REFERENCES

[1] D. E. Livesay and K. M. Chen, "Electromagnetic fields induced inside arbitrary shaped biological bodies," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 1273–1280, 1974

[2] K. M. Chen and B. S. Guru, "Internal EM field and absorbed power density in human torsos induced by 1–500 MHz EM waves," *IEEE Trans. Microwave Theory Tech* , vol. MTT-25, pp. 746–756, 1977.

[3] M. J. Hagmann, O. P. Gandhi, and C. H. Durney, "Numerical calculation of electromagnetic energy deposition for a realistic model of man," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 804–809, 1979.

[4] M. J. Hagmann and O. P. Gandhi, "Numerical calculation of electromagnetic energy deposition in man with ground and reflector effects," *Radio Sci.*, vol. 14, No. 6(5), pp. 23–29, 1979.

[5] I. Chatterjee, M. J. Hagmann, and O. P. Gandhi, "Electromagnetic energy deposition in an inhomogeneous block model for near-field irradiation conditions," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 1452–1459, 1980.

[6] M J. Hagmann, O. P. Gandhi, J. A. D'Andrea, and I. Chatterjee, "Head resonance: Numerical solutions and experiment results," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 809–813, 1979.

[7] A. Ralston and P. Rabinowitz, *A First Course in Numerical Analysis*, 2nd ed. New York: McGraw-Hill, 1975.

[8] C. C. Johnson and A. W. Cory, "Nonionizing electromagnetic wave effects in biological materials and systems," *Proc. IEEE*, vol. 60, pp. 692–718, 1972.

[9] D. J. Morton, *Manual of Human Cross-Section Anatomy*. Baltimore: Williams and Williams, 1944.

[10] M. J. Hagmann, "Numerical studies of absorption of electromagnetic energy by man," *Ph.D. Dissertation*, Univ. of Utah, 1978.

[11] T. R. Ferguson, T. H. Lehman, and R. J. Balestri, "Efficient solution of large moment problems: Theory and small problem results," *IEEE Trans. Antennas Propagat.*, vol. AP-24, pp. 230–235, 1976.

Letters

Comments on "Capabilities of Multi-Applicator Systems for Focused Hyperthermia"

PAUL F. TURNER

In the above paper[1], the author has incorrectly assumed that aperture size must be limited to a lateral dimension of not less than one wavelength in fat tissue in order to prevent excessive heating of superficial fat. The reference cited to support this conclusion [1] did not make such a generalization, but rather provided an example which implied this restriction at a particular frequency and with a certain aperture size. In actuality, however, focussed co-phased applicators are useful across a much broader range than Knoechel has suggested.

The work to which he has referred stems in turn from that of Guy and Lehmann [2]; this material indicates that an optimum frequency exists at which a single aperture produces minimum surface fat heating and maximal penetration depth through a fat/muscle boundary. Guy's study shows that only small changes in fat heating at lower frequencies occur through near-field effects.

The use of a dielectric (i.e., water-filled) bolus was alluded to by Knoechel, but he mentioned nothing of the effects of this device. In fact, such a bolus displaces the aperture near fields from the tissue surface and at the same time acts as a dielectric waveguide to maintain energy confinement within the bolus. Fat heating can therefore be reduced at lower frequencies and with smaller apertures. The primary advantage of using lower frequencies in a co-phase applicator array is that this produces a larger central hot zone because of the longer wavelengths used.

A rather dramatic example of the use of synchronously arrayed radiators is the Annular Phased Array (APA), developed at BSD Medical Corporation, which is composed of 16 apertures surrounding the patient in an annular fashion. I first reported on this device and its test results in June of 1980 [3]; these initial tests demonstrated that a large central heating zone was created in muscle phantom models of the human trunk and in large pigs. No selective fat heating has been observed in subsequent animal experiments or in any of the more than 430 patient treatments to date.

A water bolus is placed between the apertures of the APA and the tissue in order to reduce near-field effects by lowering the medium impedance at the aperture and displacing the tissue from the near fields. This allows broad-band operation of the Annular Phased Array at frequencies of 50–110 MHz. Each of the 16 apertures of this device has a minimal size of 23 cm, which is one-eighth of a wavelength in fat at 50 MHz. The wavelength in muscle at 50 MHz is 47 cm [1]; thus, the central co-phase reinforcement zone is on the order of 24 cm wide.

Knoechel, however, in his article, did not clearly state the necessity for aligning the electric fields of co-phased apertures in

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[1]R. Knoechel, *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, Jan 1983.

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order to ensure that within the central region of overlapping beams these electromagnetic fields will sum. Simple rotation of the alignment of one aperture with respect to another by 90° would produce the pattern of a randomly-phased pair. The importance of this alignment could therefore be easily missed by readers of that article who intend to apply the co-phase method in hyperthermia treatments, and this should be brought to their attention.

Reply[2] by R. Knoechel[3]

Hoping that Turner's comments on my short paper [4] have been understood correctly, his remarks can be summarized as follows.

1) It is claimed that efficient deep heating can be obtained with an antenna array, where the lateral dimensions of a single aperture are much smaller than one wavelength.

2) It is assumed that the work which is reviewed in [1] does not allow the statement that an applicator smaller than one wavelength results in a reduced penetration depth (compared to $1/e$ penetration of a plane wave), strong near-field effects, and superficial heating, thus implying the risk of skin burns, when the applicator is brought into contact with living tissue.

3) It is mentioned that a dielectric bolus made from high permittivity material reduces near-field effects.

4) It is stressed that electrical field vectors have to be parallel in space in order to sum the field strength.

5) It is claimed that a 90° spatial rotation of one field vector leads to the heating pattern of a randomly phased pair, although the applicators are driven in co-phase with respect to time.

Turners comments are supported by experience with an annular phased array, described in [7]. Reference [3] of the above comment was not available at the time my short paper was written, since it appeared in June 1982.

To answer 1) and 2), the citation of the review article [1] referred to work which is described in more detail in [5]. This work considers TE_{10}-waveguide apertures as applicators and concludes that maximum penetration depth is obtained only with larger apertures having the lateral dimension of one wavelength. Extensive measurements have been made in our laboratory with TE_{10}-waveguide and various other types of antennas, i.e., helix antennas, spiral antennas, dipoles, microstrip patch antennas, slot antennas, and ring antennas, at 2450 and 915 MHz, confirming the results of [5]. TE_{10}-waveguide apertures are near optimum for direct contact applicators, and a similar relation between size and penetration depth exists for all kinds of applicators. Also, Turner's own results, as reproduced in [6], can be used to deduce that too small an aperture size leads to a decrease in penetration depth compared with a plane wave, and that a reduction of frequency does not increase the penetration depths.(See Fig. 1.)

As to 3), it is not doubted that a dielectric bolus reduces near-field effects, although we do not have experimental experience. The antenna beam is spread when traveling through the bolus, and when it enters the tissue, unwanted heating effects may be reduced, provided that the beam is now wide enough. Unwanted effects of boluses are internal standing waves, and

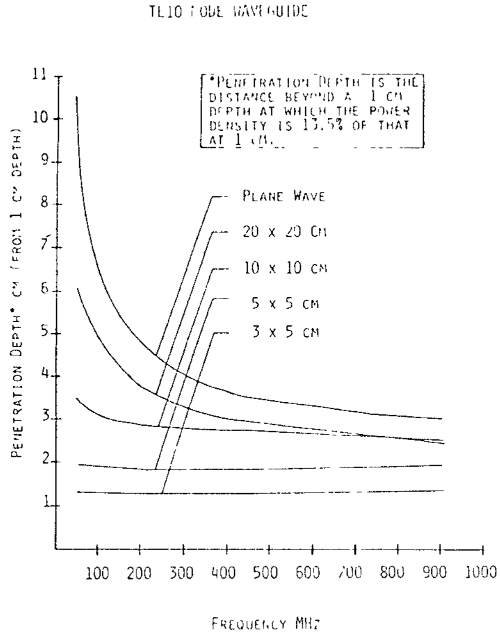

Fig. 1. Frequency dependence of penetration depth with TE_{10}-mode waveguide (from Turner *et al*, "Computer solution for applicator heating patterns," NCI Monograph 61, pp. 521–523, June 1982.)

reduction of penetration depth to attenuation in the bolus.

Concerning 4), it is clear that co-phase driving has to be understood with respect to time *and* space, when a constructive interference is wanted. However, the assumption 5), that a spatial phase of 90 degrees between the applicators leads to the pattern of a randomly phased pair, is incorrect. The E-vector is then $\sqrt{2} \cdot E_0$ oscillating in the 45° direction. This case leads to twice the temperature as produced by a single applicator, as is obvious.

My short paper aimed mainly at the application of focused hyperthermia to heat a deep-sited localed spot. However, what is described by Turner in [3] rather can be termed regional hyperthermia than localized hyperthermia, and effects by "focused" heating and surface cooling through the bolus seem to be superimposed.

Last, but not least, I would like to thank P. F. Turner for his stimulating remarks.

References

[1] A. W. Guy, J. F. Lehmann, and J. B. Stonebridge, "Therapeutic applications of electromagnetic power," *Proc. IEEE*, vol 62, pp. 55–75, 1974.

[2] A. W. Guy and J F. Lehmann, "On the determination of an optimum microwave diathermy frequency for direct-contact applicator," *IEEE Trans. Biomed. Eng.*, vol. BME-13(2): 76–87, Apr. 1966.

[3] P. F. Turner, "Deep heating of cylindrical or elliptical tissue masses," presented at the Third Int. Symp. on Cancer Therapy by Hyperthermia, Drugs and Radiation, June 1980; NCI Monograph 61, pp. 493–495, June 1982.

[4] R. Knoechel, "Capabilities of multiapplicator systems for focussed hyperthermia," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31, pp. 70–73, Jan. 1983.

[5] A. W. Guy, "Electromagnetic fields and relative heating patterns due to a rectangular aperture source in direct contact with bilayered biological tissue," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 214–223, 1971.

[6] G. Kantor, "Evaluation and survey of microwave and radiofrequency applicators," *J. Microwave Power*, vol. 16, pp. 135–150, 1981.

[7] F. A. Gibbs, "Clinical evaluation of a microwave/radio-frequency system (BSD Corporation) for induction of local and regional hyperthermia," *J. Microwave Power*, vol. 16, pp. 185–192, 1981.

[2]Manuscript received June 2, 1983.

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