Chapter 1

Introduction

Magnetic resonance (MR) imaging is based on the principle of nuclear magnetic resonance (NMR). Invented in 1973, MR imaging is used annually in about 13 million clinical exams around the world. While clinical MR imaging consists predominantly of brain, spine and joint imaging, MR research includes cardiovascular imaging and abdominal imaging as well as functional MR imaging (fMRI) of the brain.

MR imaging is one of many medical imaging modalities that include plain-film X-ray, computed tomography (CT), ultrasound, positron-emission tomography (PET). Like ultrasound, MR is non-invasive and does not use ionizing radiation. MR also allows arbitrary selection of the scan plane and true three-dimensional imaging. Finally in MR, unlike all of these other modalities, image contrast is based on multiple physical principles with the result that image contrast is flexible. Historically the major limitations to MR, particularly compared with X-ray CT are high cost, long scan time and poor resolution, though much research is being done to improve all of these areas.

The major challenge in MR research is to maximize the diagnostic value of images given certain constraints on hardware while minimizing the total exam time. The length of an exam, which usually consists of several of different types and orientations of scan, tends to determine the cost of an MR diagnosis. MR hardware has certain
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limits on both field strength and switching rates, partly for safety reasons, that limit how quickly data can be acquired in individual scans. Two effective ways to reduce scan time are to improve image quality, perhaps reducing the number of scans in an exam, and to speed up the acquisition of individual scans. The work of this thesis focuses both on fast imaging and on generating diagnostically useful contrast for specific applications.

One of the limitations of MR imaging is the spatial resolution. As the feature size is decreased, the signal available for imaging is diminished. This can be compensated for by averaging over more acquisitions, with a cost of increasing scan time. However, certain MR methods provide higher signal levels than others, though sometimes this depends on the tissue being imaged. “Signal-efficiency” is a measure of signal per unit scan time of a method.

MR imaging of articular cartilage is limited by low image signal, and contrast between cartilage and other structures. Joint-imaging exams, such as a knee exam, must focus on many possible disorders other than specific cartilage disorders. The first major part of this thesis describes an efficient method of improving the signal and contrast for cartilage imaging. Additionally, this three-dimensional imaging method can potentially replace multiple two-dimensional scans, decreasing the overall exam time.

Steady state sequences excite tissue with a scheme that offers very high signal-efficiency and low scan times. However, these methods depend on the ability to set up a consistent steady state, which usually takes a significant time. This time requirement can limit scan times as well as feasibility of the method for certain applications. Two chapters of this thesis describe the dynamics of steady-state imaging and methods to quickly set up the steady state.

Improvements in MR hardware allow stronger fields and faster switching, and continue to enable faster imaging. The final part of this thesis re-examines an existing fast three-dimensional imaging method, spiral imaging, in the context of improved magnetic field gradient capability. The result is to produce faster images as well as to allow use of steady-state excitation with spiral imaging. Additionally,
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the faster imaging can be used to resolve the flow of an injected contrast agent in
the bloodstream, which can be useful for studying perfusion of blood within the
body.

1.1 Outline

The main content of this thesis is divided into several different parts. First, a new
cartilage imaging technique is examined in detail, compared with other methods, and
implemented for the purpose of clinical evaluation. Second, the dynamics of steady-
state imaging are studied in detail with the purpose of significantly reducing the
“set-up” time required before imaging. Finally, some improvements are presented
for a three-dimensional spiral imaging technique that allows rapid imaging of flowing
material with low sensitivity to motion.

This thesis is organized as follows:

Chapter ??: Magnetic Resonance Imaging Concepts

Some of the general concepts used in MR imaging, including polarization,
excitation and imaging are explained. To provide a foundation for most of the
other chapters, some the principles of excitation such as signal calculation, spin
echoes and contrast, are covered in greater detail. Finally, noise in imaging is
briefly discussed. Much of this chapter is motivated by [1]

Chapter ??: Driven Equilibrium Imaging of Articular Cartilage

The clinical challenges of imaging articular cartilage are outlined, with an
overview of some of the many MR methods currently used to study cartilage.
Driven equilibrium Fourier transform (DEFT) imaging is introduced as a new
cartilage imaging method. Signal levels for cartilage and contrast between
cartilage and other knee tissues are compared both theoretically and experi-
mentally using two-dimensional imaging sequences. The implementation and
results of a three-dimensional driven equilibrium sequence are also presented.
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Chapter ??: Steady-State Sequence Analysis
The magnetization dynamics during both the transient response and steady state of periodic imaging sequences are analyzed using a matrix-algebra formulation. An intuitive examination of the transient response is provided using an eigenvalue analysis. The steady-state dynamics are also studied in preparation for Chapter ??.

Chapter ??: Transient Reduction in Steady-State Sequences
A new two-stage approach to “catalyzing” the steady state is presented. A spectrally-selective catalyzation sequence is designed, simulated, and experimentally tested. The result is a method for significantly reducing the time during which signal is unusable for imaging as magnetization approaches the steady state. This decreases imaging time and improves cardiac-gated imaging.

Chapter ??: Short-Readout Spiral Imaging
Fast spiral waveforms are designed to compromise between short readout length and short scan times. The method is applied to rapid three-dimensional flow-independent angiography and rapid imaging of the brain, as well as time-resolved contrast-enhanced perfusion studies.

Chapter ??: Summary & Future Work
The contributions presented in the other chapters are summarized with recommendations for future work in each area.