].

Each HRP and CYP102 A1 reaction is accompanied by the fluctuation of the protein globule with approximately the same amplitude (in the order of 0.08 nm). The microwave emission effect could be explained by rotational transitions of molecules and ions excited during catalysis ( $\text{OH}^-$ ,  $\text{H}_2\text{O}$  and  $\text{H}_2\text{O}_2$ ) in GHz (the change in the ratio between para- and ortho-isomers of  $\text{H}_2\text{O}$  in GHz), with increased mobility of the protein globule during the catalytic reaction [33,34].

MWR does not require any isotopes or fluorescent labels. It is simple and low-cost in comparison with calorimeters and optical

spectrometers and provides new opportunities for R&D studies. Measurements can be recorded every 4 s and time series data can be analyzed, which is very important for enzyme kinetics studies. The method could be particularly useful in enzymatic and metabolic research, and for inhibitor screening. Microwave emission could be used as a direct readout to measure enzyme–substrate binding and inhibition effects. Further experiments with changing substrate and inhibitor concentrations are required to calibrate the method for particular biochemical systems. It is possible to determine kinetic parameters of biochemical processes. So, the method could be used to obtain data for modeling of biochemical reaction and quantitative dynamics modeling of cells, tissues and organs.

### AI for microwave radiometry: big data

Large volumes of microwave data can be generated inexpensively in comparison with other temperature measurements. An expert system has been developed to analyze these data [58,59] and, recently, AI deep learning has been applied to provide advice regarding the diagnosis of breast cancer. The dataset consists of 363 pairs of mammary glands of which 77 are classified as healthy or low risk (labeled as class 0) and 286 classified as potentially cancerous or high risk (labeled as class 1). The Deep Neural Networks (DNN) was able to obtain a G-mean loss of 0.2843, accuracy of 0.7703, sensitivity of 0.8103 and specificity of 0.625. The prediction will be increased when more data will be used in a training set. A human annotated dataset >2000 healthy and diseased breasts is under construction. Recently, we initiated a worldwide initiative to collect MWR data from patients and healthy people.

### Concluding remarks

It was shown that MWR has many advantages compared with IR thermography (IRT). MWR is not as expensive as fMRI. It benefits from passive sensors, a lack of radiation, no side-effects and high sensitivity. It can detect pathologies deep in the human body at an early stage and visualize and analyze results with advisory diagnostics software. It does not require any consumables. MWR could

be considered the ‘poor people’s fMRI’. This is a reason why MWR is very popular in developing countries but not in the West.

We have demonstrated that MWR can be used at all stages of the pharmaceutical R&D process, and as a rapid and cost-effective clinical diagnostic, as well as to monitor effects of therapies. As a companion diagnostic tool, MWR can increase the informativeness of existing X-ray and ultrasound diagnostics at the early stages of diseases. The high-resolution data obtained could be used for systems biology, quantitative systems pharmacology and deep neural network models to make predictions. Such models could be used for preclinical research, clinical trials, better diagnostics and monitoring effects of treatment.

Recently, the FDA issued a warning that IRT cannot be used as a diagnostic tool for breast cancer, because IR can only measure skin temperature [60]. MWR is an alternative technology that could be used for breast cancer diagnostics and screening programs from childhood. The technology is currently popular among traditional and holistic medicine practitioners, as well as beauty salon professionals. With the proven hardware, associated AI software and more clinical evidence we expect MWR will be used worldwide in the near future. More clinical studies and collaboration between academia and the pharma industry are required in different therapeutic areas.

### Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Acknowledgments

Sergey Vesnin’s research was supported by Russian Foundation for Basic Research (grant no. RFBR 19-19-00349). Yuri Ivanov’s research was supported partly by the Program for Basic Research of State Academies of Sciences for 2013-2020. The authors thank MMWR LTD., UK for funding and support in preparation of this publication.

### References

- Chelton, D.B. and Wentz, F.J. (2005) Global microwave satellite observations of sea surface temperature for numerical weather prediction and climate research. *Bull. Am. Meteorol. Soc.* 86, 1097–1116. <http://dx.doi.org/10.1175/BAMS-86-8-1097>
- Barrett, A.H. and Myers, P.C. (1975) Subcutaneous temperatures: a method of noninvasive sensing. *Science* 190, 669–671
- Leroy, Y. *et al.* (1998) Non-invasive microwave radiometry thermometry. *Physiol. Meas.* 19, 127
- Carr, K.L. (1989) Microwave radiometry: its importance to the detection of cancer. *IEEE Trans. Microwave Theory Tech.* 37, 1862–1869
- Hand, J.W. *et al.* (2001) Monitoring of deep brain temperature in infants using multi-frequency microwave radiometry and thermal modelling. *Phys. Med. Biol.* 46, 1885
- Levick, A. *et al.* (2011) Validation of microwave radiometry for measuring the internal temperature profile of human tissue. *Meas. Sci. Technol.* 22, 065801
- Bardati, F. and Iudicello, S. (2007) Modeling the visibility of breast malignancy by a microwave radiometer. *IEEE Trans. Biomed. Eng.* 55, 214–221
- Vesnin, S.G. *et al.* (2017) Modern microwave thermometry for breast cancer. *J. Mol. Imag. Dynamic.* 7, 10–1109
- Cheboksarov, D. *et al.* (2015) Diagnostic possibilities of noninvasive thermomonitoring of the brain. *Anesthesiol. Resus.* 1, 66–69 (in Russian)
- Butrov, A.V. *et al.* (2012) Non-invasive daily thermocartication of the brain in the dynamics of ischemic stroke with craniocerebral hypothermia. *Bull. Pflur. Ser. Med.* 7, 62–64
- Rodrigues, D.B. *et al.* (2018) Microwave radiometry for noninvasive monitoring of brain temperature. In *Emerging Electromagnetic Technologies for Brain Diseases Diagnostics, Monitoring and Therapy* (Crocco, L., ed.), pp. 87–127, Springer
- Stauffer, P.R. *et al.* (2014) Non-invasive measurement of brain temperature with microwave radiometry: demonstration in a head phantom and clinical case. *Neuroradiol. J.* 27, 3–12
- Karanasiou, I. (2012). “Functional brain imaging using non-invasive non-ionizing methods: towards multimodal and multiscale imaging,” in *Neuroimaging - Methods*, ed P. Bright (InTech). Available online at: <http://www.intechopen.com/books/neuroimaging-methods/functional-brain-imaging-using-non-invasive-non-ionizing-methods-towards-multimodal-and-multiscale-i>.
- Groupas, E. *et al.* (2020) Real-time passive brain monitoring system using near-field microwave radiometry. *IEEE Trans. Biomed. Eng.* 67, 158–165
- Kublanov, V.S. and Borisov, V.I. (2017) Biophysical evaluation of microwave radiation for functional research of the human brain. *EMBECC NBC 2017*, 1045–1048
- Toutouzas, K. *et al.* (2015) Incremental predictive value of carotid inflammation in acute ischemic stroke. *Stroke* 46, 272–274
- Toutouzas, K. *et al.* (2017) Noninvasive detection of increased carotid artery temperature in patients with coronary artery disease predicts major cardiovascular events at one year: results from a prospective multicenter study. *Atherosclerosis* 262, 25–30
- Toutouzas, K. *et al.* (2018) Increase in carotid temperature heterogeneity is associated with cardiovascular and cerebrovascular events: long-term results of a multicenter trial. *Circ. Cardiovasc. Imag.* 11, e008292

- 19 Toutouzias, K. *et al.* (2016) Inflamed human carotid plaques evaluated by PET/CT exhibit increased temperature: insights from an *in vivo* study. *Eur. Heart J. Cardiovasc. Imag.* 18, 1236–1244
- 20 Drakopoulou, M. *et al.* (2018) The role of microwave radiometry in carotid artery disease. Diagnostic and clinical prospective. *Curr. Opin. Pharmacol.* 39, 99–104
- 21 Crandall, J.P. *et al.* (2018) Measurement of brown adipose tissue activity using microwave radiometry and 18F-FDG PET/CT. *J. Nucl. Med.* 59, 1243–1248
- 22 Pentazos, G. *et al.* (2018) Microwave radiometry-derived thermal changes of small joints as additional potential biomarker in rheumatoid arthritis: a prospective pilot study. *J. Clin. Rheumatol.* 24, 259–263
- 23 Laskari, K. *et al.* (2018) SAT0657 microwave radiometry-derived thermal changes of sacroiliac joints as a biomarker of sacroiliitis in patients with spondyloarthritis. *Annal. Rheum. Dis.* 77 (Suppl. 2), 1–1178
- 24 Zampeli, E. *et al.* (2013) Detection of subclinical synovial inflammation by microwave radiometry. *PLoS One* 8, e64606
- 25 Zamechnik, T.V. *et al.* (2015) Kombinirovannaya radiotermometriya kak metod issledovaniya venoznogo krovoobrascheniya nijnih konechnostei [Combined radiothermometry as a method for the study of venous circulation of the lower extremities]. *Volgograd* 2015, 252
- 26 Paul R. Stauffer, Paolo F. Maccarini, Kavitha Arunachalam, Valeria De Luca, Sara Salahi, Alina Boico, Oystein Klemetsen, Yngve Birkelund, Svein K. Jacobsen, Fernando Bardati, Piero Tognolotti, Brent Snow, "Microwave radiometry for non-invasive detection of vesicoureteral reflux (VUR) following bladder warming," Proc. SPIE 7901, Energy-based Treatment of Tissue and Assessment VI, 79010V (22 February 2011); <https://doi.org/10.1117/12.875636>.
- 27 Kaprin, A.D. *et al.* (2019) Microwave radiometry in the diagnosis of various urological diseases. *Biomed. Eng.* 53, 87–91
- 28 Tarakanov, A.V. *et al.* (2020) Microwave radiometry (MWR) temperature measurement is related to symptom severity and duration in patients with low back pain. *LBP*
- 29 Tarakanov A.V., Efremov V.V., Tarakanov A.A. PERSPECTIVES OF MICROWAVE RADIO THERMOMETRY APPLICATION AT DORSOPATHY IN HOSPITAL DEPARTMENT OF THE EMERGENCY CALL SERVICE. EMERGENCY MEDICAL CARE. 2016;17(1):59-62. (In Russ.) <https://doi.org/10.24884/2072-6716-2016-17-1-59-62>.
- 30 Spiliopoulos, S. *et al.* (2017) Multi-center feasibility study of microwave radiometry thermometry for non-invasive differential diagnosis of arterial disease in diabetic patients with suspected critical limb ischemia. *J. Diabetes Complications* 31, 1109–1114
- 31 Zinoviyev, S.V. (2018) New medical technology – functional microwave thermography: experimental study. *KnE Energy* 2018, 547–555
- 32 Ivanov, Y.D. *et al.* (2016) Monitoring of brightness temperature of suspension of follicular thyroid carcinoma cells in SHF range by radiothermometry. *Patol. Fiziol. Eksp. Ter.* 60, 174–177
- 33 Ivanov, Y.D. *et al.* (2016) Monitoring of microwave emission of HRP system during the enzyme functioning. *Biochem. Biophys. Rep.* 7, 20–25
- 34 Ivanov, Y.D. *et al.* (2019) The registration of a biomaser-like effect in an enzyme system with an RTM sensor. *J. Sensors*. <http://dx.doi.org/10.1155/2019/7608512>
- 35 Goryanin, I. *et al.* (2019) Monitoring protein denaturation using passive microwave radiometry. *JoVE*
- 36 Ivanov, Yu.D., Malsagova K.A., Tatur, V.Yu., Vesnin, S.G., Ivanova, N.D., Ziborov, V.S. SHF radiation from albumin solution upon external excitation, *Patologicheskaya fiziologiya i eksperimental'naya terapiya* (Pathological Physiology and Experimental Therapy, in Russian). 60 (3), 101-104 (2016).
- 37 Livanos, N.A. *et al.* (2018) Design and interdisciplinary simulations of a hand-held device for internal-body temperature sensing using microwave radiometry. *IEEE Sensors J.* 18, 2421–2433
- 38 Karabetos, S. *et al.* (2015) Development of the RF front-end of a multi-channel microwave radiometer for internal body temperature measurements. *J. Phys. Conf. Ser.* 637, 012010
- 39 Akki, R.S. *et al.* (2019) Multi-physics modeling to study the influence of tissue compression and cold stress on enhancing breast tumor detection using microwave radiometry. *Bioelectromagnetics* 40, 260–277
- 40 Sedankin, M. *et al.* (2018) Development of a miniature microwave radiothermograph for monitoring the internal brain temperature. *Eastern Eur. J. Enterprise Technol* 3, 26–36
- 41 Gudkov, A.G. *et al.* (2019) Use of multichannel microwave radiometry for functional diagnostics of the brain. *Biomed. Eng.* 53, 108–111
- 42 Sedankin, M.K. *et al.* (2018) Antenna applicators for medical microwave radiometers. *Biomed. Eng.* 52, 235–238
- 43 Oikonomou, A. *et al.* (2010) Phased-array near field radiometry for brain intracranial applications. *Prog. Electromagnet. Res.* 109, 345–360
- 44 Popovic, Z. *et al.* (2014) Toward wearable wireless thermometers for internal body temperature measurements. *IEEE Commun. Mag.* 52, 118–125
- 45 Momenroodaki, P. *et al.* (2017) Noninvasive internal body temperature tracking with near-field microwave radiometry. *IEEE Trans. Microwave Theory Tech.* 66, 2535–2545
- 46 Warburg, O. (1956) On the origin of cancer cells. *Science* 123, 309–314
- 47 Heber, D. *et al.* (1982) Abnormalities in glucose and protein metabolism in noncachectic lung cancer patients. *Cancer Res.* 42, 4815–4819
- 48 Nolop, K.B. *et al.* (1987) Glucose utilization in vivo by human pulmonary neoplasms. *Cancer* 60, 2682–2689
- 49 Karaszewski, B. *et al.* (2006) Measurement of brain temperature with magnetic resonance spectroscopy in acute ischemic stroke. *Annal. Neurol.* 60, 438–446
- 50 Ginsberg, M.D. *et al.* (2013) High-dose albumin treatment for acute ischaemic stroke (ALIAS). Part 2: a randomized, double-blind, Phase 3, placebo-controlled trial. *Lancet Neurol.* 12, 1049–1058
- 51 Sandeep, F. *et al.* (2017) Prognosis significance of serum albumin in acute ischemic stroke. *Eur. J. Pharm. Med. Res.* 4, 138–142
- 52 Belayev, L. *et al.* (2001) Human albumin therapy of acute ischemic stroke: marked neuroprotective efficacy at moderate doses and with a broad therapeutic window. *Stroke* 32, 553–560
- 53 Stanford, K.I. *et al.* (2013) Brown adipose tissue regulates glucose homeostasis and insulin sensitivity. *J. Clin. Invest.* 123 (Jan(1)), 215–223. <http://dx.doi.org/10.1172/JCI62308>
- 54 Chondronikola, M. *et al.* (2014) Brown adipose tissue improves whole-body glucose homeostasis and insulin sensitivity in humans. *Diabetes* 63, 4089–4099
- 55 Berbée, J.F.P. *et al.* (2015) Brown fat activation reduces hypercholesterolemia and protects from atherosclerosis development. *Nat. Commun.* 6, 6356
- 56 Available at: <https://edrid.ru/rid/218.016.42ed.html>.
- 57 Galazis, C. *et al.* (2019) Application of artificial intelligence in microwave radiometry (MWR). *Proc. Bioinformatics*. <http://dx.doi.org/10.5220/0007567901120122>
- 58 Losev, A.G. *et al.* (2015) Problems of measurement and modeling of thermal and radiation fields in biological tissues: analysis of microwave thermometry data. *Math. Phys. Comput. Simul.* 6, 31–71
- 59 Bondar, S.S. *et al.* (2017) Assessment of transcapillary water exchange in the lungs by active radiometry. *Biomed. Eng.* 51, 211–214
- 60 FDA warns thermography should not be used in place of mammography to detect, diagnose, or screen for breast cancer: FDA safety communication. Available at: <https://www.fda.gov/medical-devices/safety-communications/fda-warns-thermography-should-not-be-used-place-mammography-detect-diagnose-or-screen-breast-cancer>.