DOI 10.1007/s10527-019-09928-7
Biomedical Engineering, Vol. 53, No. 4, November, 2019, pp. 288-292. Translated from Meditsinskaya Tekhnika, Vol. 53, No. 4, Jul.-Aug., 2019, pp. 45-49.
Original article submitted April 25, 2019.

Microwave Radiometry of the Pelvic Organs

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The problems of designing a microwave radiometer for thermal monitoring of pelvic organs were considered. Based on mathematical modeling, a waveguide antenna for intracavitary diagnostics was developed. The antenna was tested in various phantoms and biological tissues. The obtained results can be used in various fields of medicine and robotics.

Introduction

Various medical devices can be used as diagnostic tools for medical systems. In particular, medical radiometers can be used to search for pathological changes in the human body. Oncological diseases of the pelvic organs are an important medical problem. In 2012, 527,600 cases of cervical cancer were diagnosed worldwide, of which 265,700 were fatal. In Russia, in 2004-2015 there was an increase in the incidence of cervical cancer from 110.3 to 119.7 cases per 100,000 population [1, 2]. Various diagnostic techniques are used to identify cervical cancer. Nevertheless, there is a certain dissatisfaction in the medical community with the existing techniques for the diagnosis and treatment of malignant tumors of the cervix. In particular, it is very important to introduce techniques for measuring the temperature of biological objects into cervical cancer diagnostics. Such measurements are painless and provide valuable diagnostic information. Around the world, two types of thermometric diagnostic devices are being developed: for measuring temperature through the skin and through the body's natural cavities. Robotization of thermometric measurements is needed to increase their effectiveness.

In 2009, a scientific team from the University of Beira Interior, Covilhã, Portugal, developed an intracavitary sensor for intravaginal temperature monitoring [3, 4]. The temperature meter (MA100 thermistor) is placed in a tampon to provide comfortable placement in the body. The device makes it possible to examine the fertility of women. Tests showed that there is a correlation between the intravaginal temperature and various physiological processes. A similar wireless sensor is described in [5]. It comprises a thermistor, a microcontroller, a transceiver (IEEE 802.15.4), and a battery. The device provides temperature imaging using an application installed on the smartphone or tablet. Using such devices [3-6], a woman can track temperature changes in real time to determine the exact time of ovulation, etc. These sensors measure only the average intravaginal temperature and are designed for pregnancy planning, so using them for targeted diagnosis is ineffective. The female pelvic organs are located inside the body, so that inflammation of the ovaries or other pathology does not lead to an increase in the temperature of the abdominal and vaginal walls. For examination of the cervix, it is advisable to use the technique of microwave radiometry (MR). The standard antennas used in MR of the mammary glands cannot be applied here due to their significant size. For examination of the cervix, an antenna should be designed so as to provide insertion into a biological cavity.

The first use of MR in gynecology in Russia was described in [7]. The examination was carried out transab-

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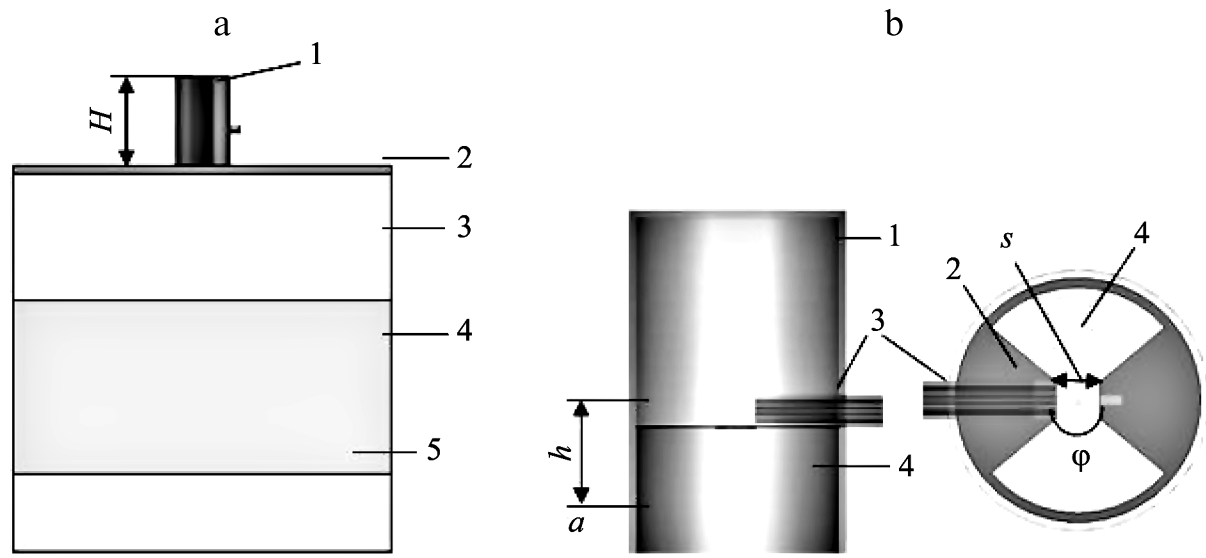

Fig. 1. a) Multilayer model: 1 – antenna; 2 – mucous membrane; 3 – layer of the cervix; 4 – layer of the uterus; 5 – absorber. b) Antenna: 1 – waveguide; 2 – emitter; 3 – coaxial cable; 4 – dielectric.

dominally, i.e., the antenna was installed on the abdominal cavity in the projection of the uterus. However, such an examination provides only indirect information about the processes in the pelvis. In [8], a radiometer with an intracavitary single-channel antenna was used. The use of an intravaginal sensor made it possible to diagnose acute salpingo-oophoritis, exacerbations and subacute course of chronic salpingo-oophoritis, as well as inflammatory processes in the area of uterine appendages [9].

An intracavitary antenna for measuring the temperature of the prostate is implemented as a slot antenna. It measures the temperature through a slot in the cylinder. Measurements are conducted through the lateral surface, so that the antenna cannot be used for targeted diagnostic examination of the cervix and internal tissues. This work considers the problem of developing an intracavitary antenna for examination of the cervix based on a waveguide antenna.

Methods

A microwave antenna in contact with the human body measures the average brightness temperature (BT) T_{rad} in the bulk of the biological tissue below the antenna. The brightness temperature measured by the medical radiometer depends on the thermodynamic temperature $T(r)$ and the radiometric weight function $W(r)$ of the antenna as follows [9, 10]:

$$T_{rad} = \int_{-\infty}^{\infty} T(r) \cdot W(r) dV; \tag{1}$$

$$W(r) = \frac{\sigma(r)|E(r)|^2}{\int_{-\infty}^{\infty} \sigma(r)|E(r)|^2 \, dV}, \tag{2}$$

where $E(r)$ is the intensity of the electric field generated by the antenna and $\sigma(r)$ is the electrical conductivity of biological tissues.

To develop an intracavitary antenna, calculations of its electric field $E(r)$ in the near field zone were made using electrodynamic simulation software. Maxwell's equations were numerically solved in a finite-difference form using the finite-difference time-domain (FDTD) method. The object under study is a multilayer structure (Fig. 1). The thickness of the layers of the model corresponds to the anatomy of the body. All layers of the model are isotropic in their physical properties. The software automatically creates a model grid. The grid step varies from subdomain to subdomain.

The region under study was 100 × 100 × 100 mm in size. The axis of the antenna was located in the center of region under study at $X_0 = 50$ mm, $Y_0 = 50$ mm. The minimum step of the spatial grid was chosen to be 0.01 mm, as corresponding to the minimum size of the model elements (the thickness of the metal coating of the emitter is 0.1 mm). At the boundary of the region under study, the electric field has no tangential components. The antenna

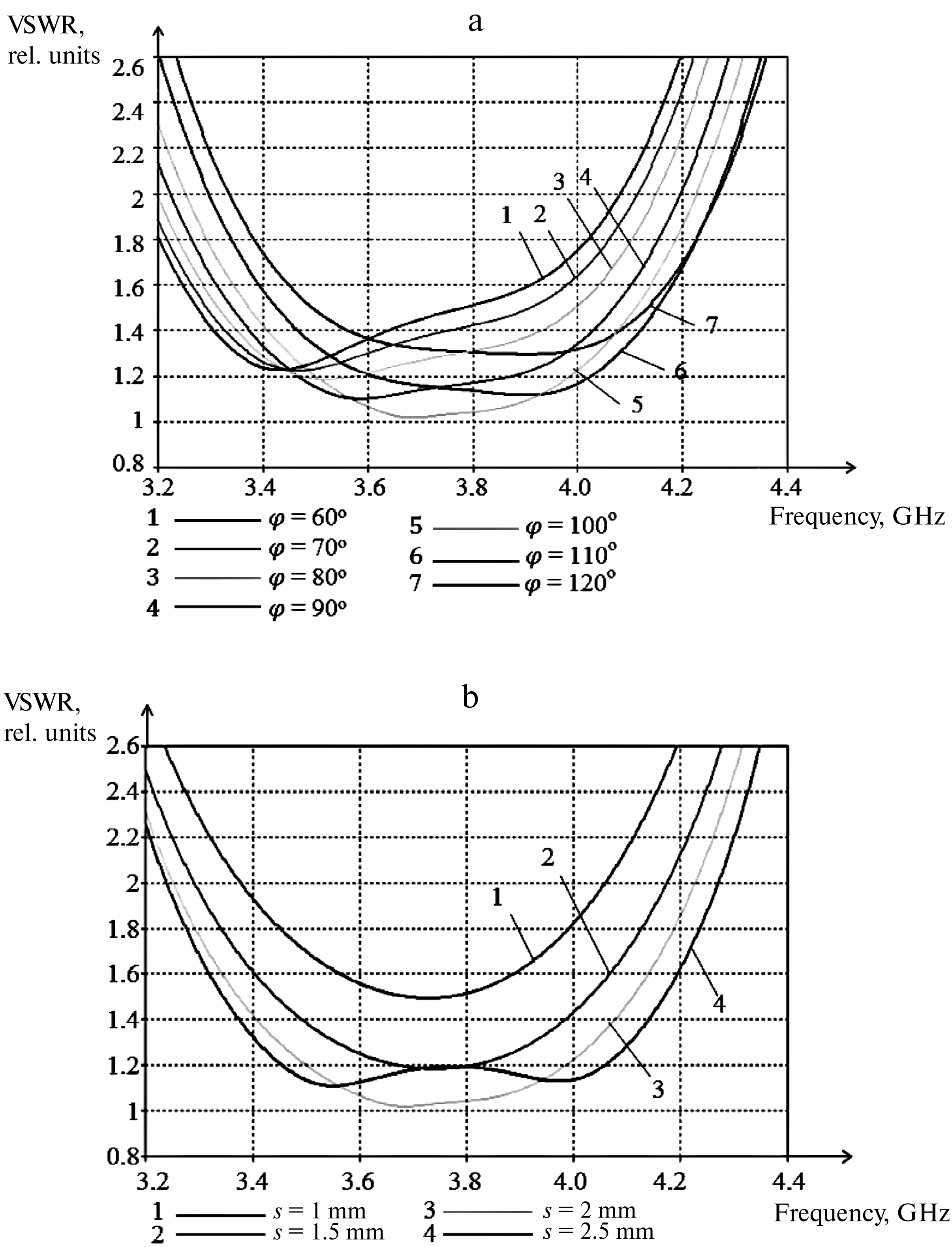

Fig. 2. VSWR vs. frequency curves at different values of φ (a) and *s* (b).

is a circular cross-section waveguide filled with microwave ceramics. After consulting with doctors, the total diameter of the antenna was chosen to be 15 mm; the antenna length, 170 mm. In the model, the antenna is excited using a coaxial cable. Most antennas are designed as operating in the active mode. However, it must be understood that the MR technique is passive and does not involve radiation emission into the biological object. A critically important characteristic of the antenna is its matching to biological tissues. Accordingly, the voltage standing wave ratio (VSWR) was used to assess the effectiveness of application of waveguide antennas for examination of the cervix. The electrophysical parameters of biological tissues in the 3.8 GHz range are as follows: mucous membrane (conductivity, 2.54 S/m; permittivity, 41.09; thickness, 2 mm), cervix (2.77 S/m; 45.95; 20 mm), uterus (3.54 S/m; 55.63; 40 mm); absorber (3.45 S/m; 55.44; 38 mm) [11]. The following values are taken as the initial geometric parameters of the antenna model: opening angle of the slot, $\varphi = 90°$; dielectric height, $h = 5$ mm; permittivity, $\varepsilon = 25$; slot gap width, $s = 2$ mm; antenna height, $H = 20$ mm; antenna diameter, 15 mm.

Results

The VSWR can be optimized by varying the geometric parameters listed above. A series of calculations was performed for various values of the geometric parameters of the antenna. First, h was varied from 9 to 20 mm. The

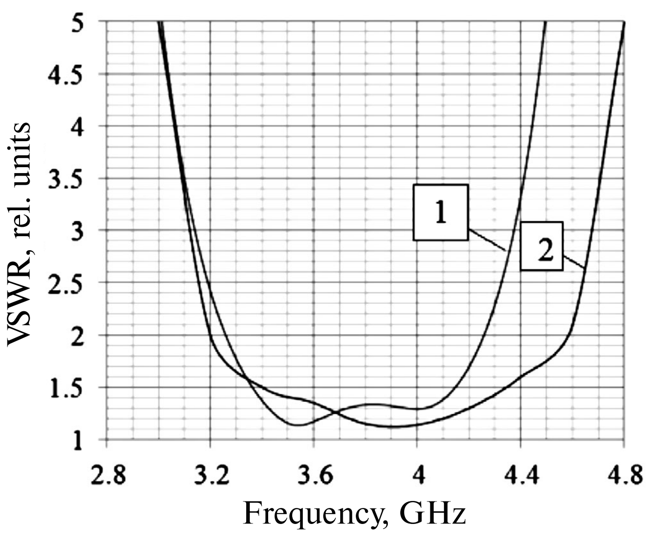

Fig. 3. Antenna VSWR: 1) experiment; 2) simulation.

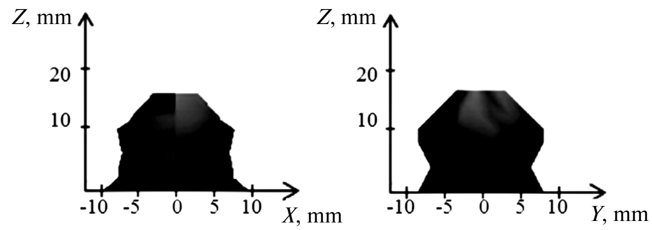

Fig. 4. Brightness temperature measurement area: a) E-plane; b) H-plane.

operating band was selected so as to provide VSWR < 2, minimizing thereby the mismatch between the antenna and the body. According to the simulation results, the best VSWR was attained at $h = 9$ mm. Variation of the angle φ showed that the best VSWR was attained at $\varphi = 100°$. Further simulation involved variation of s.

The analysis of the curves presented in Fig. 2 showed that for $s = 2$ mm the VSWR at the central frequency was optimal. As the result of the simulation, the optimal geometric parameters of the antenna were determined: $h = 9$ mm, $\varphi = 100°$, $s = 2$ mm, $H = 24$ mm.

Experimental studies were performed in liquid phantoms using an Agilent Technologies E5071C network analyzer in the frequency range of 3-4.6 GHz. Figure 3 shows the VSWR vs. frequency curves for the antenna obtained experimentally and by mathematical simulation. The two curves are close enough, which confirms the correctness of the calculations. The brightness temperature was measured in a volume under the antenna, in which 85% of the total power received by the antenna is concentrated. As shown in Fig. 4, the estimated measurement depth provided by the antenna is 16 mm, which is sufficient for detecting cervical cancer.

Conclusions

The microwave radiation emitted by the cervix was mathematically simulated. A waveguide antenna for intracavitary examination was developed. The developed antenna can serve as the basis for designing an intracavitary radiometer. The design characteristics of the antenna ensure the detection of thermal radiation emitted by small tissue volumes (cervix pathologies located at a depth of 4.5-16 mm or deeper) and the monitoring of small changes in the temperature of the cervix (<0.4°C) associated with an increased metabolism of degenerate cells or an inflammation. The experimental studies confirmed the promise of using the antenna in medicine. The practical implementation of the results of this study would consist in the creation of innovative products and the integration of MR devices into medical (including robotic) systems of various kinds.

This work was financially supported by the Russian Science Foundation (project No. 19-19-00349).

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