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Short communication

Imaging and diffraction: the Mansfield legacy☆

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It is a great pleasure to be able to speak in honor of Sir Peter Mansfield and especially in the context of his many contributions in the study of porous media using MRI methods. But I also want to use this talk to draw attention to a very important foundation stone in modern NMR which was laid down by Mansfield at the start of the development of MRI. In 1973 Mansfield and Grannell [1] published a paper entitled 'NMR diffraction in solids?' in which they demonstrated that the FID acquired from a regularly spaced stack of camphor sheets, in the presence of magnetic field gradient applied normal to the stack, resulted in a characteristic diffraction pattern which, on Fourier transformation, yielded a one-dimensional image of the spatially periodic sample. Fig. 1 shows the diffraction data taken from that 1973 paper.

I think that it would be fair to say that the original paper by Mansfield and Grannell has sometimes been poorly understood by those who perhaps have taken a narrow view of MRI as a tool for making two dimensional pictures, but with the benefit of historical hindsight we can now see just how momentous that contribution was. The formalism used to describe the Mansfield and Grannell experiment was derived from optics and drew upon the language of real space and reciprocal space conjugacy. This paper was published in the same year that P.C. Lauterbur [2] demonstrated that back projection methods could be used to derive an NMR image from FID data acquired in the presence of magnetic field gradients. These two very different approaches laid the basis for what has become one of the most important developments in tomography and radiology, the technique of MRI.

As we celebrate the achievements of Sir Peter Mansfield, I would like to take this opportunity to point out that the diffractive formalism laid down by Mansfield at the start of the history of MRI, has impacted in a positive and highly influential way, not only in MRI itself, but also on a number of other closely related fields. Let's start however with MRI itself. The most important consequence of the optical description has been the use of the k-space formalism. Just imagine how hard it would be to describe the various imaging modalities without the concept of traversing reciprocal space. One clear example of the insight gained by using reciprocal space methods can be seen in considering the well-known spin warp and projection reconstruction methods, techniques which look so dissimilar at first sight, but which are both two-dimensional k-space traverses, one in Cartesian space and one in polar coordinates.

One of the many significant contributions to MRI by Sir Peter Mansfield has been his invention of echo planar imaging [3]. Now that the technical problems associated with its implementation have been solved (mostly due to the work of Mansfield and his collaborators), this technique is now becoming the method of choice in most modern MRI applications. The raster for EPI is shown in Fig. 2. I would guess that it was the reciprocal space insight which gave Mansfield the opportunity to see how to do the EPI trick, recycling the magnetization in the most efficient way possible while continuing to traverse k-space.

Mansfield's use of optical analogies has been highly influential in a related field of research in which I have been involved. In 1991 David Cory and Al Garroway [4] proposed that the examination of restricted diffusion in a pore using the pulsed gradient spin echo (PGSE) method of Stejskal and Tanner, could be thought of in terms of an optical diffraction picture while Ken Packer and I, along with some other BP collaborators, David MacGowan and Fernando Zelaya [5], published a paper in Nature suggesting that PGSE NMR diffraction effects played a role for fluids diffusing in inter-con-

☆ In honor of Sir Peter Mansfield

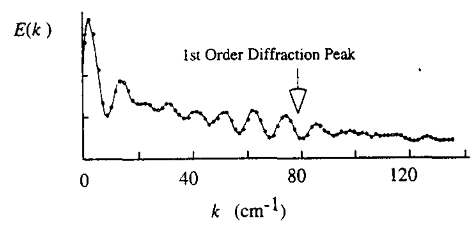

Fig. 1. k-space diffraction data obtained from the stack of regularly space camphor sheets in which the proton NMR signal is acquired in the presence of magnetic field gradients (data taken from Mansfield and Grannell, 1973 [1]).

nected porous media. This led to quite a lot of work on q-space diffraction by my own group, and others such as Olle Soderman [6], Philip Kuchel et al. [7] and coworkers. The basic idea is that the displacements of molecules over the time between the two gradient pulses of the PGSE experiment, are conjugate to the q-vector defined by the area under the gradient pulses [8]. Whereas k-space imaging measures a signal Fourier conjugate to the spin density, q-space imaging obtains a signal conjugate to the 'average propagator' a probability density for displacements. Of course in the traditional Stejskal–Tanner experiment, where the displacement distribution for Brownian motion is Gaussian, that signal is also Gaussian and no coherence effects are directly manifest. In the case of restricted

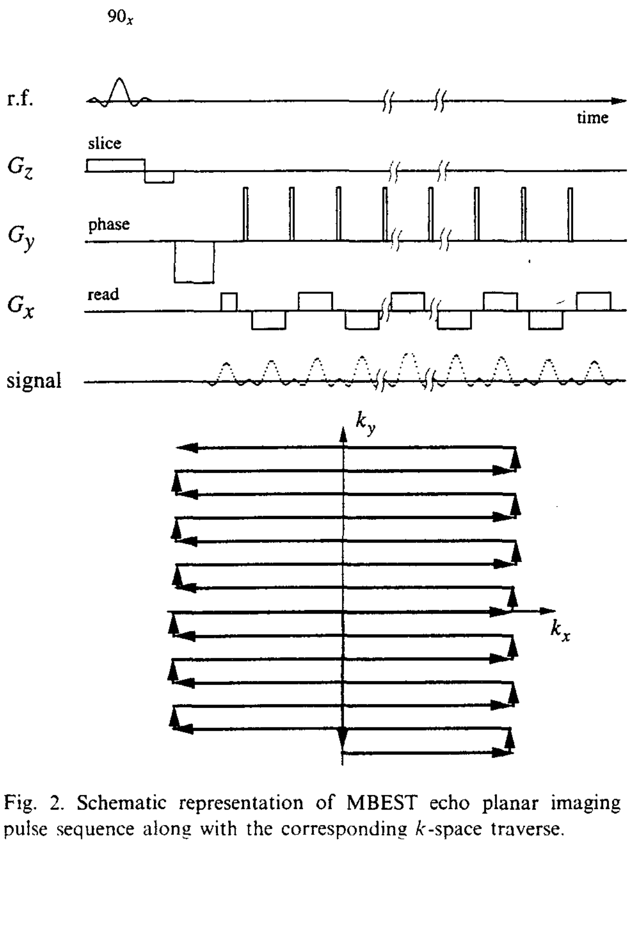

Fig. 2. Schematic representation of MBEST echo planar imaging pulse sequence along with the corresponding k-space traverse.

diffusion the influence of the boundaries in limiting spin displacements, results in dramatic coherence effects and the whole phenomenon can be nicely handled using the mathematical language of diffraction. The field has developed in a number of directions, including the application to generalized gradients by Janez Stepisnik, Eiichi Fukushima and coworkers, and my own group, to the influence of edge effects in NMR microscopy, and to the study of flow in porous media.

Of course the coherence phenomena due to boundary restrictions on molecular displacements are not limited to diffusive transport. The fact that flow could lead to diffraction effects was demonstrated in a very early paper by Ken Packer and coworkers [9]. Recently Joe Seymour and I showed [10] that dispersion in a porous medium would yield diffraction effects, but the effects here are quite subtle since the pore sampling in flow depends on the streamline characteristics. The study of flow in porous media leads me to another important contribution of Peter Mansfield and his coworkers, namely the application of NMR imaging methods to the study of fluids in a solid matrix. I believe that Mansfield and Blackband were the first to study the inter diffusion of a solvent into a polymer in their imaging of water ingress into nylon using a sequence of images obtained at different times to measure an exact solvent profile and then to fit the concentration gradient to obtain a quantitative measure of the diffusion process[11]. More recently Peter and his colleagues have seen some rather intriguing hysteresis effects when studying the flow of water in porous matrix. This work has stimulated a great deal of interest and also some theoretical work by the Mansfield group which can explain why such phenomena can occur, even under laminar flow conditions.

I would like to shift my focus, at this point, to another link with the NMR of fluids in porous media. This concerns the very first NMR work undertaken by Peter Mansfield as an undergraduate student at Queen Mary College back in 1968, when he carried out Earth's field free precession experiments under the supervision of Dr Jack Powles, who was later to become his PhD supervisor. The earth's field method has also been the approach which we have taken in our research concerning the mobility of brine in Antarctic sea ice. This has involved three journeys to McMurdo Sound under the auspices of the New Zealand Antarctic program and our work comprises part of a much larger team study of the formation, dispersal, mechanical, thermal and optical properties of sea ice. The formation of this ice represents the biggest seasonal event on the planet and is immensely important to global climate and ecosystems. I mention the Antarctic work because in that environment the human dimension in scientific work is especially important and it is those personal aspects which we have all gathered here today to celebrate by honoring the contributions of Sir Peter Mansfield.

Our Antarctic work is carried out within sight of the 1911–1913 winter quarters of Robert Falcon Scott. These scientists and explorers from the early years of this century had a view of discovery which, while naive, was also more optimistic and straightforward than the perspective 'fin de siècle'. None expressed this view more powerfully than Apsley Cherry-Garrard in his wonderful account of the Scott 'Terra Nova' expedition, 'The Worst Journey in the World.' In particular Cherry-Garrard [12] recounts the terrible suffering that he, Edward Wilson and Birdie Bowers experienced in their winter journey behind Ross Island, undertaken in order to find some Emperor penguin eggs. In the last pages of his book, he writes about the experience as a metaphor for the human dimension in scientific discovery.

> For we are a nation of shopkeepers and no shopkeeper will look at research which does not promise him a financial return within a year. And so you will sledge nearly alone but those with whom you sledge will not be shopkeepers: that is worth a great deal. If you march your winter journeys you will have your reward, so long as all you want is a penguin's egg.

Being in the Antarctic is about shared experience, about depending on each other and trusting each other. I believe that all our experiences in science are not far removed from those qualities. The personal elements which motivate us as scientists are seldom expressed, and yet they are often the very factors which we as teachers need to convey to our students in order to inspire and to motivate.

As part of that theme let me now turn full circle and go back to the origins of our beautiful science of NMR. I would like to quote the words Ed Purcell used in his Nobel address when describing his thoughts after the first NMR experiments.

> I remember, in the winter of our first experiments ... looking on the snow with new eyes. There the snow lay around my doorstep — great heaps of protons quietly precessing in the earth's magnetic field. To see the world for a moment as something rich and strange is the private reward of many a discovery.

What a nice link between the very first experiments of Peter Mansfield, our own work in the Antarctic, and the very beginnings of NMR. In honoring Peter today, we emphasize not only the human role in scientific discovery but we also focus on what it means to be a scientist

> If you march your winter journeys you will have your reward, so long as all you want is a penguin's egg.

I think, that is, in the end why we do our science. In the hope of discovering our penguin's eggs, and in the good fellowship of the companions with whom we sledge.

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