Microwave Radiometry: Its Importance to the Detection of Cancer

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(Invited Paper)

Abstract —**Developments in the application of microwave technology to the solution of medical problems, particularly the detection and treatment of cancer, have been very encouraging. In the treatment of cancer, for example, microwave hyperthermia has been accepted as an adjunctive procedure to radiation therapy in the treatment of superficial lesions. While not as widely reported, the use of microwave radiometry as a noninvasive, passive technique for the early detection of cancer appears very promising. Wider acceptance of these methods, however, awaits fundamental improvements in the ability to focus energy at depth in human tissue, an important and nontrivial antenna problem. Further development in the areas of antennas and antenna arrays is required if microwave technology is to provide a practical solution to the detection and treatment of cancer.**

This paper discusses developments in the medical uses of microwave radiometry, particularly in relation to the early detection of cancer, as well as the significance of and progress in related antenna technology.

I. Introduction

AMERICAN Cancer Statistics [1] indicate that in 1981 there were 30000 estimated deaths, with an estimated 111000 new cases, as a result of breast cancer. Over the 50-year period between 1930 and 1980, there has been no appreciable change in death rate, and tragically, approximately one in every 11 women in the United States will experience breast cancer during her lifetime. In 1987 there were 40000 estimated deaths, with an estimated 119000 new cases. It is an established observation that survival depends upon the pathologic stage of disease at the time of treatment. Table I indicates the dramatic increase in survival as a result of early detection [2]. (In 1930, for example, cancer of the uterus was the leading cause of death due to cancer in women in the United States. Cancer of the uterus has declined steadily since that time due in part to improved hygiene, but primarily due to the development of an early detection technique [i.e., the Papanicolaou test]). Today, 95 percent of all breast tumors are found by physical examination by either the patient or the examining physician. The result is that long before a breast tumor can be detected by present technology, nodal involvement may occur [3], [4].

Fig. 1 illustrates the long preclinical existence of breast carcinoma [5], [6]. The curve was generated by measuring the growth over a period of time and assuming the growth rate to be constant—in this case, using a tumor "doubling time" of 100 days and extrapolating to establish the time of its inception. Accordingly, the visible or clinical phase (i.e., when a tumor diameter of 1 cm is achieved) occurs on the average of 8 years after inception. Unfortunately, the average tumor diameter when first detected and diagnosed as malignant is approximately 2 to 2.5 cm and typically not a localized disease.

TABLE I
20 Year Survival Rate—Breast Cancer*

SIZE AT TIME OF DETECTION	APPROXIMATE SURVIVAL RATE
3 CM DIA	50%
2	65%
1	80%
< <1	95%

*Source: [2].

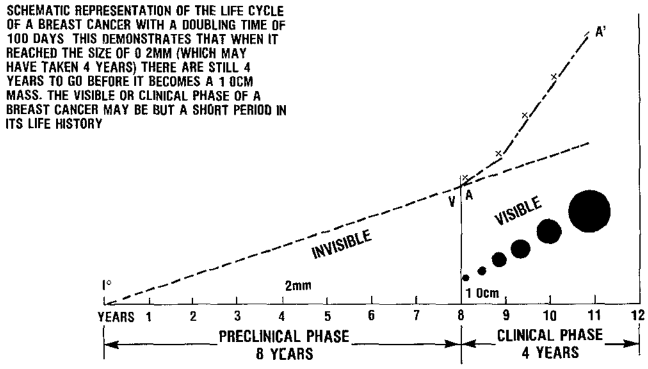

Fig. 1. Doubling time of tumor in relation to clinical phase.

While cancer cells can be released at any time during tumor growth, the larger the tumor the larger the number of cells released. According to Gullino [7], "We know that the great majority of circulating neoplastic cells are destroyed, but the higher their number the higher is the frequency of metastasis. On this ground, *early diagnosis and removal of the primary tumor is essential.*"

Mammography will remain the standard against which new screening techniques will be compared. According to Lundgren [6], however, the average diameter detected by mammography was 75 percent of the average diameter detected by palpation. This is not adequate lead time. (The

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time assumed to be gained in the diagnosis of breast cancer by screening a population of apparently well women is known as the lead time.)

We discuss in the following microwave thermography, or, more correctly, radiometry, which is defined as the measurement of natural electromagnetic radiation or emission from the body at microwave frequencies to allow the detection and diagnosis of pathologic conditions in which there are disease-related temperature differentials. The application of radiometry has, for the most part, been directed at the early detection and diagnosis of breast cancer.

Present detection techniques *other* than radiometry require that the tumor have mass and contrast with respect to the surrounding tissue (i.e., palpation or physical examination, mammography, ultrasonography, and diaphonography). Despite the life-saving potential of mammography and the progress made in less radical forms of breast cancer surgery, only about 5 percent of women over the age of 50 undergo annual mammography. Only about one third of these women, who qualify for mammography under the American College of Radiology and the American Cancer Society guidelines, had even one examination. The factors contributing to this low screening rate are complex and diverse, and are not completely understood. Due to late detection, approximately 85 percent of all determinations of breast disease result in extensive surgical procedures (i.e., discovery of a tumor usually means loss of breast and with it a negative attitude toward detection). Early detection could lead to a more conservative treatment and a positive attitude toward detection. Suspicious results found by screening using microwave radiometry could then be referred for mammography.

Radiometric techniques represent a passive, noninvasive, nonionizing procedure determining thermal activity rather than mass that, when used in conjunction with one or more of the other methods, could provide early detection. The determination of thermal activity is a measurement of tumor activity, or growth rate [8], providing data beyond the physical parameters (i.e., size and depth determined by mammography).

II. Technical Discussion

Radiometry, as mentioned earlier, is defined as the technique for measuring electromagnetic energy considered as thermal radiation. Clinical thermography, in turn, is the measurement of natural emission from the human body. Any object above absolute zero will radiate electromagnetic energy to an extent governed by its emittance. A body upon which electromagnetic radiation falls may transmit, reflect, or absorb all of the incident radiation or energy is known as a "black body." To remain in equilibrium, a perfect absorber is also a perfect emitter, or radiator, and from black body theory, any perfectly absorbing body emits radiation at all frequencies in accordance with Planck's radiation law [9], [10].

The level of emission is a function of both temperature and frequency. Fig. 2 illustrates the intensity of the radiated signal with respect to frequency. Transmission loss, or attenuation of muscle (high water content tissue), is greater than that of fat or bone (low water content tissue). Correspondingly, the amplitude of emittance of muscle is much greater than that of fat or bone at a given temperature.

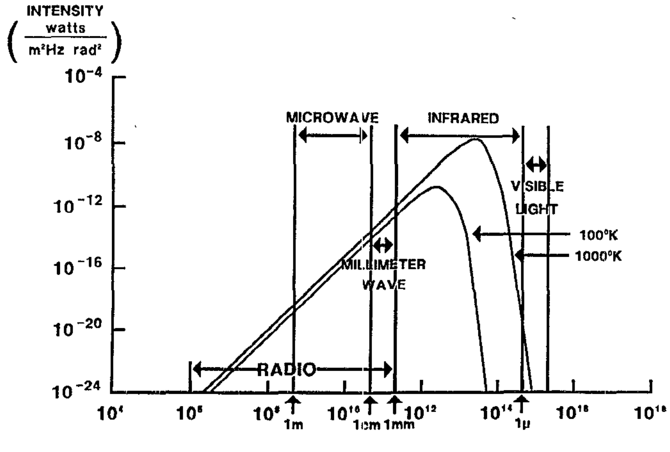

Fig. 2. Black body radiation: intensity of emission versus frequency.

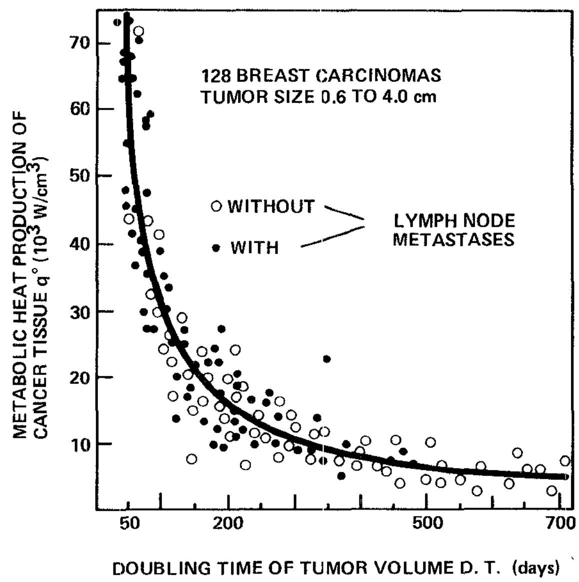

Fig. 3. Growth rate and specific heat production of breast carcinomas.

The use of thermography in cancer detection is based upon the assumption that a temperature differential exists between a malignant tumor and the surrounding tissue [11]–[13]. Gautherie and Albert [8] demonstrated (see Fig. 3) that metabolic heat production is directly related to the doubling time of tumor volume. This would suggest that a tumor having a high growth factor would be accompanied by significant thermal activity and, therefore, would not be difficult to detect using thermographic techniques. U *et al.* [14] measured tumor temperature with respect to surrounding tissue prior to the application of microwave hyperthermia. In 16 of 17 patients at various sites, temperature differentials of 1° to 3°C were observed.

The development of early diagnostic thermography equipment occurred at the infrared frequency range, taking

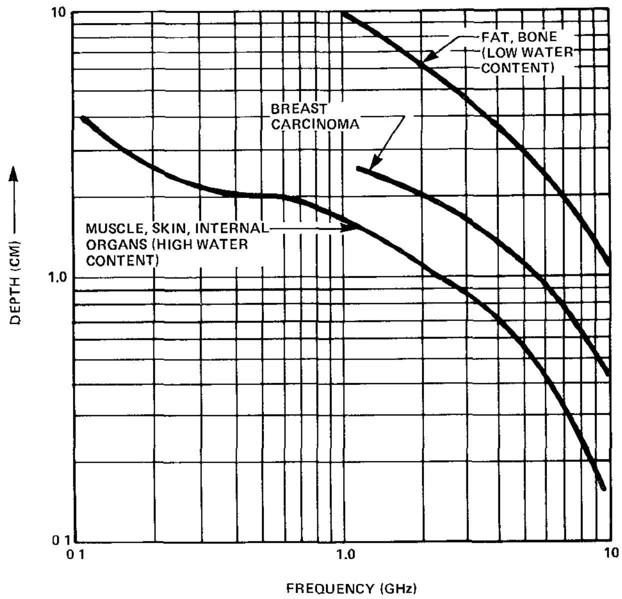

Fig. 4. Microwave penetration versus frequency (homogeneous media).

advantage of the corresponding higher levels of emission, as evident in Fig. 2. The potential of detecting thermal anomalies, such as malignant tumors in the female breast using microwave radiometry, was recognized by researchers Barrett and Myers [15], [16], followed by others [17]–[21]. Improved transmission characteristics at the lower microwave frequencies tend to offset the corresponding lower level of emission. The dielectric properties of various biological tissues at the microwave frequencies have been presented in the literature [22]–[25]. Fig. 4 illustrates the attenuation, or depth of penetration, with respect to frequency and water content [26]. The shift to lower frequencies will allow detection at greater depths.

Every component in the radiometer generates noise power that contributes to the overall noise of the system; therefore, the total system output contains not only noise received by the antenna but also noise generated within the system. Also, gain variations within the system can produce output fluctuations far greater than the signal level to be measured. To overcome these system gain variations, Dicke [27] developed the common load comparison (Dicke) radiometer. This configuration greatly reduces the effects of short-term gain variations of the radiometer since the switch provides a mechanism to allow both the reference and the unknown signals to pass through the amplification essentially at the same time relative to the expected gain drift in the amplifiers. Thus, any drift in gain will be applied equally to both the known and unknown signals. The receiver input is switched at a constant rate between the antenna and the constant temperature reference load, or reference antenna. The switched, or modulated, RF signal is therefore inserted at a point prior to RF amplification and as close to the antenna as possible. In turn, it is then amplified and coherently detected. The final output is proportional to the temperature differential between the antenna and the reference load. In the case where long integration times are involved, the long-term gain variations in the receiver must be considered. The long-term gain variations can degrade the minimum detectable temperature sensitivity (ΔT_s) in accordance with the following expression:

$$\Delta T_s = \Delta G / G (T_1 - T_2) \qquad \text{K rms} \qquad (1)$$

where ΔG is the receiver gain change, G is the nominal receiver gain, T_1 is the temperature of the reference load in kelvins, and T_2 is the temperature of the antenna in kelvins. Obviously, if T_1 approaches T_2 the effect on long-term receiver gain variations becomes negligible. It becomes advantageous, therefore, to maintain the temperature of the reference load approximately equal to the temperature of the unknown.

The radiometer design can be further modified to take into account antenna mismatch. If the receive antenna is noncontacting or remote, for example, the mismatch at the surface relative to the air can be significant, resulting in a dramatic reduction in surface emission. Ludeke and Kohler [28] have suggested the use of a radiation balancing radiometer employing noise injection, thus making the receiver temperature equal to the object temperature to eliminate the error due to reflectivity. However, if the radiometer is designed for a specific application, the use of site-optimized contact antennas could eliminate the need for this added complexity [29]. In this situation, however, thermal drift results from prolonged contact between a microwave antenna at room temperature and a subject at a different temperature. Appropriate antenna heating (i.e., thermal matching of the antenna) can minimize thermal drift and realize a more accurate temperature measurement [30].

The choice of radiometer frequency is based upon several factors—intensity of emission, which increases with increasing frequency; resolution, which improves with increasing frequency; and transmission characteristics, which deteriorate with increasing frequency.

The Dicke radiometer design pertaining to the following discussion is described in the literature [20]. The bandwidth of the radiometer is approximately 500 MHz centered at 4.7 GHz with a temperature sensitivity well within the design goal of 0.1°C.

III. Status

What has been accomplished? As stated earlier, the potential for detecting thermal anomalies such as malignant tumors in the breast using microwave radiometry was recognized by researchers Barrett and Myers [15], [16], who measured the temperature differentials between adjacent sites on the same breast and corresponding sites on the right and left breasts. It was further substantiated [16], [31], [32] that left to right breast symmetry on healthy volunteers was consistently within ± 0.2°C and, therefore, is suitable for comparison. Fig. 5 is representative of a

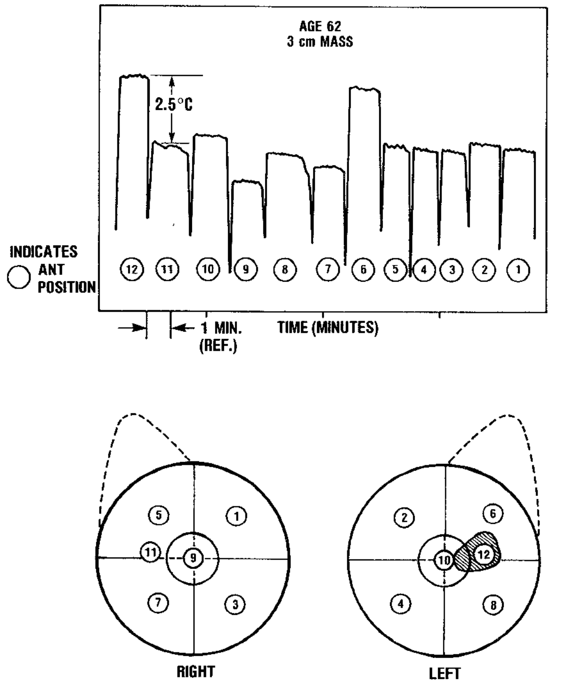

Fig. 5. Microwave thermogram demonstrating bilateral symmetry.

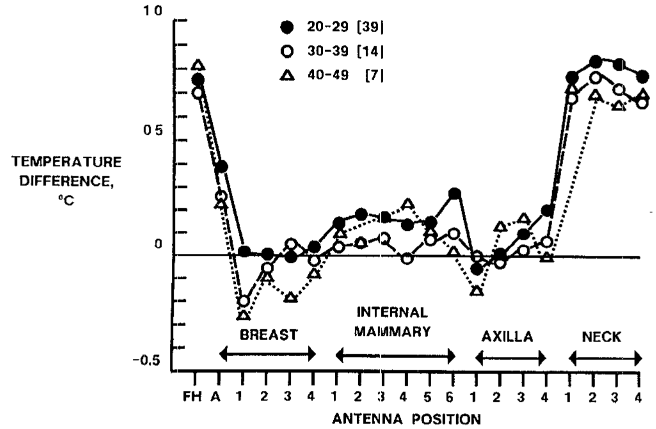

Fig. 6. Consistency of thermal patterns with increasing age: ages 20 through 49 with a total of 60 healthy volunteers.

microwave thermogram demonstrating the bilateral symmetry [32] using the 4.7 GHz radiometer described in the text. This case was that of a 62-year-old female having a palpable 3 cm mass on the left breast. A single dielectric-filled waveguide antenna was mechanically positioned as one would position a stethoscope. Utilizing the thermal symmetry that exists between the right and left breasts, common points are compared (i.e., the upper inner quadrant of the right breast (position 1) is compared with the corresponding upper inner quadrant (position 2) of the left breast). Repeating this procedure through the various positions revealed a very significant temperature differential between positions 5 and 6 (i.e., the upper outer quadrants). Similarly, there are temperature differences between positions 9 and 10 and, to a lesser degree, between positions 7 and 8. This grouping of elevated temperatures on the left breast indicates a thermal anomaly that was found to be at maximum at position 12. The temperature differential between position 12 in the left breast and the corresponding position 11 on the right breast was 2.5°C.

Fig. 6 demonstrates the consistency of thermal patterns with increasing age, indicating that a baseline microwave thermogram could indeed be useful in much the same way that a baseline mammogram is used. Future studies involving healthy volunteers up to an age of 66 indicated similar consistency.

It was further demonstrated [31] that, in contrast to infrared thermography, core temperature measured at 4.7 GHz was not significantly affected by menstrual cycle. Microwave thermography has been shown to be effective in the monitoring of the course of radiation treatment [33], [34]. Experience has shown using the single antenna that appropriate antenna heating (i.e., thermal matching of the antenna to the human subject) can minimize thermal drift and realize a more accurate temperature measurement [35]. It has been proven [34], [36]–[40] that the application of heat, regardless of the heating method used, will enhance detection. Thompson *et al.* [36] indicate that microwave heating is more effective than ultrasound. Experiments have been conducted [34], [36]–[39] proving the feasibility of increasing tumor detectability through the application of electromagnetic energy to induce significant temperature differential between the tumor and the surrounding tissue. Microwave power levels needed to achieve improved detectability are small, resulting in minimal heating of healthy tissue. Multiple-frequency radiometry has been investigated. Barrett *et al.* [16] had shown that infrared in combination with microwave, the complementary detection statistics are considerably improved and approaching that of mammography. Prionas and Hahn [41], with a detailed analysis of energy distribution versus depth and frequency, have established that multiple-frequency radiometry is a feasible technique to enhance noninvasive microwave detection.

It should be noted that a wide separation of microwave frequencies will preclude the use of a common antenna due to the inability to optimize antenna element performance over an appreciable bandwidth. For the same reason, the wide frequency separation may preclude the use of common microwave components in the front end of the radiometer.

IV. Antenna

The use of microwave radiometry as a noninvasive, passive, early detection technique indeed appears promising. Eventually, microwave radiometry could be used to provide noninvasive thermometry to control hyperthermia. It is also generally agreed that hyperthermia will play an increasingly important role in cancer therapy.

The critical component limiting system performance and acceptance is the antenna. Antenna design, coupling into a layered inhomogeneous media, is complex and difficult, with results determined generally by test rather than design. Antenna measurements are normally evaluated in the radiate mode rather than the receive. However, the antenna reciprocity theorem states that transmit and receive antenna patterns are identical [42]. The antenna can be remote or in direct contact with the tissue. The direct-contact antenna can be matched to the tissue, minimizing the tissue-to-air interface and providing maximum coupling of the emitted signal to the transmitter or receiver. If the antenna is noncontacting, or remote, the mismatch at the surface relative to the air can be significant, resulting in a dramatic reduction in surface emissivity in the case of passive radiometry, or a significant reflection as in the case of hyperthermia.

Ludeke *et al.* [28], as discussed earlier, have suggested the use of a radiation balancing radiometer to eliminate the error due to the mismatch at the tissue interface. The added complexity associated with this noise injection technique can be eliminated through the use of site-optimized contact antennas [29].

Antenna design operating in the near-field region in a layered inhomogeneous media is complex and difficult, with results determined generally by test rather than design. Equipment to date has employed waveguide antennas rather than microstrip. Microstrip antennas [43]–[46] are small, lightweight, and inexpensive and can be constructed on a flexible substrate material providing the ability to conform to body surface. The use of microstrip, however, will reduce overall system performance (i.e., increased noise figure) due to increased insertion loss when compared with waveguide and, hence, lower efficiency.

For the most part, design data available for microstrip antennas pertain to mating to an air dielectric ($\epsilon_r = 1$) rather than tissue. The effect on the design as a result of mating to lossy material having a high dielectric constant is dramatic. Bahl and Stuchly [44] have discussed the design of the microstrip covered with a lossy dielectric layer.

It had been determined by Guy [47] that the optimum direct-contact waveguide aperture size to achieve effective coupling of microwave energy to biological tissue is the simple TE_{10} mode. At the higher microwave frequencies and particularly at the millimeter-wave frequencies, waveguide antennas can be of convenient size. On the other hand at the lower frequencies, where greater depth can be achieved, the physical size of the antenna is significant and, oftentimes, unacceptable for clinical use, necessitating the need for dielectric loading [48]–[50]. The reduction in aperture size is proportional to $\epsilon_r^{1/2}$ where ϵ_r is the dielectric constant of the material used. The geometrical dimensions of the aperture determine the amount of thermal energy received. Increasing the size of the aperture will, therefore, improve the signal-to-noise ratio.

The size and shape of the aperture will determine the pattern, directivity, or beam. A reduction in aperture size, however, can result in a decrease in effective detection depth. The beam width of the antenna [51] will increase with decreasing aperture width, corresponding to reduced gain or, in this case, reduced detection or heating. Allowing the aperture width to approach zero creates, in essence, a point source at which the antenna becomes omnidirectional with minimal depth of penetration.

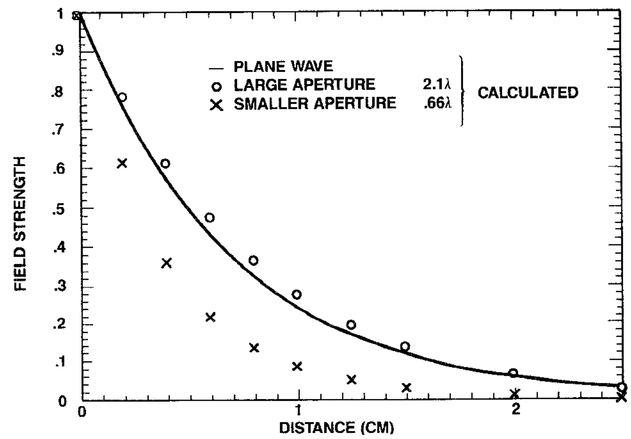

Fig. 7. Depth of penetration with respect to aperture size at 4.7 GHz when mated with ethanol or lower water content equivalent tissue.

Fig. 7 illustrates the calculated [52] effective aperture size at a given frequency on depth of penetration when mated with ethanol or lower water content equivalent tissue. The larger aperture has an area of 10.5 cm^2, whereas the smaller unit has an area of 1.24 cm^2. When mated to a material having a high dielectric constant, such as water, the calculations show no appreciable difference in penetration. The results indicate that for optimum performance the aperture must be larger than the wavelength measured in the mating tissue area.

Fig. 8 demonstrates the spatial resolution at 4.7 GHz associated with the dielectric-filled 1.24 cm^2 antenna, using the tissue equivalent phantom shown in Fig. 9. The diameter of the hole, or "hot line," is 0.4 cm at a depth of 1 cm below the surface. The height, or b dimension, of the waveguide is 0.79 cm. The liquid pumped through the hole was at a temperature 3.15°C above the phantom temperature.

Attempts to utilize noninvasive multiple antennas to achieve a phased array in order to focus energy at depth in human tissue have met with little success. A phased array or, in the case of radiometric correlation techniques [53], [54], require overlapping antenna patterns (Fig. 10) in which the overlapping portion is in phase, or coherent, allowing additive beam forming. If coherency could be achieved, the radiated pattern of the aperture formed by the multiple elements would become more narrowed in beam width and, therefore, more directive.

In a nonhomogeneous, layered and lossy media, phase coherency and significant overlapping are extremely difficult to achieve through the use of normal phased array techniques. Multiple antennas using less sophisticated commutation techniques, as in the case of microwave thermography, will prove useful if used merely to reduce examination time.

The use of multiple antennas will increase system complexity and cost. As stated earlier, every component in the radiometer generates noise power that contributes to the

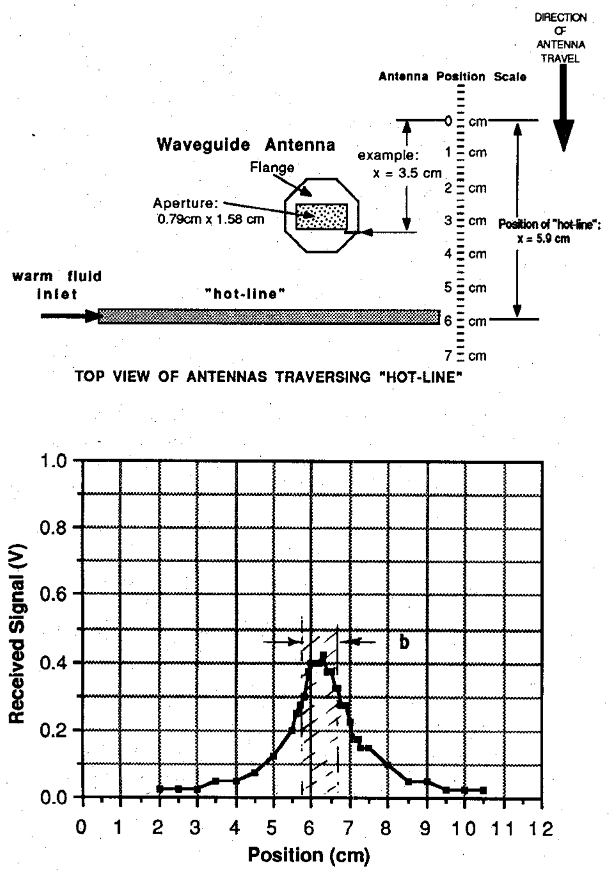

Fig. 8. Spatial resolution at 4.7 GHz using the dielectric-filled waveguide antenna.

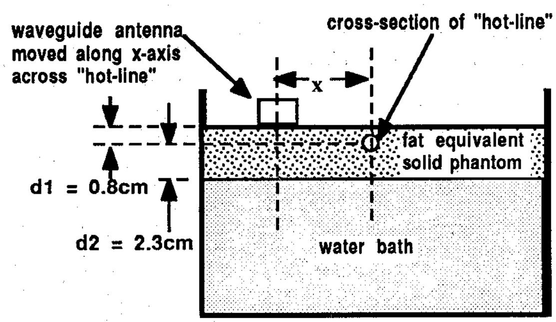

Fig. 9. Tissue equivalent phantom.

overall noise received. Components inserted prior to amplification will result in increased noise figure, with a corresponding reduction in minimum detectable temperature sensitivity.

The most successful use of multiple antennas has involved invasive, simple, coaxial monopoles. These invasive applicators are generally used in combination with interstitial radiotherapy. The applicator is normally inserted into the catheter used to insert the radioactive material. Multiple antennas, or applicators of this type, are coaxial structures, with heating patterns projecting radially from the exposed center conductor, creating an interference pattern. Proper spacing of the antenna will provide predictable and

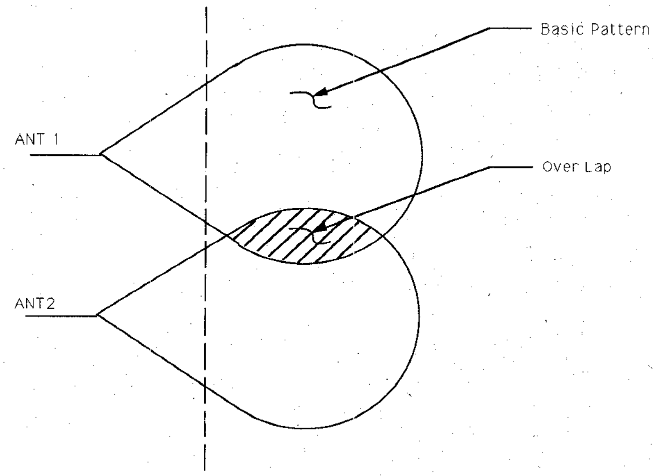

Fig. 10. Overlapping antenna pattern.

uniform heating at depth. Realizing that coaxial cables having small cross sections are lossy, resulting in system degradation, this type of antenna is not considered efficient in radiometric applications [55]–[57].

V. Conclusion

The application of microwave technology to the solution of medical problems, specifically to the detection and treatment of cancer, has been very encouraging. It is generally agreed that hyperthermia (i.e., the application of microwave energy to elevate tumor temperature to cause cell necrosis) will play an increasingly important role in cancer therapy.

The use of microwave radiometry (i.e., a noninvasive, passive technique to allow the detection and diagnosis of pathologic conditions in which there are disease-related temperature differentials) is currently an experimental technique with studies being conducted by several teams around the world with limited yet encouraging results. Performance improvements and cost reduction in these areas will be assisted by the rapid progress in microwave devices, components, and signal processing techniques.

The antenna has become the critical component limiting system performance. The near-field region of a layered, absorptive, and inhomogeneous medium represents a difficult and challenging problem of electromagnetic theory. Further development in the areas of antennas and antenna arrays is required if microwave technology is to become an accepted and practical solution to the detection and treatment of cancer.

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