V. S. Troitskiĭ, A. V. Gustov, I. F. Belov, V. M. Plechkov, V. P. Gorbachev, and L. K. Siz'mina. *Possible Use of the Intrinsic Microwave Thermal Radio Emission of the Human Body to Measure the Temperatures of Its Internal Organs: Results and Prospects.* The possibility of indefinitely continued and painless measurement of temperature inside the bodies of humans and animals is of great importance for medicobiological research and in medical practice. It is known that many illnesses are accompanied by local changes in the temperatures of affected areas of the body as a result of inflammatory processes or the presence of neoplasms. Internal-temperature changes offer new opportunities for diagnosis and the localization of the seats of diseases within the organism.

Until recently, no procedures were available for bloodless determination of the temperatures of internal organs. Thermovision, which is based on measurement of the infrared thermal radiation of the body, gives the true temperature only for an outermost skin layer a fraction of a millimeter thick. It reflects very poorly the subsurface and deep temperatures of a living organism.

Methods for determination of internal temperature by measuring the intensity of thermal radioemission escaping from deep within the body have recently been developed in the Soveit Union and abroad.[1,2] The measurements are made with radiometers, which have been used for many years in radio astronomy, and a special probe antenna that must be applied flush to the subject's body. The human body's thermal radio emission comes from a layer with a thickness of the order of the penetration depth of the corresponding wavelength. The penetration depth l in any human tissue is approximately equal to the wavelength in the tissue, i.e., $l = \lambda = \lambda_0/\sqrt{\varepsilon}$, where λ_0 is the wavelength in vacuum and ε is the dielectric constant of the tissue. For fatty and bone tissue $\varepsilon \approx 6$ and $l \approx 0.5 \times \lambda_0$, and for muscle tissue $\varepsilon \approx 50$ and $l \approx 0.15\lambda_0$.

The resolution at the surface is determined by the dimensions of the probing antenna, the optimum diameter of which is of the order of the wavelength in the medium, i.e., $D \approx \lambda_0/\sqrt{\varepsilon}$. The Fresnel zone of this antenna in the tissues is $2D^2\sqrt{\varepsilon}/\lambda_0 \approx 2\lambda_0/\sqrt{\varepsilon}$, i.e., equal to twice the penetration depth of the wave. For practical purposes, therefore, the radiation is collected from a cylinder of tissue with a base diameter D and a height of the order of magnitude of the penetration depth. This makes it clear that use of lens antennas much larger than the wavelength in the medium will not provide focusing or increased resolution because of the strong absorption of the peripheral rays as compared to the central rays. Only a central area comparable to the focal length, which should be of the order of $l = \lambda_0/\sqrt{\varepsilon}$, will "work."

The first applications of radiometry to measure internal temperatures were reported in Ref. 1 (wavelength $\lambda_0 = 10$ cm). However, only relative temperatures across the body, and then for the most part between symmetric points, could be measured with any degree of reliability. Therefore diagnostic studies were made only for paired organs (mammary glands).

For the method to be useful in measuring deep temperatures in medicobiological research and medical practice, it will be necessary to measure the absolute values of the temperatures at any point from the surface of the body with an error no worse than ± 0.1°C. This specification stems from the fact that the departures of local temperatures from the 37°C average usually range through $\pm (2-3)$°C.

The basic difficulty in accurate temperature measurement results from reflection at the antenna-body boundary, the coefficient varying strongly as a function of the point at which the antenna is applied to the body. At $\lambda_0 = 30$ cm, for example, the power reflection coefficient Γ^2 varies from 0.0 to 0.25. As a result, even a loss-free antenna measures not the true temperature T_x of the body (in degrees Kelvin), but the quantity $T_s = T_x \times (1-\Gamma^2)$. In the previously cited Ref. 1, an attempt was made to allow for reflection by measuring Γ^2. However, this does not help, since errors of the order of magnitude of one degree remain, and this limits use of the method to relative measurements in which the position of the antenna on the body does not change. There is also a significant interference error.[3]

This error results from the fact that the probe antenna

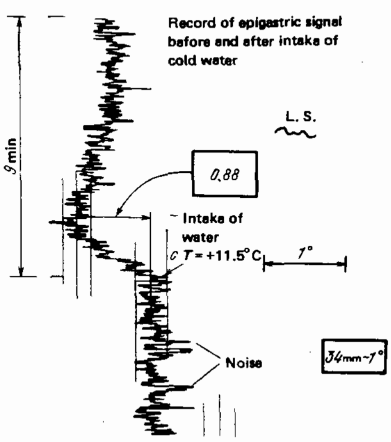

FIG. 1. a—Record of epigastric signal before and after intake of cold water. b—L. S. c—Intake of water $T = +11.5$°C. d—Noise.

is incapable in principle of receiving all the radiation coming from the body owing to the inevitable presence of the back lobes of the probe-antenna directional pattern.

Our theoretical and experimental analysis of noise in the input system and of antenna performance has enabled us to state principles and methods for complete elimination of these errors.

In brief, the principle consists of use of the properties of a system at thermal equilibrium, which is obtained when the radiometer input element and the body to be investigated are placed in a black cavity and are at the same temperature. In this case, the signal coming from the antenna is exactly equal to the temperature of the corresponding zone of the body.

Let us consider a simplified input scheme in which the antenna is combined with the radiometer via an ideal rectifier. It can be shown that, with allowance for antenna intrinsic noise, the signal coming from the antenna equals $T_s = T_\Sigma \eta (1-\Gamma^2) + T_a(1-\eta)(1-\Gamma^2)$, where η is the efficiency of the antenna, T_a is the temperature of its material, and T_Σ is the antenna temperature for the received radiation. It equals $T_\Sigma = T_x(1-\beta) + T_b\beta$, where β is the leakage coefficient outside of the half-space occupied by the body and T_b is the temperature of the black cavity or, in general, the radiation temperature in the space around the body.

The ideal-rectifier thermal radiation aimed at the antenna has a temperature T_s. On reflection from the antenna, this radiation produces an additional signal $T_\Sigma \Gamma^2$. The total signal entering the radiometer is $T_s = [T_x(1-\beta) + T_b\beta] \times \eta(1-\Gamma^2) + T_a(1-\eta)(1-\Gamma^2) + T_s\Gamma^2$. It is easily seen that on establishing thermal equilibrium, when $T_a = T_s = T_b = T_x$, we obtain $T_s = T_x$, i.e., an undistorted body-temperature measurement.

Actually, however, T_x is unknown and must be measured. Here thermodynamic equilibrium can be guaranteed only approximately. Therefore equilibrium is established for the 37°C average human body temperature $\overline{T}_x$. Putting $T_x = \overline{T}_x + \tau$, where as we indicated $0 \leq |\tau| \leq 2$, we obtain $T_s = T_x - \tau(1-\eta+\beta+\Gamma^2)$. This does not completely eliminate the effects of antenna losses, scattering, and reflection, but it reduces them to the point that, for example, variations of Γ^2 in the range 0.0–0.20 do not introduce errors larger than 0.1–0.2°C.

On the basis of the above principles, a radiothermometer operating at $\lambda = 32$ cm with a threshold sensitivity of 0.02°C (and averaging over 4 sec) was developed by the Scientific Research Radiophysics Institute (NIRFI); it is capable of absolute measurements of temperature with errors smaller than ± 0.1°C. Surface resolution is about 4 cm at temperature-sensing depths of up to 20 cm. Various test measurements of human-body temperature and tissue equivalents made with the radiothermometer showed good agreement with classical thermometer measurements.

To make certain that the device does indeed measure deep temperatures, we measured the epigastric-region temperature of a subject after he had drunk cold and hot

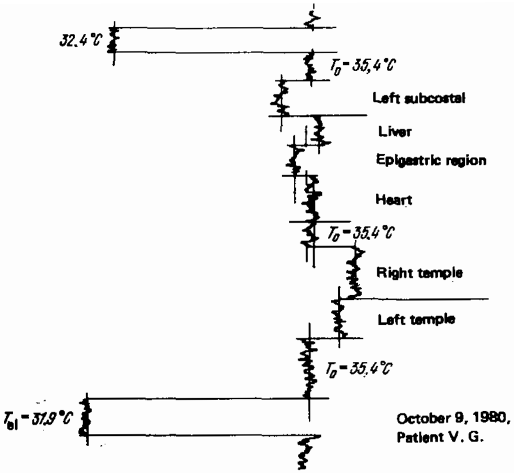

FIG. 2. a—Left subcostal. b—Liver. c—Epigastric region. d—Heart. e—Right temple. f—Left temple. g—October 9, 1980, Patient V. G.

water. A sample of the record appears in Fig. 1, which shows an immediate ~0.9°C temperature drop after intake of cold water, followed by gradual recovery. The variation of the temperature and the rate of its recovery are different for different patients. Figure 2 shows typical records of deep temperatures in various organs.

In 1979, preliminary studies were made of 20 healthy subjects and 80 patients in clinics of the Gor'kiĭ Institute of Medicine at the Semashko Regional Hospital. The results showed that the internal temperatures differed significantly in various parts of the body in both the healthy subjects and the patients. Deep temperature was shown to depend on the state of the blood circulation. The rise in human brain temperature after administration of nicotinic acid in various doses was investigated. The effects of various physiological procedures on the temperatures of certain organs were studied. The investigation showed that malignant neoplasms of the stomach caused a 0.5 – 0.8°C elevation of temperature above normal, with a maximum scatter of ±0.4°C. Temperature increases amounting to 0.8 – 2°C were observed in diseases of the liver (hepatitis, gallstones).

An elevation of brain temperature in the presence of tumors and, conversely, a decrease in the presence of hemorrhages were observed.

Thus, first experience in the medical use of the new radiothermometer is quite encouraging, and indicates great potential for the new method in medicobiological research.

The studies showed that it has become possible to design radiothermometer systems to operate at various wavelengths, which will make it possible to measure the distribution of temperature inward from the surface of the body. This will make it possible to record body temperature in three dimensions.

We have no doubt that, with time, radiothermometry will become a widely accepted method in medicobiological research and clinical diagnostic work.

[1] Barrett, Myers, and Sadowsky, Radio Science 12, 1675 (1977).
[2] V. S. Troitskiĭ, E. A. Aranzhereev, V. I. Abramov, I. F. Belov, V. P. Gorbachev, A. V. Gustov, V. S. Demidova, T. N. Dobrynina, V. M. Plechkov, L. K. Siz'mina, and A. I. Shmeleva, NIRFI Preprint No. 131, 1979.
[3] V. S. Troitskiĭ, Zh. Tekh. Fiz. 25, 1428 (1955).