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Rotating frame zeugmatography

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The proton sensitivity obtainable at 5 MHz from a baby is sufficiently large to suggest the possibility of obtaining images with millimetre resolution in seconds. Such goals present difficulties; for example, the high quality factor of the receiving coil necessary for good sensitivity limits the receiver bandwidth and leads to long pulse recovery times, and large, rapidly switched field gradients require power engineering. Solutions to these problems are being pursued at the National Institutes of Health (N.I.H.), where a high speed imaging system is under construction. For example, bandwidth and recovery time problems may be resolved with the aid of a low noise preamplifier with imaginary gain and Miller feedback, large gradients may be generated with a magnet comprising two rotatable hemispherical windings and switching of gradients may be eliminated by performing zeugmatography in the rotating frame. It is upon this latter aspect of the design that the present article concentrates.

1. Introduction

Since the publication by Lauterbur (1973) of his classic paper describing nuclear magnetic resonance (n.m.r.) image reconstruction by tomographic methods (zeugmatography), considerable interest has been shown in medical applications of the technique, as is exemplified by the present Discussion Meeting. Zeugmatography is, hopefully, totally safe and, further, has the promise of providing information of clinical value that it is difficult, if not impossible, to obtain by other methods. An area of particular interest at the N.I.H. is the early detection of those afflictions to which premature babies are particularly prone, for example, hydrocephalus, cystic malformations, intercranial bleeding, abscesses, abnormal vasculature etc. Diagnosis of such congenital anomalies almost inevitably involves the use of X-rays with their attendant radiation hazard. However, as water is intimately involved with each of these defects, the hope is that n.m.r. will provide a safe and early method of clinical evaluation that eventually may be used as a screening technique for neonates.

Now the goal being pursued by the author and other researchers in the field of n.m.r. imaging is to obtain a high quality image with 1% resolution in a short period of time, say seconds. Let us therefore briefly examine the possibility of such a performance when the subject of examination is a premature baby. Following Hoult & Richards (1976) and Hoult & Lauterbur (1979), we may estimate that the signal : noise ratio from 1 μl of water within a solenoidal receiving coil of diameter 12 cm is about 1.5 : 1. (The calculation assumes a Larmor frequency of 5 MHz, a spin–spin relaxation time (T_2) of 0.1 s and Fourier transformation with an optimum filter of the free induction decay following a 90° pulse.) Thus, this theoretical limit implies that one may, with appropriate resourcefulness, obtain an image with 1 mm (or about 1%) resolution from a plane 5 mm deep in a quarter of a second. The signal : noise ratio would be about seven or eight, which is not good, but, clearly, we have the prospect of obtaining acceptable images in short periods of time. However, resourcefulness is most definitely needed, for the technical problems encountered in high speed imaging are large.

2. Technical factors

By working with a small sample, such as a baby, many of those problems of probe design, such as self-resonance and dielectric sample losses, more usually encountered in high resolution spectrometers at ultra-high frequencies, are avoided. However, the plague of low frequency n.m.r., receiver recovery time, is abundantly present. To understand the extent of the problem, the quality factor (Q) of the solenoid employed in the signal : noise ratio calculation above is about 500 (Hoult 1978). The recovery time of the receiver is therefore about 470 μs (15 times the time constant of the ringing following the transmitter pulse). To put this another way, the bandwidth of the receiving system is about 10 kHz. But, to obtain an image with 1% resolution in a $\frac{1}{4}$ s, a bandwidth of *ca.* 100 kHz, or an accumulation rate of one complex data point every 10 μs, is needed. High sensitivity and high speed would, therefore, appear to be incompatible. Fortunately, a resolution of this conflict is possible. A full description (Hoult 1979*a*) of the method of negative feedback damping employed to reduce the Q of the probe-tuned circuit without sacrifice of sensitivity lies outside the scope of this talk; suffice it to say that a recovery time of 10 μs or so is feasible and that an increase in bandwidth of three or four is possible with only a small loss (3 dB) in sensitivity.

Another problem encountered is that of creating the large field gradients needed to spread the n.m.r. signal from the sample over a 100 kHz range. Conventional correcting (or shim) coil design may need large amounts of conductor (say, $\frac{1}{2}$ t) and correspondingly large amounts of power (kilowatts) to produce rapidly gradients of the order of 2.5×10^{-2} T m^{-1}, particularly when those gradients are transverse to the main field direction. However, it is possible to build the magnet for the imaging experiment so that production of gradients in three orthogonal directions is an integral part of the magnet design. Production of such a magnet is well under way at the N.I.H. The windings are on two hemispherical castings. Axial gradients are generated by creating an imbalance between the currents in the two halves, while transverse gradients are produced by tilting the hemispheres towards one another, in the appropriate directions. On paper at least, strong linear gradients are produced by means of these techniques, with no extra consumption of power. Winding of the magnet is now under way and testing should commence in the summer.

We now turn to the methods actually used for producing an image. Mansfield & Pykett (1978) and Kumar *et al.* (1975) have suggested techniques that gather information simultaneously from all points in a sample, with great speed, and these techniques therefore offer possibilities for attaining the goal of high speed imaging. The major difficulty with both methods is that they require rapid changes of field gradients. Such changes need large instantaneous powers and the phenomenon of eddy current damping in adjacent conductors, such as the magnet housing or the probe shielding, presents a major difficulty. Budinger (1978) has also raised questions as to the safety of rapidly switched gradients, and is seems clear that much work is needed before these techniques can be used routinely. An alternative approach lies in the production of a gradient in the irradiating (B_1) field used to stimulate the sample (Hoult 1979*b*). This method, to be described below, does not require any changes of field gradient, but large instantaneous powers (albeit radio frequency) are again needed for the method to work quickly, and so the safety of the method will have to be rigorously checked with animal subjects before babies are examined.

3. ROTATING FRAME ZEUGMATOGRAPHY

If the n.m.r. probe is of the crossed coil variety, we may, by employing suitably asymmetric windings, generate a transmitter B_1 field that, like its static counterpart, comprises a homogeneous field with a linear gradient superimposed. In other words, while the main field may be described by an equation of the form

$$B_0 = B_{00}+B_{01}z, \tag{1}$$

the transmitting field may be described by an equation of the form

$$B_1 = B_{10}+B_{11}x, \tag{2}$$

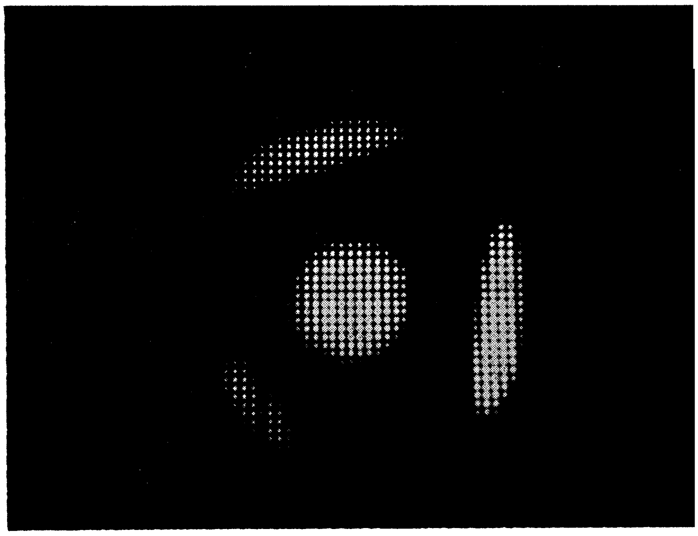

FIGURE 1. An image of a triangular teflon phantom with a hole drilled through its centre, placed in a 6 mm n.m.r. tube containing concentrated phosphoric acid. Because of the nature of the spectrometer available, the signals were from ^{31}P nuclei at 24 MHz and were obtained in about 3 min.

where x and z are spatial coordinates and other right hand terms are constants. The receiving coil is a solenoid operating in the usual way. In the simplest experiment that was used to evaluate the method, a slice of sample was placed in the probe, in the xz plane, and transmitter power was applied for a length of time $n\tau$, where n is an integer. Initially $n = 1$ and the condition $B_1 \gg B_{01}z$ was fulfilled at all points in the sample. In the frame rotating at frequency $\omega_{00} = -\gamma B_{00}$, the magnetization, $M_0(x, z)$, was therefore tipped an angle $-n\tau\gamma B_1$ from the equilibrium z axis and, after the pulse, the signal received from an element of sample at point (x, z) was proportional to

$$\xi = M_0(x, z) \sin (n\tau\gamma B_1) \exp (\mathrm{i}\omega_{01}-1/T_2)\, t\, \mathrm{d}x\, \mathrm{d}z, \tag{3}$$

where we assume quadrature detection at frequency ω_{00}, and $\omega_{01} = -B_{01}z$. We therefore see from equation (3) that the *amplitude* of the received signal varies sinusoidally with the conjugate variables $n\tau$ and position x (both determining the flip angle), while the *frequency* varies with the position z, the conjugate variable being, of course, time, t. For the first free induction decay collected, n was set to unity. The second decay was initiated by a pulse of length 2τ, the third by a pulse of length 3τ and so on, about 100 decays being collected in total. All these stored data were then subjected to two-dimensional Fourier transformation and the resulting matrix of data represented $M_0(x, z)$. An example of an image of a crude phantom obtained by the above method is shown in figure 1 and the probe arrangement used is shown in figure 2. Full details of the method are described elsewhere (Hoult 1979*b*), but the important points to note are that the method receives signal simultaneously from all points in the sample and is, therefore, efficient and sensitive and that, being a relatively conventional n.m.r. experiment, spin echo techniques may be used to compress the data accumulation into a few free induction decays.

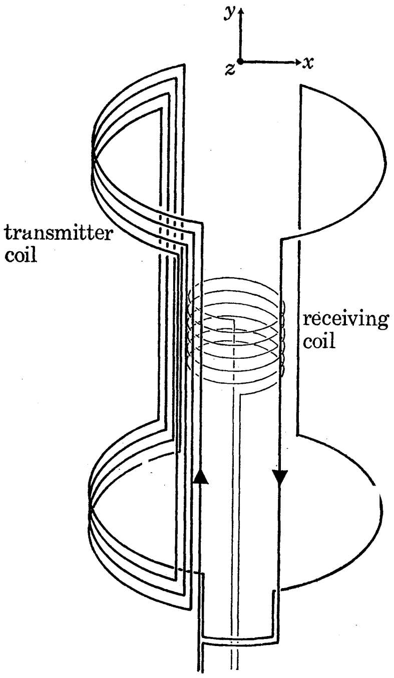

Figure 2. The experimental probe configuration used to obtain the image in figure 1. The saddle-shaped transmitter coils produce a powerful gradient in the B_1 field, in addition to the usual homogeneous field.

The limiting factor on the experiment, quite apart from the considerations of receiver recovery and field gradient outlined earlier, is the radio frequency power needed to perform the experiment quickly. The constraint $B_1 \gg B_{01}z$ implies that γB_1 must be at least 200 kHz if the information needed is all to be collected in one decay and this, in turn, implies at least 15 kW of radio frequency power for times approaching 1 ms. The engineering needed to obtain such power is, of course, well known, but nonetheless formidable. To be realistic, data collection lasting ten decays and taking, say, 5 s would appear to be a goal well within the bounds of possibility and we may, no doubt, look forward to faster images as technique in the subject improves.

Finally, in a three-dimensional sample, we must be able to select the plane of interest if the technique is to be useful. Probably the simplest way of performing such a task is to saturate all but the plane of interest by means of coils that produce a field that varies as $B_2 = B_{21}y^3$. If broadband noise is then applied to the coils before *and during* the experiment with the aid of so-called 'gated decoupling' (Jesson *et al.* 1973) all but the plane about $y = 0$ remains saturated. Signal therefore emanates only from that plane, and the thickness of the plane is of course determined by the power of the broadband noise, and to a lesser extent, T_1 and T_2.

It is essential to continue the irradiation during data accumulation on a time-sharing basis to prevent spurious signals arising from protons with short spin–lattice relaxation times.

To conclude, the obtaining of zeugmatographic images in short periods of time presents a considerable technical challenge, with the prospect of important medical applications presenting themselves in the years ahead, once those challenges have been met.

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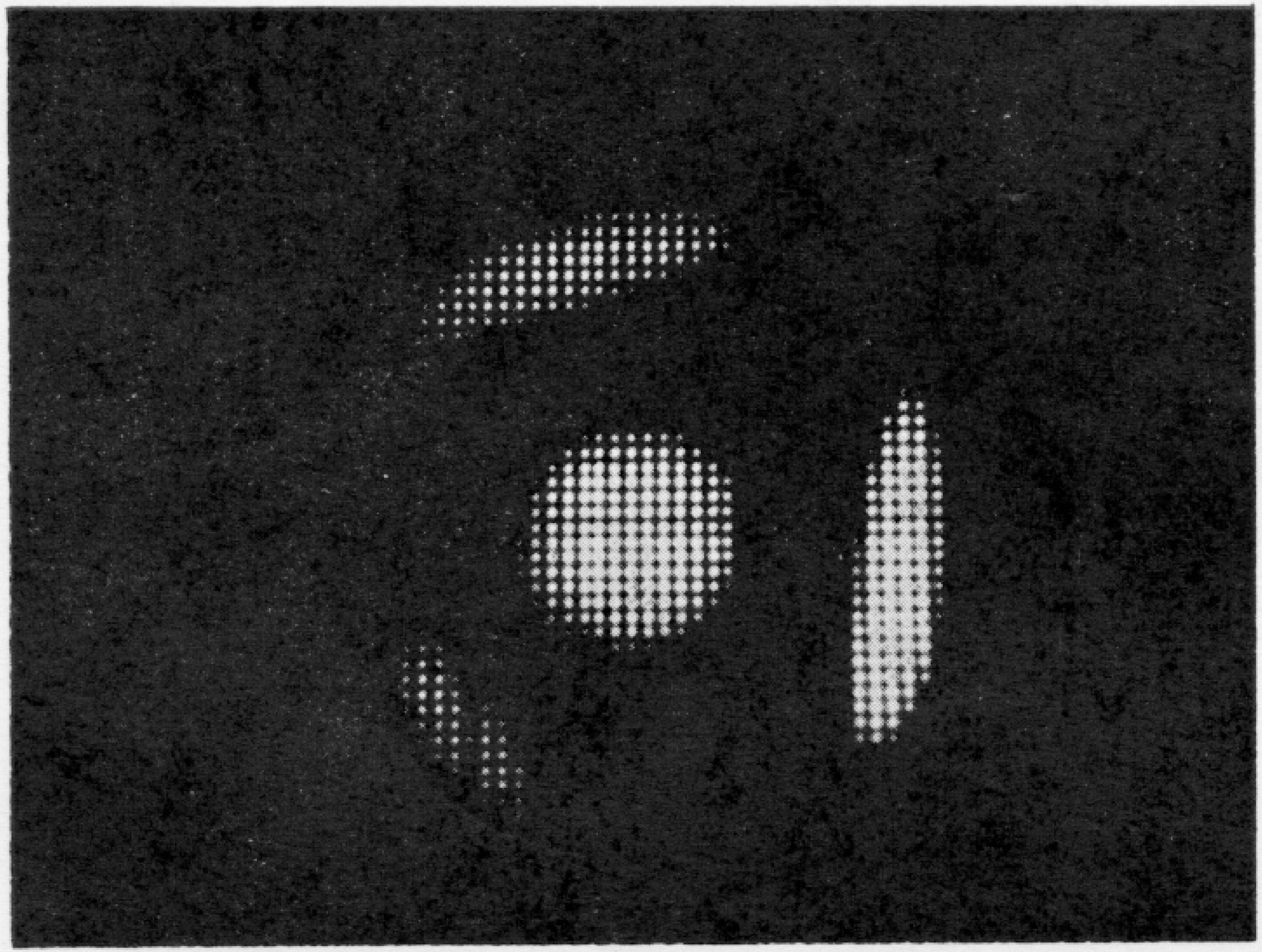

IGURE 1. An image of a triangular teflon phantom with a hole drilled through its centre, placed in a 6 mm n.m.r. tube containing concentrated phosphoric acid. Because of the nature of the spectrometer available, the signals were from ^{31}P nuclei at 24 MHz and were obtained in about 3 min.