

Microwave Thermography in the Detection of Breast Cancer

Alan H. Barrett¹
Philip C. Myers¹
Norman L. Sadowsky²

Microwave thermography, a method of sensing subcutaneous temperatures, was used in a breast cancer detection study of about 5,000 female patients. The data were taken at wavelengths of 9.1 and 23 cm. Microwave thermography at 23 cm has true-positive and true-negative detection rates of 0.8 and 0.6, respectively, comparable to those of infrared thermography (0.7) and inferior to those of xeromammography (0.9). However, a potential advantage results if microwave and infrared thermography are used together for screening, and if mammography is used only for follow-up on those patients who were positive on either the microwave or the infrared thermograms. It is then possible to obtain true-positive and true-negative detection rates of 0.9 and 0.9, respectively, while only half the number of patients need be subjected to x-rays.

Microwave thermography is the detection of microwave radiation from the human body and may be most clearly envisioned as the microwave analog of infrared thermography. Whereas infrared thermography uses wavelengths of 10 μm (typical), microwave thermography makes use of much longer wavelengths, typically 1–20 cm; this leads to important and fundamental differences between the two techniques. These have been described in detail in our previous publications [1–4] and can be summarized as follows:

1. Microwave radiation is capable of penetrating human tissue and therefore the emission provides information related to subcutaneous conditions within the body. Infrared radiation is incapable of such penetration and therefore relates to conditions primarily on the surface.

2. The intensity of microwave emission is linearly proportional to the temperature of the emitter. Therefore a measurement of the emission may be easily related to the temperature of the emitter. Infrared intensity measurements may also be related to temperature but in a less direct (and nonlinear) manner.

3. Microwave emission, being at a longer wavelength than infrared, gives correspondingly coarser spatial resolution. Typical spatial resolution is on the order of 1 cm for microwaves, whereas infrared thermography usually yields spatial resolutions of the order of 1 mm.

The first two items above imply that microwave thermography provides information on internal body temperatures. The depth of penetration, and hence the depth from which microwave radiation may escape from the body, depends on the wavelength, the dielectric properties of the tissue, and, most importantly, on the water content of the tissue. Typical values of the depth of penetration are given in figure 1.

Microwave thermography is a noninvasive, passive technique, like infrared thermography, and does not subject the patient to radiation hazards, pain, physical stress, or discomfort. It may be repeated as often as desired without harmful effects.

Received April 10, 1979; accepted after revision September 24, 1979.

Presented at the joint session of the Society of Photo-Optical Instrumentation Engineers and the American Roentgen Ray Society, Toronto, March 1979.

A. H. Barrett and P. C. Myers were supported in part by grant 2 R01 GM20 370-05 from the U.S. National Institute of General Medical Sciences.

¹ Department of Physics, Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139. Address reprint requests to A. H. Barrett.

² Department of Radiology, Faulkner Hospital, Boston, MA 02130.

AJR 134:365-368, February 1980
0361-803X/80/0134-0365 \$00.00
© American Roentgen Ray Society

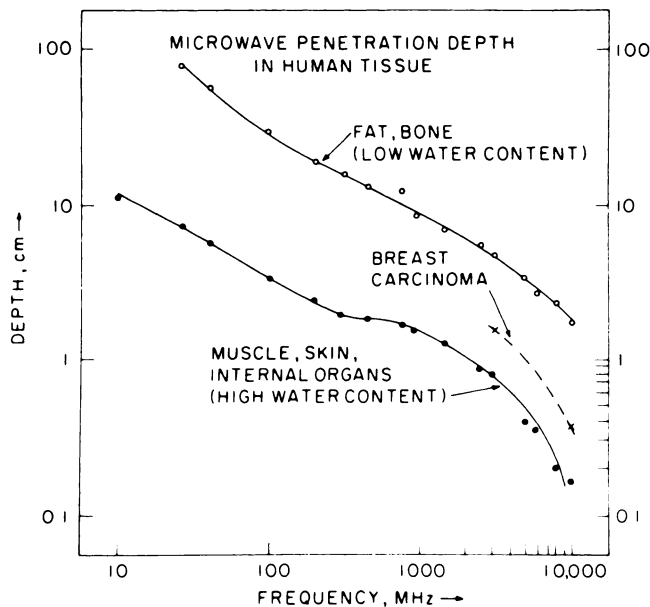


Fig. 1.—Typical values of depth of penetration (cm) versus frequency (MHz) for human tissue of different water content. Depth of penetration is defined as depth at which radiation will be reduced by e^{-1} or 36.8% of its original intensity. Frequency is inversely proportional to wavelength. Wavelengths of 30 and 3 cm correspond to 1,000 and 10,000 MHz, respectively.

The initial clinical evaluations of microwave thermography have been in the detection of breast cancer. This area was chosen for several reasons: (1) progress in the passive, noninvasive detection of breast cancer has been slow; (2) infrared thermographic examinations could be compared with microwave thermograms; (3) the microwave emission would arise from a relatively homogeneous volume of tissue; and (4) there seems little doubt that breast cancers are frequently correlated with a region of elevated temperature. Since November 1974, we have performed microwave thermographic examinations on over 5,000 female patients at the Sagoff Breast Cancer Detection Clinic at Faulkner Hospital, Boston. This paper summarizes our findings and indicates the capability of microwave thermography for potential use in other diagnostic applications.

Materials and Methods

The receivers used in microwave thermography are adaptations of those used by radio astronomers to detect cosmic radio emission, since the power levels are comparable. The receiver sensitivities are typically 0.1°C for an integration time of 5 sec. This sensitivity corresponds to changes in the detected power level of 3×10^{-17} watts/cm² at a wavelength of 9 cm. We have built receivers operating at wavelengths of 23, 9.1, and 5 cm and have used the 23 and 9.1 cm instruments to examine about 1,000 and 4,000 patients, respectively. The 5 cm unit has been in operation at Faulkner Hospital only since December 1978, therefore we have not accumulated sufficient data to report at this time.

A microwave thermographic examination is conducted as follows: The patient lies supine on an examining table, opens her robe above the waist, and a technician places the microwave antenna in contact

with the breast at the first position to be measured, usually the right nipple. The antenna is held in position for 15 sec, during which time the receiver integrates the microwave emission and a microprocessor converts the measured signal to a temperature. This temperature is then shown, if desired, on a cathode-ray tube (CRT) display terminal. The antenna is then moved to the symmetrically opposite position on the other breast for another 15 sec measurement. The process is continued until data are taken at nine positions on each breast. The spacing between adjacent positions is typically 3 cm, consistent with the antenna aperture dimensions of 1×2 cm. Each microwave thermographic examination requires about 10 min for each wavelength.

With 18 data points per patient, there are obviously many ways in which these data can be analyzed. We believe the data analysis should be *quantitative* so that the microwave data could be interpreted without requiring the time and training of a skilled "reader." Therefore, a microprocessor and CRT display terminal are used to digitize the data, perform simple statistical analyses, and display the results for the examining technician so that positions may be repeated if desired. A paper copy of the CRT display is made at the completion of the examination and becomes a part of the patient's permanent record.

We have tested many mathematical combinations of the measured temperatures in order to find those that best discriminate between known breast cancers, as determined by biopsy, and normal cases. We find the most significant discriminator to be that which reveals a right-left asymmetry, although an ancillary detection criterion is that which reveals a localized region of elevated temperature.

The microprocessor is programmed to compute three quantities: (1) the temperature difference between symmetrically opposite positions on the right and left breast (nine such differences per patient); (2) the average temperature of the right breast minus the average for the left; and (3) the temperature of the hottest position minus the average temperature of that breast. Items (1) and (2) reveal right-left asymmetries, whereas (3) may indicate a region of anomalously high temperature. The results of computations (2) and (3) and the maximum difference in (1) are displayed on the CRT terminal at the conclusion of the examination and printed out on the paper copy.

Results

We report the results of about 1,000 patients who underwent microwave thermographic examinations at both 23 and 9.1 cm wavelengths. In addition, each patient had infrared thermography, mammography, and clinical examinations. Breast cancer was confirmed by biopsy in 29 cases; these plus the 979 "normal patients" (all others examined) constitute the data base. No follow-up was done on the normal patients.

Our statistical analysis has shown the most effective detection criterion to be the maximum temperature difference between symmetrically opposite points on the right and left breast. If this difference exceeds a threshold temperature T_0 , the microwave examination is considered positive; if the difference is less than T_0 the examination is considered negative. Therefore as T_0 increases, the true-positive detection rate decreases and the true-negative detection rate increases. Figure 2 summarizes our results and shows how the true-positive and true-negative rates change with T_0 . The curves labelled M(1) and M(3) are the results for the microwave instrument operating at 23 and 9.1 cm wave-

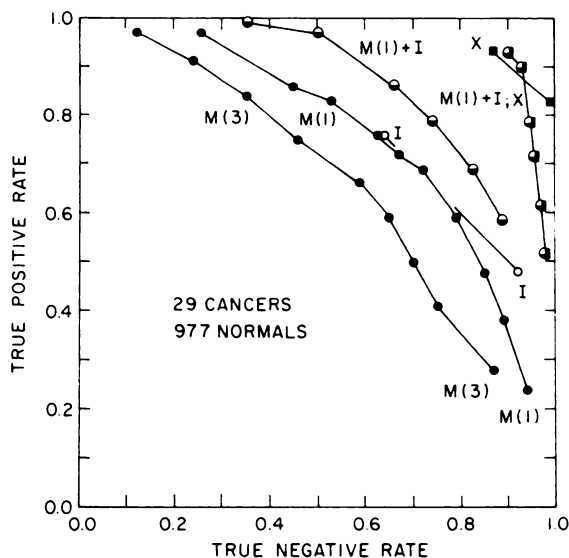


Fig. 2.—Breast cancer detection rates of various diagnostic techniques. True-positive rate (TP) is fraction of cancers diagnosed correctly and true-negative rate (TN) is fraction of normals diagnosed correctly. Microwave thermography at wavelengths of 23 and 9.1 cm are designated M(1) and M(3), respectively. I = infrared thermography; X = xeromammography. Each curve results from a different choice of detection thresholds.

length, respectively. In these curves, T_0 varies from 0.6°C (extreme upper left) to 1.4°C (extreme lower right). At any value of the true-negative rate, M(1) has a considerably higher true-positive rate than M(3), indicating that, in this trial, microwave thermography was more effective in detecting cancer at longer wavelengths.

For each patient the infrared and mammographic examination films are graded by a staff radiologist according to the estimated likelihood of cancer. The possible infrared grades are 1 (normal or negative), 2 (suspicious), or 3 (abnormal or positive); the possible mammography grades are 1 (negative), 2 (positive benign), 3 (suspicious), or 4 (positive malignant). In figure 2 the curve labeled I shows the infrared true-positive and true-negative performance for grade 3 (lower right point) and for grade 2 or 3 (upper left point). The curve labeled X shows the mammography true-positive and true-negative rates for grade 4 (lower right) and for grade 3 or 4 (upper left). It is apparent from these data that microwave and infrared thermography give comparable results, but that each is decidedly inferior to mammography.

Also shown (fig. 2) are the true-positive and true-negative results for the microwave and infrared tests together. The curve labeled M(1)+I shows the detection rates when either the microwave or the infrared instrument indicates a positive result. The detection statistics are considerably improved, because each technique detects some cancers that the other technique does not.

Finally, the curve labeled M(1)+I;X (fig. 2) shows the detection statistics that result from using the x-ray technique only on those patients who were positive on either the microwave or the infrared thermograms. By a proper choice of the microwave threshold, the microwave and infrared

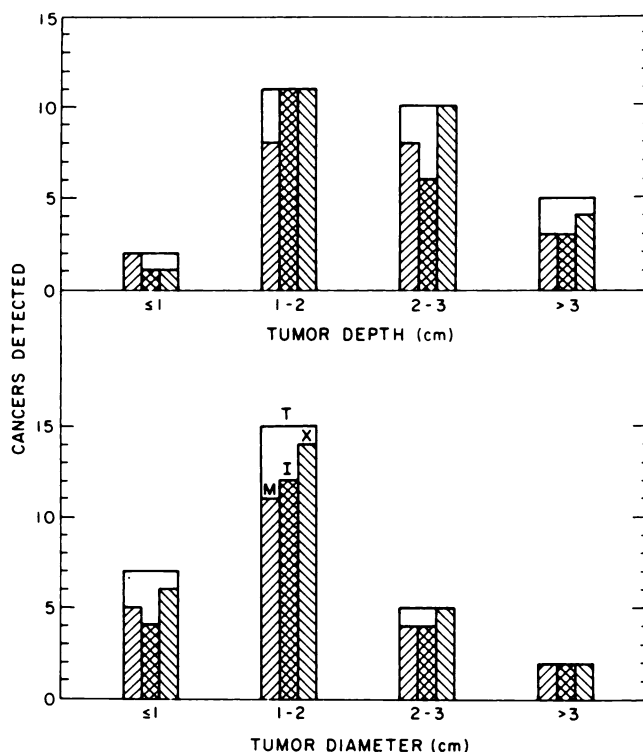


Fig. 3.—Histograms of number of cancers detected in terms of tumor diameter and tumor depth. Detections by microwave thermography (23 cm wavelength) are indicated by the left vertical bar (M); infrared thermography (I), middle bar; and xeromammography (X), right bar.

techniques, both passive and therefore completely safe, can be used to screen patients for subsequent mammography. This procedure detects as many lesions as mammography alone, without significant deterioration of the true-negative rate, but with a significant reduction (50%) in the number of women exposed to x-rays.

The size and depth of the 29 cancer tumors studied is shown in the histograms of figure 3. The size and depth data are from biopsy reports and are generally uncertain by about 1 cm. In each histogram, the upper horizontal line (T) indicates the total number of cancers in that size or depth category. The left bar (M) indicates the number of microwave detections (using the criterion of grade 2 or 3). The right bar (X) indicates the number of mammography detections (using the criterion 3 or 4). It is to be noted that no method has a clear superiority over the others in detecting small or deep-seated tumors.

Discussion

We have chosen to present the results for which we have data at two microwave wavelengths. The data on some 3,000 patients for whom we have examinations only at 9.1 cm wavelength give similar results, except that we have noticed an apparent deterioration of the 9.1 cm results over the last 3 years. This is not fully understood and is now under investigation.

We call attention to the fact that the microwave and infrared techniques disagree in 41% of the cancer cases. This is undoubtedly because the two techniques extract different thermal information, a direct result of the consequences of the widely different wavelengths used in the two techniques. Thus microwave and infrared thermography complement each other and perhaps could be used together with benefit in other research and/or diagnostic applications.

Our data have been checked for correlations between the magnitude of the indicated temperatures and the size and depth of the malignant tumors. We find no significant correlation in either case.

The detection criterion that reveals a localized region of elevated temperature, that is, the highest temperature minus the average temperature for each breast, has proved to be relatively ineffective at a wavelength of 23 cm. This fact, coupled with the lack of correlation between microwave temperatures and tumor depth and size, leads us to conclude that breast cancers cannot be modeled simply by a local maximum in temperature at the tumor site.

Figure 2 provides evidence that the longer wavelength (23 cm) provides better detection statistics than the shorter wavelength (9.1 cm). However, we caution against this

conclusion until the apparent deterioration of the 9.1 cm receiver is fully understood. Our current data acquisition at 5 cm wavelength should prove extremely beneficial in establishing the general trend of breast cancer detectability as a function of wavelength.

ACKNOWLEDGMENTS

We thank J. W. Barrett, H. M. Lindsay, D. C. Papa, B. Rosen, and V. Taylor for engineering, data taking, and data analysis.

REFERENCES

1. Barrett AH, Myers PC. Microwave thermography. *Bibl Radiol* **1975**;6: 45-56
2. Barrett AH, Myers PC. Subcutaneous temperatures: a method of noninvasive sensing. *Science* **1975**;190: 669-671
3. Barrett AH, Myers PC, Sadowsky NL. Detection of breast cancer by microwave radiometry. *Radio Science* **1977**;12 [suppl]: 167-171
4. Myers PC, Barrett AH, Sadowsky NL. Microwave thermography of normal and cancerous breast tissue. Conference on thermal characteristics of tumors: applications in detection and treatment, New York, March 1979. *Ann NY Acad Sci*. In press, **1980**