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Bottomley P A & Andrew E R. Magnetic field penetration, phase shift and power dissipation in biological tissue: implications for NMR imaging. *Phys. Med. Biol.* 23:630-43, 1978.
[Department of Physics, University of Nottingham, England]

Imaging the human body by nuclear magnetic resonance requires the penetration of an electromagnetic field into the body. This paper investigates this penetration in the frequency range 1-100 MHz. [The *SCI*® indicates that this paper has been cited in over 100 publications.]

NMR Penetration into the Body

E.R. Andrew
Department of Physics
University of Florida
Gainesville, FL 32611

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In the mid-1970s we were carrying out early experiments in Nottingham on nuclear magnetic resonance (NMR) imaging and were obtaining good proton images of such small objects as a lemon and other fruit, a rat and a rabbit, and a human hand, wrist, and arm.[1-6] In our laboratory and elsewhere, magnets were being prepared large enough to accept the whole human body, to work initially at about 5 MHz with probable later extension to higher frequencies. The human body is well known to be an electrical conductor, and the question arose whether the electromagnetic field would in fact penetrate the whole body adequately. Would the "skin depth" be too short? Would there be a serious phase distortion? Would there be undesirable heating of the body? This paper set out to provide a first answer to these questions.

A very good research student, Paul A. Bottomley, had just joined me from Australia. He is now a leading researcher at GE Schenectady and a gold medalist of the Society of Magnetic Resonance in Medicine. The human body was modeled as a homogeneous cylinder of 40 cm diameter. Some people approximate to such a geometry better than others! Maxwell's equations of electromagnetism were solved for this model. We then needed numerical values of the resistivity and permittivity as a function of frequency. Biologist colleagues advised us that rat tissue was a good substitute for human tissue (not flattering!), and Paul made impedance measurements for a variety of rat tissues over the whole frequency range at 37° C, the body temperature. This enabled penetration depth, phase distortion, and power deposition to be calculated.

It was clear that at 5 MHz there would be complete penetration with negligible phase distortion and little power deposition, and this was found to be correct when whole-body NMR imaging was carried out at this frequency. However, the paper forecast that significant effects would be found at 30 MHz. These results were useful predictors of behavior, though they have turned out to be rather too pessimistic and should be regarded as upper limits of behavior. At 85 MHz, corresponding to an imaging field of 2 tesla, penetration is actually rather complete, though incomplete penetration has been reported at twice this frequency in fields of 4 tesla. The reasons for the discrepancy lie with the approximate nature of the model. Not many patients have a circular cross section of 40 cm diameter; many are only half this thickness from front to back and of course the head is much smaller. Secondly, the human body is not homogeneous and contains many cavities, for example, the lungs, where there is no significant radio frequency attenuation. In fact, our human model has been described as "the homogeneous sausage model"!

It is important that not too much radio frequency power is dissipated in the human body causing unwanted heating. The amount of heat that may be deposited is regulated by national guidelines, intended to restrict the local temperature rise to one degree. The paper has provided a basis for estimating the safe deposition of radio frequency heat.

There are now about a thousand whole-body NMR scanners installed in hospitals worldwide, and about a million patients have now been imaged. This paper has played a part in considerations of performance and safety in such systems.

1. **Andrew E R, Bottomley P A, Hinshaw W S, Holland G N, Moore W S & Simaroj C.** NMR images by the multiple sensitive point method: application to larger biological systems. *Phys. Med. Biol.* 22:971-5, 1977. (Cited 65 times.)
2. **Hinshaw W S, Andrew E R, Bottomley P A, Holland G N, Moore W S & Worthington B S.** Internal structural mapping of nuclear magnetic resonance. *Neuroradiology* 16:607-9, 1978. (Cited 15 times.)
3. ————. An in vivo study of the forearm and hand by thin section NMR imaging. *Brit. J. Radiol.* 52:36-43, 1979. (Cited 55 times.)
4. **Andrew E R.** NMR imaging of intact biological systems. *Phil. Trans. Roy. Soc. London B* 289:471-81, 1980. (Cited 30 times.)
5. ————. Nuclear magnetic resonance imaging in medicine: physical principles. *Proc. Roy. Soc. London Ser. B* 225:399-410, 1985.
6. Front cover of *Nature*, 22/29 December 1977.

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