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**Static and Dynamic Imaging
using Magnetic Field Gradients**

静态与动态核磁成像

A thesis presented in partial fulfilment of
the requirements for the degree of
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by

Yang Xia

夏 阳

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Abstract

The theory and techniques of NMR imaging are described together with a detailed description of the Filtered Back Projection (FBP) technique used in an existing NMR imaging system.

The existing 'static' NMR imaging system has been modified to be capable of performing 'dynamic' NMR imaging experiments, as well as better 'static' NMR imaging experiments.

The potential of NMR microscopy in the imaging of both the static spin distribution $P(\mathbf{r}_0)$ and the dynamic spin correlation function $P(\mathbf{r}_0|\mathbf{r},t)$ has been investigated. Both homogeneous and inhomogeneous systems have been studied. Detailed theoretical analysis and experimental considerations of dynamic imaging experiments have been given.

A transverse resolution of $15\ \mu\text{m}$ for a 1 mm slice thickness is obtained from a static imaging experiment of a phantom using the modified system. The rabbit trachea imaging experiment has revealed the asymmetrical collapse of tracheas under negative pressures, a collapse which had previously been considered as symmetrical process.

The Poiseuille flow experiment has involved the first simultaneous measurement of flow and diffusion at the microscopic level. Maps of two dimensional distribution functions of flow and diffusion are given by this experiment, highlighting this totally non-invasive dynamic imaging technique.

As an example of dynamic imaging, the wheat grain experiment has displayed the flow and diffusion maps within a single wheat grain *in vivo*.

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List of Symbols

| | | |
|--------------------|--|-----|
| a | RF coil radius | 29 |
| a_{mj} | Complex admixture amplitudes of a spin system | 3 |
| A | An operator representing an observable quantity | 5 |
| A | Signal amplitude | 44 |
| A | Cross sectional area | 108 |
| B_{eff} | Effective field in the rotating frame | 7 |
| \mathbf{B} | Magnetic field | 6 |
| B_0 | Amplitude of the main magnetic field | 3 |
| \mathbf{B}_0 | Main magnetic field, directed along the z axis | 3 |
| B_1 | Amplitude of the transverse rf field $\mathbf{B}_1(t)$ | 7 |
| $\mathbf{B}_1(t)$ | RF field (in the transverse plane) | 7 |
| D | Self-diffusion coefficient | 32 |
| \mathbf{D} | Self-diffusion tensor | 33 |
| D_e | Extra broadening due to velocity spread | 47 |
| $E(m_j)$ | Energy eigenvalues of a spin system | 3 |
| f | Spectrometer frequency | 29 |
| F | Noise figure of the spectrometer | 16 |
| $F\{ \}$ | Fourier transform of the function in $\{ \}$ | 23 |
| $F_s\{ \}$ | sin transform of the function in $\{ \}$ | 23 |
| $F_c\{ \}$ | cos transform of the function in $\{ \}$ | 23 |
| g | Amplitude of PGSE gradient | 32 |
| \mathbf{g} | PGSE gradient in dynamic imaging | 32 |
| g_m | Maximum gradient employed in dynamic imaging | 40 |
| G | Amplitude of field gradient | 32 |
| \mathbf{G} | Field gradient | 19 |
| $h(t)$ | Fourier transform of frequency domain function $H(f)$ | 38 |
| H_I | Imaginary part of the discrete function H | 42 |
| H_R | Real part of the discrete function H | 42 |
| $H(f)$ | Fourier transform of time domain function $h(t)$ | 38 |
| \mathcal{H} | Hamiltonian operator | 3 |
| $\mathcal{H}_1(t)$ | Perturbation term in Hamiltonian operator | 7 |
| i | $(-1)^{1/2}$ | 4 |
| I | Function selected in dynamic imaging analysis program | 91 |
| $\text{Im}[\]$ | Imaginary part of a complex function in $[\]$ | 36 |
| j | Spin quantum number | 3 |
| \mathbf{J} | Spin angular momentum operator | 3 |
| k | Frequency domain (digital) variable | 38 |
| \mathbf{k} | Static reciprocal space vector | 24 |
| k_B | Boltzmann constant | 5 |
| K | Numerical factor in the calculation of S/N | 16 |
| l | Length of the pipe in Poiseuille sample system | 119 |
| L | Length of the conductor | 16 |
| m_j | Azimuthal quantum numbers | 3 |
| \mathbf{M} | Macroscopic magnetization vector | 5 |
| M_0 | Magnitude of \mathbf{M} in the equilibrium state | 6 |
| M_{\perp} | Transverse component of \mathbf{M} | 9 |
| n | Time domain (digital) variable | 38 |
| n_D | Maximum number of data images | 36 |
| n_1 | A constant in the 'tube law' | 109 |

| | | |
|------------------|--|-----|
| N | Number of spins per unit volume | 5 |
| N | Total number of digits in time domain | 38 |
| N_h | Number of hydrogen nuclei per unit volume | 16 |
| N_p | Number of projections | 29 |
| N_{acc} | Number of accumulations per projection | 25 |
| p | Perimeter of the conductor | 16 |
| P | Transmural pressure difference | 109 |
| P_1 | Constant asymptotic pressure | 109 |
| P_s | Self-correlation function of the nuclear spin | 33 |
| P^* | Filtered profile | 25 |
| Q | Quality factor of the coil | 16 |
| Q | Volume amount of fluid | 120 |
| q | Dynamic reciprocal space vector | 34 |
| r | Position vector | 18 |
| R | Attenuation factor | 33 |
| R | Radius of the pipe in dynamic imaging experiment | 120 |
| $Re[]$ | Real part of a complex function in [] | 24 |
| S | Fluid displacement vector | 33 |
| $S(t)$ | FID signal | 24 |
| S^* | Complex conjugate of S | 25 |
| t_p | Duration of the pulse | 9 |
| t_{rep} | Repetition time of in experiments | 25 |
| T | Absolute temperature of a spin system | 5 |
| T | Time domain sampling interval | 38 |
| T | Sampling time in imaging experiments | 96 |
| T_c | Probe temperature | 16 |
| T_s | Sample temperature | 16 |
| T_1 | Spin-lattice relaxation time | 10 |
| T_2 | Spin-spin relaxation time | 10 |
| T_2^* | Transverse relaxation time | 10 |
| $Tr()$ | Trace of the operator in () | 4 |
| $U_E(t)$ | Evolution operator | 4 |
| $U_{Rz}(\theta)$ | Rotation operator | 4 |
| v | Velocity of fluid flow | 33 |
| V_c | Volume of the coil | 16 |
| V_s | Sample volume | 16 |
| w | Weight of the fluid | 120 |
| α | A variable in discrete Fourier transform | 38 |
| γ | Gyromagnetic ratio | 3 |
| δ | Duration of the PGSE pulse | 32 |
| η | Fraction of the coil volume occupied by the sample | 16 |
| η | Dynamic viscosity of the fluid | 120 |
| θ | Rotation angle of the magnetization vector | 9 |
| λ | Wave length | 61 |
| μ_0 | Permeability of free space | 16 |
| μ | Magnetic moment vector | 3 |
| ν | Kinematic viscosity of the fluid | 119 |
| ξ | Complex FID signal | 35 |

| | | |
|--------------------------|---|-----|
| ρ | Density operator | 4 |
| ρ | Density of the fluid | 119 |
| ρ_I | Imaginary part of nuclear spin density | 35 |
| ρ_R | Real part of nuclear spin density | 35 |
| ρ_T | Resistivity of the conductor | 16 |
| $\rho(\mathbf{r})$ | Nuclear spin density | 24 |
| σ | RF coil proximity factor | 16 |
| $\sigma(n)$ | Noise function | 127 |
| τ | Short time interval | 10 |
| ω | Larmor precession frequency | 7 |
| ω_0 | Larmor precession frequency due to B_0 | 4 |
| ω_1 | Larmor precession frequency due to B_1 | 8 |
| ω_{eff} | Precession frequency in the rotating frame | 7 |
| Δ | Separation of the PGSE pulses | 32 |
| ϕ | Projection angle in imaging experiment | 24 |
| $ j m_j\rangle$ | Basis eigenket set of a spin system | 3 |
| $ \psi\rangle$ | General quantum state of a spin j system | 3 |
| $\langle A \rangle$ | Ensemble average of the observable quantity A | 4 |
| $\overline{ a_{m_j} ^2}$ | Normalized population in the eigenstate $ j m_j\rangle$ | 5 |
| Δf | Bandwidth of the receiver | 16 |
| Δh | Height difference | 120 |
| Δv | Velocity spread between the adjacent pixels | 47 |
| Δx | Transverse resolution | 29 |
| Δz | Slice thickness | 29 |
| ΔE | Energy difference between the two adjacent states | 7 |
| ΔP | Pressure difference along the length of the pipe | 119 |
| $\Delta \phi$ | Step angle in imaging experiment | 25 |
| ∇B_0 | Magnetic field gradient | 19 |
| ∇P | Pressure gradient | 119 |
| \hbar | Planck's constant divided by 2π | 3 |

Chapter 1 Introduction

1.1 Introduction

Nuclear Magnetic Resonance (NMR) Imaging is a non-invasive technique which gives the spatial distribution of the NMR signal intensity or other NMR parameters in a heterogeneous sample. The first experimental demonstration of the feasibility of macroscopic NMR imaging was given by Lauterbur in 1972 (1,2).

In conventional NMR it is usual to place the sample, which is homogeneous and small, in a very uniform magnetic field, so that the resonant frequency depends upon the external field modified slightly by the local environment. NMR spectra obtained in this way yield details of the local molecular environment.

By contrast, NMR Imaging concerns a sample which is heterogeneous, and usually not small. Furthermore, the sample is placed in a deliberately non-uniform magnetic field, which enables the hetero-structure of the sample to be derived and displayed.

Many different techniques have been described for NMR Imaging^(3,4,5). Among these the Projection Reconstruction technique, originally from X-ray Tomography, is the most sensitive one⁽⁶⁾.

The proton (^1H) is the most commonly used nucleus when doing imaging experiments, Hydrogen being the most abundant element in the living systems. ^1H is isotopically almost 100% abundant, and has the highest magnetic moment among stable nuclei, thus yielding optimum sensitivity. ^{19}F and ^{31}P nuclei are next in sensitivity and have some practical interest. Other nuclei are, in practice, difficult to image.

Traditionally NMR imaging reveals some stationary distribution functions of a nuclear spin system, for example, the spin density distribution. Such imaging is termed '**static**' NMR imaging in this thesis.

By incorporating the Pulse-Gradient-Spin-Echo (PGSE) technique, the NMR imaging can describe time-dependent functions. This technique is termed '**dynamic**' NMR imaging. Simultaneous imaging of flow and diffusion at the microscopic level can be performed using this new technique, which has been demonstrated by some imaging experiments in this work.

1.2 Organisation of the Thesis

This thesis is divided into 6 chapters.

Chapter 2 provides a description of NMR and NMR imaging. One of the most commonly used imaging techniques, **Filtered Back Projection (FBP)**, is described in detail. The theory of dynamic imaging is discussed extensively in this chapter.

In Chapter 3 a brief description of an existing static NMR microscopic imaging system is given first, followed by some developments and modifications to this system which form part of the present work. These have improved this system and enabled the performance of the flow and diffusion imaging experiments.

The static imaging experimental results are presented in Chapter 4, while the dynamic results are in Chapter 5.

A brief summary and some comments about possible future work are given in Chapter 6.

Appendix A gives the complete software listings for the flow and diffusion imaging experiments. Appendix B gives the software listings for the simulating the uniformity of G_y field gradient.