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Cross-sectional image by focused NMR (FONAR) of simulated chest. First FONAR image of live human chest appears on inside back cover, this issue. (Details on page 97 et seq.)

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NMR IN CANCER: XVI. FONAR IMAGE OF THE LIVE HUMAN BODY

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• *The FONAR technique that achieved the first chemical image of the live human being is described. Color and black-and-white video images of a cross-section through the chest at the level of the eighth thoracic vertebra were generated. The imaging showed the heart and mediastinum in the midline between the left and right lungs with the heart encroaching on the left lung space as it does at this level. Also seen was the descending aorta just left and anterior to the vertebral body.*

Since the introduction in 1971 by Damadian of the nuclear resonance technique for detecting cancers, instrumentation has been under development for their visualization in live animals. The goal of these efforts by Damadian and co-workers has been a non-invasive means for visualizing not only tumors but also other biological structures in man. The method of Damadian has achieved this objective by focusing the NMR signal within the sample (FONAR).[1] This method was developed in 1972.[1] Subsequent methods have taken other approaches.[2-4]

In the NMR experiment, the irradiating ac field and the dc magnetic field applied across the sample must satisfy an exact ratio of frequency to field strength to obtain a signal from the sample. This ratio, the gyromagnetic ratio for the spinning nucleus, is a characteristic constant for each element and different for each magnetic nucleus. It is therefore possible by shaping the rf and dc fields within the sample to control the size of the resonating volume and thereby restrict, or focus, the signal-producing region within the sample to a small volume that can be examined independent of its surroundings.[5]

This resonating volume, or *FONAR resonance aperture* as we have designated it, can then be directed to any region within the interior of the sample for direct examination of the NMR chemistry of the locus, or it can be used to systematically scan through the sample to generate an image. The first tumor of a live animal was visualized by the FONAR method in 1976, utilizing a mouse with a tumor surgically implanted in the anterior thorax.[5] In the human, however, the largest structure subsequently possible to image by NMR has been the finger.[4] We wish now to report the achievement by FONAR of the first NMR images of the live human body, a cross-sectional visualization through the torso at the level of the eighth thoracic vertebra.

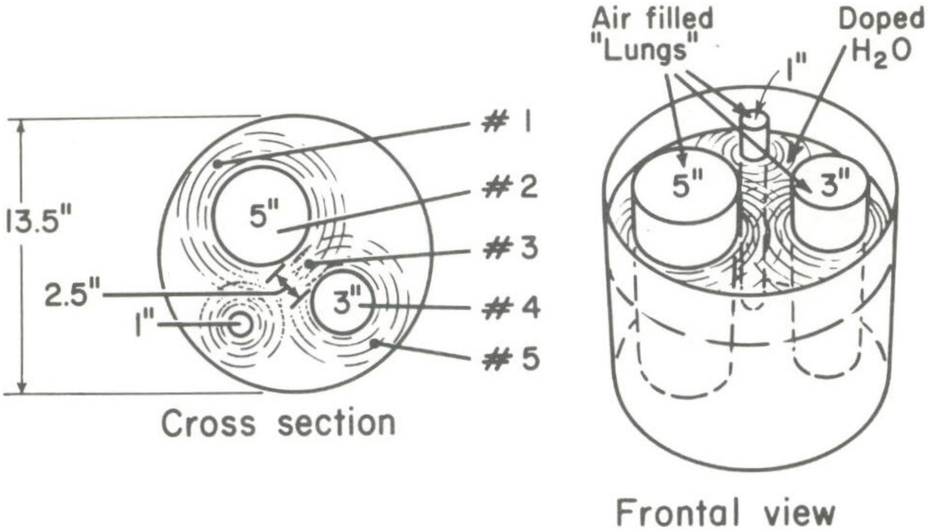

FIGURE 1. Schematic of the simulated (phantom) human chest used to obtain the FONAR image reproduced on the front cover of this issue of the journal. In the image, zero proton signal is color-coded blue while 3 shades of yellow represent the various signal intensities from doped H_2O. The phantom consisted of a cylindrical polypropylene tank (13.5 inches in diameter) filled with doped H_2O and containing 3 air-filled lucite cylinders with dimensions as indicated serving as "lungs." The numbered regions in the drawing correspond to the position of the FONAR spot for the NMR signals shown in Fig. 2. Note that the FONAR process easily detected the smallest structure in the phantom (1-inch "lung") with a 14-inch exploring coil (see front cover).

Experimental. To achieve this visualization we found it necessary to construct a superconducting magnet and cryogen designed to provide sufficient range in H_0 to maximize S/N and sufficient bore size to minimize inductive coupling of the human rf coil to the metallic mass of the magnet. A Helmholtz pair of superconductive magnets was constructed to optimize H_0 uniformity of the working field. The images presented in this paper, however, were achieved using only one of the pair, operating at 508 G. The details of construction of this magnet, and of the helium dewar, are given in the accompanying two papers of this series.

The rf pulses were delivered to a tape-wound 14-inch single-coil probe powered by a variable frequency Seimco model RD spectrometer operating at 2.18 MHz and delivering 10 W of power over 60 μsecs. 90° pulses were repeated with a period of 800 μseconds. The NMR images shown are stored video records of the maximum P-P amplitude of a constant 5-kc off-resonance beat pattern of the phase-detected proton signal. For the phantom chest, the off-resonance beat signal was visible without signal averaging because of the $NiCl_2$ doping of the H_2O. For the human chest, signal averaging was required. The proton images of the chest are therefore composites of

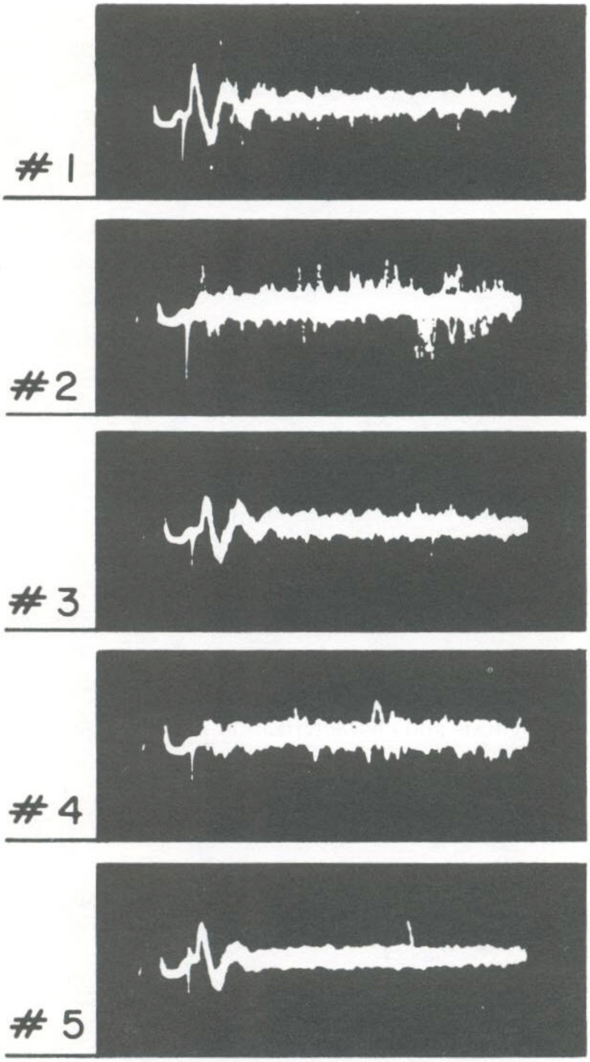

FIGURE 2. Off-resonance proton NMR signals (without signal averaging) from each of the numbered regions of the phantom shown in Fig. 1.

spin densities and spin-lattice relaxations, both contributing to variations in final signal amplitude and therefore to the various tissue intensities that make up the final image.

Phantom chest. For the first trial of the fully assembled FONAR apparatus, we utilized a simulated chest made up of a 13½-inch cylindrical container of $NiCl_2$-doped water with three air-filled methacrylate tubes of 5, 3, and 1 inches diameter respectively for "lungs." In these experiments the resonance aperture remained fixed along the H_0 axis and the sample was moved through it. Figure 1 gives a schematic of the phantom. The actual image is reproduced on the cover of this journal.

Figure 2 illustrates the signals observed, without averaging, as the phantom was moved along the x axis through regions of high proton density and low proton density. The experiment of Fig. 2 demonstrates prominent attributes of the FONAR method as compared to other methods in that (a) FONAR is direct, and (b) the FONAR signal is visible at each location of the scanning aperture. These capabilities allow the NMR behavior of each region of the anatomy to be visualized as the scan proceeds, rather than await a computer reconstruction of the data, as in the non-focusing methods, before information can be obtained. Furthermore, at the completion of the scan the resonance aperture can be directed back to the coordinates of a suspicious locus for more detailed examination.

Live human chest. On page 108 appears a schematic of a cross-section through the human chest at the level of the eighth thoracic vertebra. The FONAR image of the live human chest at that level is shown on the inside back cover of this journal. The scan visualized the heart and mediastinium, outlined a left lung cavity smaller than the right as it should be, detected a depression in spin density in the midline across the back that could correspond to the lowered proton density of the vertebral body, and encountered a high signal-producing region immediately anterior to the vertebral body and slightly to the left side of the thorax, which corresponds to the location of the descending aorta. We estimate the resolution of this image to be approximately ¼ inch.

Thus we completed the first chemical image of the human body, initiating a new era in medicine.

[PLEASE TURN TO PAGE 108]

We wish to thank Bill and JoAnn Akers, Clarke and Eleanor Akers, James Stewart, and John Rich for the human charity that saw this project through to the finish. Were it not for their contributions, the work would not have been completed.

We thank Dr. Joel Stutman for the computer programs that produced the color video display. The imaging algorithm and related software he developed will be reported separately.

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