ANTENNA: THE CRITICAL ELEMENT IN SUCCESSFUL MEDICAL TECHNOLOGY

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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 development of cancer, for example, microwave hyperthermia has been accepted as an adjunctive procedure to radiation therapy in the treatment of superficial lesions. While not so widely reported, the use of microwave radiometry as a noninvasive passive technique for 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.

TECHNICAL DISCUSSION

Developments in the application of microwave technology to the detection and treatment of cancer have been encouraging. Numerous presentations and publications have been made, particularly with respect to hyperthermia (i.e., the application of microwave energy to elevate tumor temperature to cause cell necrosis. It is generally agreed, based upon several important biological rationale [1-16] that hyperthermia will play an increasingly important role. While not as widely reported, the use of microwave radiometry as a noninvasive passive early detection technique indeed appears promising. [17-25] Eventually microwave radiometry could be used to provide noninvasive thermometry to control hyperthermia. Radiometry is defined as the technique for measuring electromagnetic energy, and clinical radiometry is, in turn, the passive measurement of natural emission from the human body.

Significant progress has been made in the areas of signal processing and electronic display. Consistent with technology trends, the advent of low noise/small signal and high power microwave transistors and the use of microwave integrated circuit techniques will significantly reduce size, weight and cost. However, the antenna -- the critical component to both treatment and detection -- is the single most important component limiting system performance.

Acceptance of hyperthermia, for example, is restricted to an adjunctive procedure to radiation therapy for superficial lesions. The primary reason for this limitation is related to the inability to focus energy at depth in human tissue. The acceptance of microwave radiometry as a noninvasive passive early detection technique will be subject to similar restrictions. Propagation in the near-field region of a layered absorptive and inhomogeneous medium represents a difficult and challenging microwave problem.

Antenna performance is generally determined by test rather than design. Antennas are normally evaluated in their radiate mode rather than the receive; however, the antenna reciprocity theorem states the transmit and receive antenna patterns are identical [26].

Antennas 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 and Kohler [27] 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 would eliminate the need for this added complexity [28]. In that situation, however, thermal drift results from prolonged contact between the 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 [29].

It had been determined by Guy [30] 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 [31-33].

The size and shape of the aperture will determine the directivity or beam. A reduction in aperture size, however, can result in a decrease in effective detection depth. The beamwidth of the antenna 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.

Attempts to utilize noninvasive multiple antennas to achieve a phased array in order to focus energy at depth in humans have met with little success. A phased array, or in the case of radiometric correlation techniques [34-35], requires overlapping antenna patterns 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 antennas would become more narrowed in beamwidth and, therefore, more directive.

The more 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 implant 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 antennas will provide predictable and 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 [36].

Microstrip antennas [37-40] are small, lightweight, inexpensive and can be constructed in a flexible substrate material providing the ability to conform to the body surface. The use of microstrip, however, will reduce the overall system performance (i.e., in the case of radiometry, 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 (i.e., $\varepsilon_r=1$) rather than complex tissue. The effect on the design as a result of mating to a lossy material having a high dielectric constant is dramatic. Bahl and Stuchley [41] have discussed the design of the microstrip covered with a lossy dielectric layer.

The requirement for broadband performance associated with multiple frequency radiometry will necessitate further development of printed configurations. Barrett et al [42] had shown that when infra-red is used in combination with microwave, the resulting detection data are significantly improved . . . approaching that of mammography. Prionas and Hahn [43], with a detailed analysis of energy distribution vs depth and frequency, have established that multiple-frequency radiometry is a feasible technique to enhance noninvasive microwave detection. A wide separation of microwave frequencies may preclude the use of a common antenna due to the inability to optimize antenna element performance over an appreciable bandwidth.

CONCLUSION

Developments in the application of microwave technology to the detection and treatment of cancer have been very encouraging; however, further development in the areas of antennas and antenna arrays is required if microwave technology is to become an acceptable and practical solution to the detection and treatment of cancer. The near-field region of a layered, absorptive and inhomogeneous medium represents a difficult and challenging problem.

REFERENCES

[1] T.T. Chen and C. Heidelberger, "Quantitative Studies on the Malignant Transformation of Mouse Prostate Cells by Carcinogenic Hydrocarbons in Vitro," INT. J. CANCER 4: 166-178, 1969.

[2] K. Kase amd G.M. Hahn, "Differential Heat Response of Normal and Transformed Human Cells in Tissue Culture," NATURE 225:228-230, 1975.

[3] G.C. Giovanella, J.S. Stehlin and A.C. Morgan, "Selective Lethal Effect of Supranormal Temperatures on Human Neoplastic Cells," CANCER RES. 36:3944-3950, 1976.

[4] S. Warren, "Preliminary Study of the Effect of Artificial Fever Upon Hopeless Tumor Cases," AM. J. ROENTGENOL. 33:75-87, 1935.

[5] R. Cavaliere, E.C. Ciocatto, B.C. Giovanella, C. Heidelberger, R.O. Johnson, M. Margottini, B. Modovi, G. Moricca and A. Rossi-Fanelli, "Selective Heat Sensitivity of Cancer Cells - Biochemical and Clinical Studies," CANCER 20:1351-1381, 1967.

[6] L.E. Gerweck, "Modification of Cell Lethality at Elevated Temperatures - The pH Effect," RADIAT. RES. 70:224-235, 1977.

[7] H. Bass, J.L. Moore and W.J. Coakley, "Lethality in Mammalian Cells due to Hyperthermia under Oxic and Hypoxic Conditions," INT. J. RADIAT. BIOL. RELAT. STUD. PHYS. CHEM. MED. 33:57-67, 1978.

[8] G.M. Hahn, "Metabolic Aspects of the Role of Hyperthermia in Mammalian Cell Inactivation and their Possible Relevance to Cancer Treatment," CANCER RES. 34:3117-3123, 1974.

[9] G.M. Hahn, J. Braun and I. Har-Kedar, "Thermochemotherapy: Synergism between Hyperthermia (42-43 degrees) and Adriamycin (of Bleomycin) in Mammalian Cell Inactivation," PROC. NAT. ACAD. SCI. 72:937-940, 1975.

[10] L. Kwock, P.S. Lin, K. Hefter and D.F. Wallach, "Impairment of Na+dependent Amino Acid Transport in a Cultured Human T-cell Line by

Hyperthermia and Irradiation," CANCER RES., 38:83-87, 1978.
[11] J.B. Marmor, "Interactions of Hyperthermia and Chemotherapy in Animals," CANCER RES. 39:2269-2276, 1979.
[12] Ibid, 9.
[13] Ibid, 10.
[14] P.S. Lin, L. Kwock and C.E. Butterfield, "Diethyldithiocarbamate Enhancement of Radiation and Hyperthermic Effects on Chinese Hamster Cells In Vitro," RADIATION RES., 77:501-511, 1979.
[15] G.M. Hahn, G.C. Li and E. Shiu, "Interaction of Amphotericin B and 43 degrees Hyperthermia," CANCER RES. 37:761-764, 1977.
[16] C. Song, M. Kang and J. Rhee, "The Effect of Hyperthermia on Vascular Function, pH, and Cell Survival," RADIOLOGY 137:795-803, 1980.
[17] P.C. Myers, N.L. Sadowsky and A.H. Barrett, "Microwave Thermography: Principles, Methods and Clinical Applications," J. MICROWAVE POWER, vol. 14, no. 2, 1979.
[18] J. Edrich, "Centimeter- and Millimeter-wave Thermography -- A Survey on Tumor Detection," J. MICROWAVE POWER, vol. 14, pp. 95-104, 1979.
[19] B. Enander and G. Larson, "Microwave Radiometric Measurements on the Temperature Inside the Body," ELECTRON. LETT., vol. 10, pp. 317-319, 1974.
[20] A. Mamouni, F. Bliot, Y. Leroy and Y. Moschetto, "A Modified Radiometer for Temperature and Microwave Properties Measurements of Biological Substances" in 7th EUROPEAN MICROWAVE CONF. DIGEST (Copenhagen, Denmark), pp. 703-707, 1977.
[21] K.L. Carr, A.M. El-Mahdi and J. Shaeffer, "Dual-mode Microwave System to Enhance Early Detection of Cancer," IEEE TRANS. MICROWAVE THEORY TECH., vol. MTT-29, pp. 256-260, 1981.
[22] R.A. Porter and H.H. Miller, "Microwave Radiometric Detection and Location of Breast Cancer," ELECTRO, Boston, MA, May 1978.
[23] T. Tenjin, H. Oyama, T. Maeda and O. Kanedo, "Application of Microwave Thermography for the Diagnosis of Breast Cancer," Nippon Med. Sch. Rep. Japan Thermography Association, 1984.
[24] J. Shaeffer, A.M. El-Mahdi and K.L. Carr, "Thermographic Detection of Human Cancers by Microwave Radiometry," presented at the International Symposium on Biomedical Thermology, Strasbourg, France, 1981.
[25] Y. Leroy, "Microwave Radiometry and Thermography: Present and Prospective," in BIOMEDICAL THERMOLOGY, New York: Alan R. Liss, pp. 485-499, 1982.
[26] R.F. Harrington, TIME-HARMONIC ELECTROMAGNETIC FIELDS, New York: McGraw-Hill, pp. 116-132, 1961.
[27] K.M. Ludeke and J. Kohler, "Microwave Radiometric System for Biomedical 'true temperature' and Emissivity Measurements," J. MICROWAVE POWER, vol. 18, pp. 277-283, 1983.
[28] K.L. Carr, R.J. Bielawa, J.F. Regan, A.M. El-Mahdi and J. Shaeffer, "The Effect of Antenna Match on Microwave Radiometric Thermal Patterns," IEEE MTT-S INT. MICROWAVE SYMP. DIG. pp. 189-191, 1983.
[29] J. Shaeffer, A.M. El-Mahdi, R.J. Bielawa, J.F. Regan and K.L. Carr, "Thermal Drift in Microwave Thermography," IEEE MTT-S INT. MICROWAVE SYMP. DIG. pp. 441-443, 1982.
[30] A.W. Guy and J.F. Lehmann, "On the Determination of an Optimum Microwave Diathermy Frequency for a Direct Contact Applicator," IEEE TRANS. BIOMED. ENG., vol. BME-13, pp. 67-87, 1966.
[31] F. Sterzer, R. Paglione, M. Nowogrodzki and E. Beck, "Microwave Apparatus for the Treatment of Cancer," MICROWAVE J., vol 23, pp. 39-44, 1980.
[32] P.C. Myers, A.H. Barrett and N.L. Sadowsky, "Microwave Thermography of Normal and Cancerous Breast Tissue," ANN. N.Y. ACAD. SCI., vol. 335, pp. 443-455, 1979.
[33] A.W. Guy, J.F. Lehmann, J.B. Stonebridge and C.C. Sorensen, "Development of a 915 MHz Direct-Contact Applicator for Therapeutic Heating of Tissues," IEEE TRANS. MICROWAVE THEORY TECH., vol. MTT-26: 550-556, 1978.
[34] Y. Leroy, "Microwave Thermography for Biomedical Applications," presented at 12th European Microwave Conf. (Helsinki), 1982.
[35] A. Mamouni, J.C. Van deVelde and Y. Leroy, ELECTRON. LETT., vol. 17, no. 16, pp. 554-555, 1981.
[36] A. Wu, M.L. Watson, E.S. Sternick, R.J. Bielawa and K.L. Carr, "Performance Characteristics of a Helical Microwave Interstitial Antenna for Local Hyperthermia," presented at 27th Annual Meeting, AAPM, Seattle, August 1985.
[37] I.J. Bahl, S.S. Stuchly and M.A. Stuchly, "New Microstrip Slot Radiator for Medical Applications," ELECTRON. LETT., 16:731-732, 1980.
[38] I.J. Bahl and S.S. Stuchly, "Analysis of a Microstrip Covered with a Lossy Dielectric," IEEE TRANS. MICROWAVE THEORY TECH., MTT-28: 104-109, 1980.
[39] M.F. Iskander and C.H. Durney, "An Electromagnetic Energy Coupler for Medical Applications," PROC. IEEE 67:1463-1464, 1979.
[40] I.J. Bahl, S.S. Stuchly and M.A. Stuchly, "A New Microstrip Radiator for Medical Applications," IEEE TRANS. MICROWAVE THEORY TECH., MTT-28:1464-1468, 1980.
[41] Ibid, 38.
[42] Ibid, 17.
[43] S.D. Prionas and G.M. Hahn, "Noninvasive Thermometry using Multiple-Frequency Band Radiometry: A Feasibility Study," BIOELECTROMAGNETICS, vol. 6, pp. 391-404, 1985.