N. D. Devyatkov, É. A. Gel'vich, I. B. Davydova, V. V. Kirillov, D. N. Kolmakov, V. N. Mazokhin, V. I. Sinyagovskiĭ, and P. I. Chilikin. *Microwave and Radio-Frequency Apparatus and Methods for Use in Oncology.*

1. Application of hyperthermia in oncology. In recent years, hyperthermia—artifical elevation of the human body's temperature above normal—has been used to a significant degree as a means of improving the effectiveness of treatment of malignant neoplasms.[1,2,13]

The use of hyperthermia is based on the fact that when they are overheated, cancer cells become more sensitive to the radiation and chemotherapy used to destroy them.[1,3-5,9] Some reports indicate that hyperthermia might also be used as an independent procedure for the treatment of certain diseases.[16]

Among the first methods used for controlled overheating of tumors were regional perfusion[3,12] (heating by introduction of heated blood into the affected area of the body from a heart-lung machine) and general heating of the body in a water bath or shower.[1,10,11] The perfusion technique was found to be ineffective as a means of destroying tumors and at the same time to damage surrounding healthy tissues; for this reason it is no longer used.[3]

Hyperthermia produced with the aid of electromagnetic energy has a number of advantages over most existing techniques. The electromagnetic-heating procedure does not raise general body temperature like, for example, a shower, sunbath, hot-water or hot-air bath, or other methods that transmit heat through the blood circulation and the thermal conductivity of the tissues from the surface of the skin into internal regions, but instead heats directly the whole volume of the body to be subjected to hyperthermia. This significantly shortens the time required to obtain the desired temperature regime and lowers the thermal load on the patient's skin and, consequently, on his cardiovascular system, to a considerable degree. Electromagnetic hyperthermia can be used either for general heating of the organism or for localized heating in a limited volume of the body, with comparatively simple maintenance of the required temperature regime in the heated volume and operational control of the treatment dose and time.[1,2,13]

2. Differences between hyperthermia and microwave

and uhf therapy. Although microwave and uhf therapies are widely used in medical practice, the transition to electromagnetic hyperthermia imposes certain requirements that are quite rigid and, at the moment, difficult to meet. This is because the intensity of irradiation in electromagnetic therapy is established on the basis of how the patient feels; the procedures produce no unpleasant emotional or irritated states, and their regimes are far below critical. At the same time, the optimal electromagnetic hyperthermia procedure should produce quite definite temperature levels near but not above the danger threshold ($45°C^2$) in various tissues (including superficial and deep, normal and pathologically modified tissues). Excessive heating may produce dangerous and sometimes irreversible consequences: burns, tissue necrosis, impaired performance of cardiovascular system, etc.

This results in rigid requirements as to the heating procedure and the apparatus used to produce the heating. Control of heating must be highly flexible, and monitoring of the patient's state must be clearcut. A necessary condition for the creation of such hyperthermia apparatus is automation of the heating procedure, automation of maintenance of the specified irradiation regimes, and maintenance of the specified temperature distribution in the part of the body subject to hyperthermia. The existence of critical thermal regimes naturally makes for more stringent requirements as to the accuracy of temperature measurement. The desirable error of measurement of the absolute value of temperature should be no greater than ± 0.2°C.

3. Apparatus for microwave and hf hyperthermia. Several systems for heating tissues situated at various depths in the human body have been developed and are being used successfully at the Scientific Research Institute of Oncology and Medical Radiology of the Belorussian SSR Ministry of Public Health and in certain other institutes in the country.

The "Parus-1" machine, which operates at a frequency of 2450 MHz, is used to heat subcutaneous tissues, and the "Plot" apparatus (operating frequency 915 MHz) for heating of deeper-lying tissues. They are based on the identical schematic diagram. The microwave power generators in these units are magnetrons operating in a two-frequency mode: 2450± 49 MHz and 915 ± 19 MHz, respectively, with output powers that can be controlled in the range from 5 to 200 W.[1,6]

The design features of the magnetrons make it possible to power them directly with the 50-Hz commercial-frequency voltage from the secondary winding of a high-voltage transformer. The magnetron power-supply scheme is similar to that of a full-wave rectifier—each half of the magnetron generates during part of a half-cycle of the line voltage.

Output power can be controled in either of two ways: by varying the amplitude of the supply voltage or by varying the time of microwave energy generation in each half-cycle.

In the latter case, the plate-current cutoff angle of the magnetron is adjusted with a thyristor controller. This method is also used in the "Parus-1" and "Plot" units for automatic control of output power with the object of arriving at the prescribed temperature regimes in the specified volume. Automatic feedback is provided by temperature sensors mounted in the heating zone. The temperature-sensitive elements are copper-constantan thermocouples or special-purpose solid-state components. Temperature is held to within ± 0.5° of constant at the monitoring point. The "Parus-1" and "Plot" systems have built-in magnetron-monitoring modules, indicators for the amounts power that have passed through the channels and for matching of the radiator to the biological object, and treatment-time digital-indicator modules. Systems working both at 915 and at 2450 MHz, which can be used for irradiation in accordance with the depth and dimensions of the tumors, were developed in order to broaden the hyperthermia capabilities of the microwave generators.

The uniformity and rate of heating in an electromagnetic field depend strongly on the structure of the tissues, their shapes and dimensions, blood supply, thermal conductivity, and other factors.[8,11]

The "Barkas" experimental unit was built to produce general hyperthermia by high-frequency heating with meter-band energy. Its generator operates at 13.56 MHz with controllable output power in the range from 100 to $1.3 \cdot 10^3$ W. The unit also includes various types of radiators and a microclimate setup. Depending on the radiators used, the heating rates obtained in general hyperthermia may exceed 1°C in 10 min.

The necessary heating rate is established by setting the generator tc the appropriate output-power level.

A set of inductive and capacitative radiators makes it possible to produce either general or local hyperthermia in the meter band.

The microclimate setup was designed to create and automatically maintain predetermined air temperatures and relative humidities in an enclosed volume to prevent and compensate for dehydration of the subject during the procedure.

In addition, the microclimate feature makes it possible to shorten the time required for general heating of the organism to the target temperature, and to maintain the temperature level that has been reached automatically for an extended period after the hf generator has been switched off.

The unit provides for automatic stabilization of temperature in the closed volume to within ± 1°C between 35 and 40°C and can produce relative air humidities of up to 95% in the closed space.

4. Radiators. The "Parus" and "Plot" units incorporate sets of resonant-type horn radiators with various diameters, from 30 to 90 mm.[6,7] The optimum distance from the radiator to the subject ranges from 1.5 to 2 cm.

The radiators are sections of circular waveguide with a smooth tapered adaptor to a coaxial line that terminates in a high-frequency coaxial connector.

Plates that form a capacitative gap, the element that

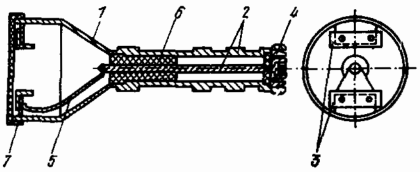

FIG. 1. Schematic design of horn radiator. 1) horn; 2) coaxial cable; 3) capacitative-gap plates; 4) microwave connector; 5) matching blade; 6) dielectric transformer; 7) protective cover.

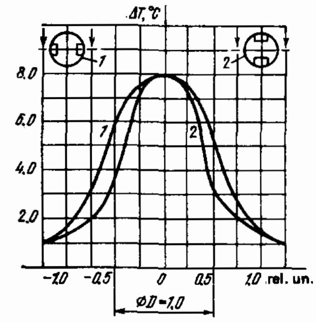

FIG. 3. Averaged characteristics of heat-field distribution in phantom during heating with horn radiator of diameter D at frequency of 915 MHz. 1) perpendicular to capacitative gap; 2) along capacitative gap.

radiates the electromagnetic field, are mounted in the opposite end of the radiator. One of the plates is connected to the central conductor of the coaxial line by a strip transformer (matching blade). A dielectric transformer is built into the coaxial section of the radiator to broaden its passband. Figure 1 shows a schematic representation of the radiator design. The weak dependence of the radiator's matching characteristics on the physical parameters of the irradiated tissues (shape, ε, tan δ) and their composition (skin, muscle, fat, bone) that is necessary for reliable operation is obtained by adjusting the length of the transformer, the configuration of the capacitative-gap plates, and the distance between them. The total operational indicator of the microwave strip and the loaded radiator ranges from 1.8 to 2.0 over the entire frequency band generated by the magnetron as ε, tan δ, and the shape and composition of the irradiated object vary within the limits encountered in clinical practice.

Averaged characteristics of the electromagnetic and thermal field distributions of these radiators appear in Figs. 2 and 3.

It is sometimes necessary to use cavity radiators. Here size and design requirements are dictated by the anatomical structure of the human body (its cavities) and by the dimensions and shapes of the tumors encountered in clinical practice and their locations in the cavities.

The microwave cavity radiators that we have developed are rod-type designs with monopole or dipole excitation that are built around a segment of coaxial cable. The radiator is placed in a colpostat of the appropriate diameter, which serves to protect it from mechanical damage and to insulate it electrically from the tissues.

A forced water-cooling system is built into the colpostat sheath to remove excess heat from the walls of the cavities and to make heating uniform over the depth of the tissues. Figure 4 shows a schematic representation of the radiator with the colpostat.

The radiators used in the "Barkas" set, which operate at a frequency of 13.56 MHz, are intended for both general and local hyperthermia. This operating frequency, which is low compared to the microwaves, makes it possible to heat deeper regions of the organism. The general-heating inductive radiators are made in the form of two 500 × 500 mm or 500 × 900 mm frames, between which the biological object is placed (Fig. 5). The distance between the frames can be adjusted from 250 to 400 mm (depending on the size of the object).[6] Each frame contains several turns of silvered copper ribbon that are connected in parallel. The efficiencies of the radiators, which are connected to the hf generator by a coaxial cable via a matching device, may range up to 40–70%, depending on the dimensions, shape, and composition of the biological object. To produce a temperature distribution with a predetermined nonuniformity in the biological object, it is necessary to consider the influence of blood flow, the time intervals of heating, and other factors.

Both inductive and capacitative radiator systems are used to obtain local high-frequency hyperthermia.

The inductive radiator system consists of three coupled resonant circuits. One of the circuits works as a matching device, while the other two are placed one on each side of the biological object to be heated and localize the electromagnetic field in the gap between them. The required localization of the induced currents in the tissues of the organism—in the plane perpendicular to the common axis of the three circuits—is obtained by using special S-shaped radiating inductors (Fig. 6).

The correct heating regime can be selected by monitoring the amplitude and phase of the high-frequency currents in the resonant circuits on either side of the

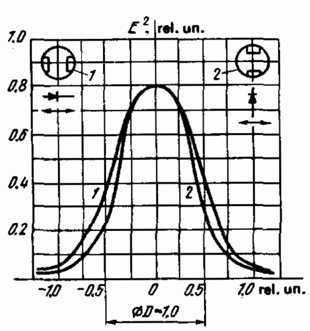

FIG. 2. Averaged characteristics of distribution of electric component of electromagnetic field of horn radiator with diameter D at frequency of 915 MHz. 1) perpendicular to capacitative gap; 2) along capacitative gap.

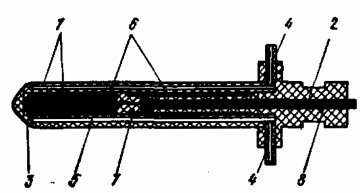

FIG. 4. Schematic representation of a cavity radiator with colpostat. 1) Inner and outer colpostat tubes; 2) mount; 3) cap; 4) cooling-water inlet and outlet; 5) coolant passages; 6) antenna dipole elements; 7) insulator; 8) coaxial cable.

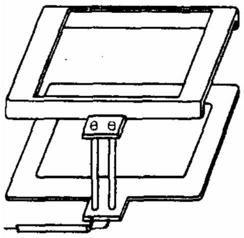

FIG. 5. Schematic representation of general-heating inductive radiator.

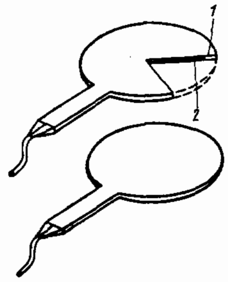

FIG. 7. Schematic representation of capacitative radiators for high-frequency heating. 1) Dielectric cover; 2) capacitor plate.

object.

The capacitative radiator system (Fig. 7) takes the form of a high frequency capacitor with two or more flat electrodes, which are connected to the generator via a special matching device. In this case, heating of specified regions of the body is accomplished largely by the electrical component of the high-frequency electromagnetic field.

Thus, the availability of different generator and radiator systems permits a more flexible approach to the local-hyperthermia procedure in accordance with the dimensions, shape, and electrophysical parameters of the tissues and the physiological peculiarities of the region of the organism to be heated.

One promising direction in which the functional capabilities of the units could be broadened would involve scanning the radiators over the surface of the object.

5. Measurement of temperature. Hyperthermic treatment of a tumor and prevention of harmful effects of the heat on nearby healthy tissues require close monitoring of temperature in the irradiated zone and provision for automatic maintenance of a predetermined temperature within certain tolerances throughout the entire time of treatment. Conditions for the measurement of temperature are made difficult by the fact that the temperature sensor must function in high-frequency or microwave fields with power fluxes of several watts per square centimeter. The metal sleeves become overheated at these power levels, and this results in temperature-measurement errors and the possibility of internal burns, which heal with difficulty. In addition, these sleeves and the connecting wires strongly influence the manner in which the field is distributed in the irradiated zone. Repeated introduction of temperature sensors into the tissue (before and during each treatment) is very unpleasant for the patient.

Metallic conductors that connect temperature-sensitive elements to measuring instruments act as hf and microwave receiving antennas; this overheats thermoresistive or semiconductor sensors on the one hand and, on the other, sets up induced currents in the measuring instruments that are difficult to suppress. Unfortunately, the arsenal of temperature-measurement tools now at our disposal, with its thermo-couple, thermoresistive, thermistor, and semiconductor sensors, is subject to the above shortocmings.

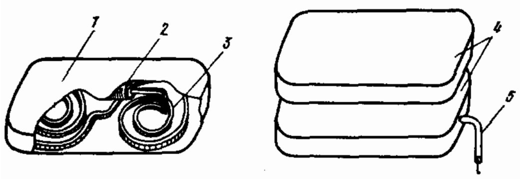

FIG. 6. Schematic representation of inductive system in radiators for local high-frequency heating. 1) Dielectric cover; 2) 3rd-circuit capacitor; 7) circuit inductance; 4) 1st- and 2nd-circuits of the system; 5) high-frequency cable.

If the range of applications of the new apparatus is to be broadened significantly, it will be vital to provide reliable measurement of temperature during the heating process, irrespective of the orientation of the sensor in the field and at any electromagnetic frequency. Therefore the development of a temperature sensor that is insensitive to electromagnetic fields is a problem of high priority.

6. Results from use of microwave hyperthermia apparatus. Local microwave hyperthermia procedures have been under development and in use at the Minsk Scientific Research Institute of Oncology and Medical Radiology since 1971. After thorough study and testing of the method on animals, it was put to use in the clinic as one component in the treatment of patients with far-advanced and recidivistic tumors of the extremities. The use of local microwave hyperthermia to treat these patients, in combination with chemo- or radiation therapy, has made it possible in some cases to avoid radical surgery or to perform palliative surgery on the extremities. The chemotherapy doses were reduced to half of the usual levels, and the radiation was given in functionated doses. Local hyperthermia has since been used successfully in the treatment of breast cancer.[4]

In recognition of the experience accumulated and the treatment results obtained, a 1975 Resolution of the USSR Main Administration of the Medical Service (GUMS) recognized local hyperthermia as clinical for the treatment patients in the early stages of disease at the clinic of the Minsk Scientific Research Institute of Oncology and Medical Radiology.

Local microwave hyperthermia was approved for use at the clinics of five more oncology institutes by a 1979 GUMS Resolution.

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