Reports

Subcutaneous Temperatures: A Method of Noninvasive Sensing

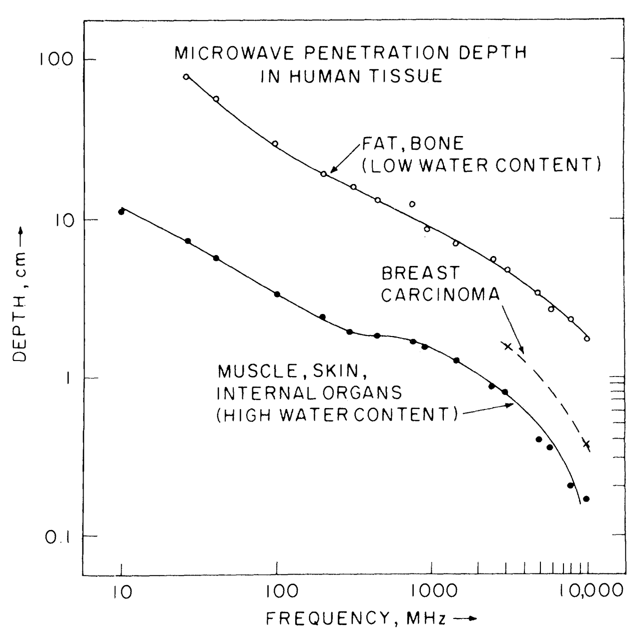
Abstract. *A new method of noninvasive sensing of the subsurface temperature distribution in human and animal tissue is described. Thermal radiation emitted from subsurface depths of several centimeters can be detected with microwave receivers. Temperature sensitivity of order 0.1°C and spatial resolution of approximately 1 by 2 centimeters have been obtained. Measurements demonstrating the technique, with feline and human tissue, are reported. A potential medical application is the detection of subsurface thermal anomalies such as malignant tumors and regions of vascular insufficiency.*

The ability of microwave radiation to penetrate biological tissues has been known in quantitative detail for more than 20 years (*1*). Such penetration forms the basis for microwave diathermy and "microwave ovens." However, this partial transparency of tissue to microwave radiation implies that thermal radiation generated internally may escape from the surface. Therefore a measurement of the microwave radiation intensity may be related to the temperature along the path of the escaping emission. The emitted power is weak, of the order of 10^{-21} watt per square centimeter per hertz at a frequency of 3 Ghz, but even this low power is easily detectable by microwave radiometers developed primarily for the purposes of radio astronomy. Thus, by externally measuring the microwave emission from the human body, one may detect anomalous temperatures within the body at depths of several centimeters. The method is entirely passive and noninvasive; the body is not irradiated with electromagnetic energy, hence the measurements may be repeated as often as desired without risk to the patient.

The technique, which we have called microwave thermography, may be described as the microwave analog of infrared thermography, the detection of surface temperature patterns by measurement of the body's thermal emission at infrared frequencies. The biological difference in the two techniques can be traced directly to the electromagnetic properties of biological tissues; radiation at microwave frequencies can escape from a depth of several centimeters, whereas the infrared radiation originates from a depth so small as to be essentially surface emission.

The penetration depth (*2*), which is also the depth from which most of the radiation may escape, is well known from Schwan's measurements on the dielectric properties of tissues (*1*). Since water is a strong absorber of microwaves, the penetration depth depends critically on the water content of the tissue. Figure 1, adapted from data by Schwan and others, depicts typical values of the penetration depth as a function of frequency for tissue of "high" and "low" water content. At 3 Ghz, for example, penetration depths of approximately 1 to 5 cm are indicated.

The primary technical problem in using microwave radiometers for medical diagnostic purposes is that of coupling the body's radiation to the measuring instrument in an optimum manner. The data of Fig. 1 argue for the use of low frequencies for greater penetration, but the spatial resolution is degraded by using lower frequencies, so that detection of a deep-seated, localized temperature anomaly may actually be more difficult. It is almost certain that different medical applications, of which there seem to be many, will require different frequencies for optimum results. For our initial clinical evaluation of microwave thermography, the observation of microwave thermal emission from suspected tumors of the female breast, we have chosen a frequency of 3.3 Ghz. The antenna, the device which couples the body's radiation to the radiometer, consists of an open-ended, dielectric-filled waveguide. A dielectric constant of 11 has been used to permit the use of a waveguide of 1 by 2.3 cm cross section (standard X-band guide). The antenna is placed in



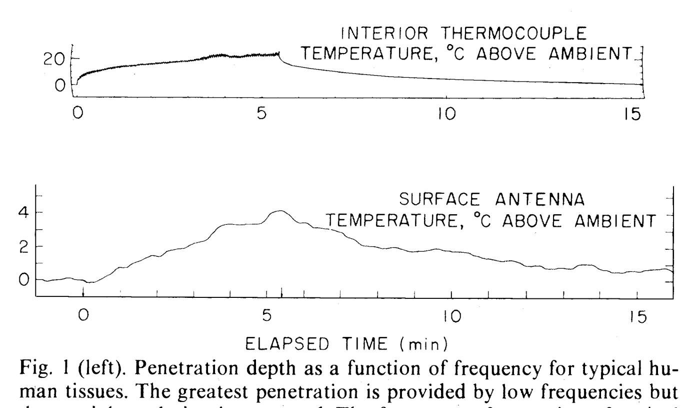


Fig. 1 (left). Penetration depth as a function of frequency for typical human tissues. The greatest penetration is provided by low frequencies but the spatial resolution is worsened. The frequency of operation of typical infrared thermographs is 10^7 to 10^8 Mhz for which there is virtually no penetration (1000 Mhz = 1 Ghz). Fig. 2 (right). Time history of (top curve) temperature of dead cat thigh muscle, heated with pulsed focused ultrasound, measured with a thermocouple implanted at the focus approximately 1.5 cm beneath the skin surface, and (bottom curve) temperature recorded by 3-Ghz microwave radiometer, with antenna fixed against skin surface. Arrows indicate start and end of ultrasonic irradiation period.

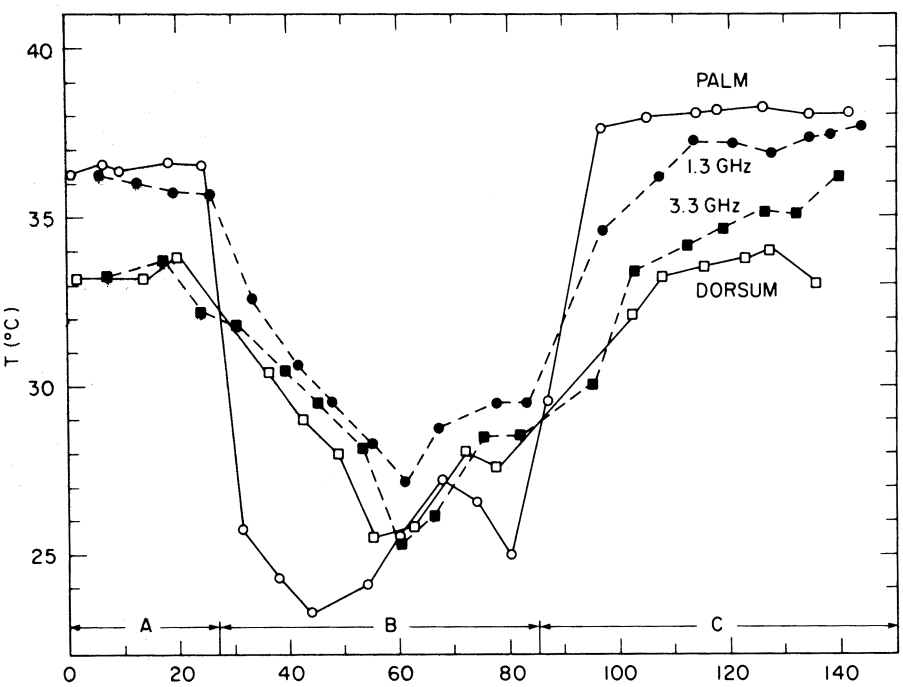


Fig. 3. The microwave emission from the dorsum, expressed in temperature units, at 1.3 Ghz (●) and 3.3 Ghz (■) as a function of time. The surface temperatures of the palm (○) and dorsum (□) are also shown. During time interval A the hand was grasping a block of wood; during interval B, a bakelite pipe carrying water at 2° to 4°C; and during interval C, the same pipe with water at 43°C.

direct contact with the patient to avoid reflections due to impedance mismatches at the tissue-air and air-antenna interfaces. A quarter wave coaxial section is added to reduce mismatch from tissue to radiometer input. The resolution properties of such an antenna are well known (*3*). The spatial resolution area of a single measurement is approximately that of the antenna aperture, 1 by 2.3 cm, in the antenna near zone (depths $0 \leq z \lesssim 1.5$ cm for fatty tissue at 3.3 Ghz), and broadens as z^2 due to diffraction in the far zone ($z \gtrsim 1.5$ cm). Thus the antenna is sensitive to radiation from a tissue volume which resembles a funnel, whose narrow end coincides with the antenna aperture. The measured temperature is a weighted average over this volume. The depth extent of the tissue volume is determined by the penetration depth, defined earlier, and is therefore independent of antenna size. For a given antenna aperture, the near zone spatial resolution remains approximately constant with frequency f, but the near zone depth extent increases in proportion to f. The far zone resolution varies as f^{-1}. The effective resolution is thus extremely crude in comparison with infrared measurements but is sufficiently small to permit an evaluation of the microwave technique.

Our radiometer, typical of many radio astronomy receivers, is a Dicke-switched superheterodyne with a tunnel diode microwave amplifier preceding the mixer. The predetection bandwidth is 100 Mhz, and the root-mean-square temperature sensitivity is 0.15°C for a 3-second integration time. A calibration signal corresponding to a temperature increase of 8°C is provided by a noise diode.

Prior to the start of clinical evaluation we made measurements on cats, a dog, and humans to (i) demonstrate the feasibility of microwave sensing of subcutaneous temperatures, (ii) provide information from which we could establish the parameters of a radiometer specifically designed for the unique application of measuring body radiation, and (iii) establish and improve our measurement technique. Beginning in 1971, experiments were conducted at frequencies of 10, 5, 3.3, and 1.3 Ghz, corresponding to wavelengths of 3, 6, 9.1, and 23 cm, respectively. At 10 Ghz the microwave emission from the human cheek was found to increase when the subject held warm water in the mouth while the external cheek temperature remained constant (*4*). Although this experiment proved the ability of microwave radiometry to detect subcutaneous temperatures, the experiment could not be conveniently conducted over long periods of time. Experiments at 3 Ghz on ultrasonically heated muscle of a necrotic cat thigh also revealed the subsurface temperature-sensing capability of microwave radiometry (*5*). Data obtained in one such experiment are shown in Fig. 2. A convenient measure of low levels of microwave power is in temperature units corresponding to the temperature of a perfect emitter radiating an equal amount of power. The internal and skin temperatures and microwave emission were monitored, and it was found that the decay with time of the microwave emission mimicked closely the decay of the internal temperature when the ultrasonic heating was terminated. The radiometrically measured temperature increase is less than that recorded by the thermocouple because of (i) impedance mismatch at the tissue-antenna interface, (ii) signal absorption by overlying muscle tissue, and (iii) the small size of the hot region in comparison to the response volume of the antenna ("beam dilution"). Attempts to detect enhanced microwave emission by artificially inducing an inflammation in the thigh muscle of an anesthetized cat gave marginally positive results (*6*).

The most convenient method that we used to observe anomalous temperatures in the human body was to measure the microwave emission from the dorsum, the back of the hand. The hand grasped a bakelite pipe through which was circulated water of varying temperatures. Both the palm and dorsum surface temperatures were measured with thermistors while the microwave emission at 3.3 and 1.3 Ghz was measured by placing the antenna on the dorsum. The results of the experiment can be expressed as four temperatures: the palm, dorsum, 3.3 Ghz, and 1.3 Ghz temperatures (Fig. 3). The microwave temperatures are corrected for antenna-tissue impedance mismatch. Since the cooled and heated areas are large relative to the antenna response area, beam dilution is negligible. After 26 minutes of stabilized behavior with the palm placed on a block of wood at room temperature (time interval A), the hand grasped the pipe through which was circulated water at 2° to 4°C. All four temperatures dropped sharply (time interval B). After approximately 60 minutes the water temperature was increased to 43°C and all temperatures increased (time interval C). The observed temperatures show several features that persist over many similar measurements and that indicate the ability of microwave thermography to sense the subsurface thermal structure and its changes. In periods A and C the temperatures are in the relation $T(\text{palm}) \geq T(1.3) > T(3.3) \geq T(\text{dorsum})$. This behavior is consistent with greater penetration by radiation at 1.3 Ghz than at 3.3 Ghz, as indicated in Fig. 1. In period B, the palm was cooled strongly with the resulting temperatures $T(1.3) \geq T(3.3) \geq T(\text{dorsum}) \geq T(\text{palm})$. Under these conditions, we believe that the temperature profile of the hand with depth may be crudely approximated by a local maximum in the interior, since (i) palmar vasoconstriction will tend to insulate the interior against the cooling at the palm surface, (ii) more warm arterial blood will be supplied to the hand interior than to the palmar and dorsal surfaces, and (iii) venous blood will be cooler than arterial blood and leaves the hand primarily through the dorsal veins. The measured temperatures suggest that most of the 3.3 Ghz radiation originates near the dorsum while most of the 1.3 Ghz radiation originates deeper, near the region of highest temperature. Thus in all time intervals, the microwave data indicate changing hand temperatures at different depths between the dorsum and the palm.

The results are representative of those obtained in several trials; the purpose of our experiments was to demonstrate subsurface temperature sensing, and not to conduct research in thermal physiology—a field quite outside our area of expertise.

We have constructed models of fatty tissue as described by Guy (*7*). These models have been useful in measuring and improving antenna properties. However, we have not used them in tests of subsurface thermal sensing, because of our belief that the homogeneity of their electrical and thermal properties departs too greatly from what happens with tissue.

There are many potential medical applications of microwave radiometry. By analogy with infrared thermography, we may expect these to include detection of subsurface thermal anomalies such as malignant tumors, especially in the female breast; localized inflammations, such as appendicitis; and vascular insufficiency in the limbs and in the brain. However, the usefulness of the technique is difficult to predict because detailed knowledge of the internal thermal structure of the human body is sparse. Extensive clinical evaluation, involving observations at more than one frequency, will be required. If simultaneous observations are made at two well-separated frequencies, the ability to determine the depth of a particular thermal anomaly will be improved. However, this depth resolution will still be crude, of order 1 cm at best, because of the long wavelengths involved. Experiments at other frequencies have been performed by others in the laboratory but have not been the subject of detailed clinical evaluation (*8*). Infrared thermography has been utilized in the detection of breast cancer for many years, and this is an area where microwave thermography is being evaluated. Microwave thermograms at 3.3 Ghz on some 30 to 40 female patients per week at Faulkner Hospital, Boston, are being correlated with mammography, infrared thermography, clinical, and, where appropriate, biopsy results. These data are the first microwave thermographic data taken in a systematic, routine manner in a clinical environment and should help establish the currently unknown microwave emission patterns from the breasts of normal patients. Once these patterns are known with confidence, an examination of departures can be carried out for diagnostic purposes. Our initial data indicate good agreement with infrared patterns, but insufficient data exist for any further conclusions.

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References and Notes

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2. The penetration depth is defined as that distance over which the intensity of propagating electromagnetic radiation will be reduced to $1/e$, or approximately 37 percent, of its original value. Engineers and physicists will recognize that what we call "penetration depth" is what textbooks call "skin depth." We avoid this term here because of the obvious confusion it can cause in a biomedical application. Use of the term "penetration depth" in connection with biological tissue did not originate with us (*1*).
3. The rectangular waveguide antenna has been analyzed by many, including S. Silver, in *Microwave Antenna Theory and Design*, S. Silver, Ed. (McGraw, New York, 1949), p. 169; R. C. Hansen, in *Microwave Scanning Antennas*, R. C. Hansen, Ed. (Academic Press, New York, 1964), vol. 1, p. 1; A. W. Guy, *IEEE Trans. Microwave Theory Tech.* **19**, 214 (1971).
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6. G. Bolen, thesis, Massachusetts Institute of Technology (1973).
7. A. W. Guy, *IEEE Trans. Microwave Theory Tech.* **19**, 205 (1971).
8. We are aware of measurements at 0.6, 0.9, and 1.2 Ghz by B. Enander and G. Larson [*Electronics Lett.* **10**, 37 (1974)]; at 0.8 Ghz by R. A. Porter and F. J. Wentz (Final Report, NASA-CR-114675, October 1973); and at 45 Ghz by J. Edrich and P. C. Hardee [*Proc. IEEE* **62**, 1391 (1974)]. Also, a discussion of the application of microwave radiometry to the study of communication in biological systems has been given by J. Bigu del Blanco and C. Romero-Sierra, in *Biologic and Clinical Effects of Low-Frequency Magnetic and Electric Fields*, J. G. Llaurado, A. Sances, Jr., J. H. Battocletti, Eds. (Thomas, Springfield, Ill., 1974), pp. 123–136.
9. We thank Dr. P. P. Lele for assistance with measurements requiring ultrasonic heating, G. K. Stimac for assistance in both laboratory and hospital measurements, Dr. N. L. Sadowsky for vital medical collaboration at Faulkner Hospital, and for numerous contributions, J. Orenstein, J. W. Barrett, and D. C. Papa. Supported by NIGMS grant GM-20370-02 and by NIH biomedical sciences support grant 5-SO5-RR 07047-09.

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Parietal Eyes in Lizards: Zoogeographical Correlates

Abstract. *Lizards without parietal eyes tend to be restricted to low latitudes, whereas lizards with parietal eyes are successful at higher latitudes also. These zoogeographical data, along with current theories of parietal eye physiology, strongly suggest that the overall significance of the parietal eye to lizards as a group is that it facilitates survival at higher latitudes, thus making possible the exploitation of a wider variety of habitats.*

In addition to their lateral eyes, many lizards have a small "third eye" located on top of their heads. The general morphology of this third eye is similar to that of the larger lateral eyes, except that the third eye (parietal eye) lacks muscles and an eyelid (*1*). The parietal eye of a few genera is known to be a functional photoreceptor (*2*), but no comprehensive data are available for lizards as a group. Neither has there been any comprehensive analysis of the pattern of parietal eye occurrence (*3*). In order to determine the possible significance of the parietal eye in the evolutionary and present-day success of lizards, we investigated the relationship of the pattern of parietal eye occurrence to their life-styles and geographic distribution.

Parietal eye occurrence is relatively nonvariable in genera of the same family (*3*). Thus, either a very high percentage or a very low percentage of the members of any particular family has a parietal eye (Table 1). These data bear no apparent correlation with life-style. Instead, occurrence of parietal eyes seems to be following lines of lizard evolution at the familial level regardless of the variety of natural history types within each family (*4*). However, there is a relationship between latitudinal distribution and parietal eye occurrence.

Virtually all geckos and teiids lack parietal eyes. Since these are the largest, most successful, and best studied parietal-eyeless groups, we chose them for an analysis of geographical distribution. Centers of abundance and range were plotted for 59 of the 79 genera in Gekkonidae and for 39 of the 42 genera in Teiidae (*5*). Gekkonidae are most abundant within 10° of the equator. Among Teiidae, the equatorial concentration is more pronounced (Table 2). It is possible that teiids were restricted in their northward distribution by the instability of the land bridge between North and South America. It is unlikely, however, that this could be the sole explanation for their equatorial concentration, since they are relatively unsuccessful at high southern latitudes as well.

For comparison, we analyzed the geographical distribution of two large success-