Chapter 7

Summary and Recommendations

Magnetic resonance imaging is becoming a common method for diagnosis of many disorders in different parts of the body. Research to improve the effectiveness of MRI includes efforts to reduce scan times and to improve image quality, both by providing higher resolution and better contrast. The work of this thesis concentrates on methods to efficiently acquire images of high diagnostic value.

The key contributions of this thesis lie in several areas, including imaging of articular cartilage as well as studying and improving the dynamics of previously-used rapid imaging methods. These contributions are summarized here:

- Driven equilibrium imaging has been evaluated theoretically and experimentally as a method for imaging cartilage with high SNR and excellent contrast characteristics. Initial comparisons between DEFT and other imaging techniques show that DEFT is a promising technique in this arena.

- A three-dimensional version of DEFT has been implemented for clinical evaluation of the method, not only for imaging cartilage, but for diagnosing other disorders in the knee joint.

- The approach to steady state, or transient response of magnetization in steady-state imaging sequences has been studied using matrix algebra methods and
Chapter 7. Summary and Recommendations

Eigenvalue analysis. The resulting general method provides much intuition about the dynamics of steady-state methods.

- A general method of catalyzing or speeding up the approach to steady state has been demonstrated. This method can be applied to arbitrary steady-state sequences, and performs well over all resonant frequencies.

- The design of spiral imaging methods has been studied with respect to stronger and faster gradient hardware. The result is a rapid imaging sequence that uses short spiral readouts allowing for rapid two- and three-dimensional imaging using steady-state sequences while maintaining the desirable properties of spiral imaging.

7.1 Future Work

Ultimately, most work in sequence development should improve the performance of clinical MR imaging. The work in this thesis ranges from the specific clinical problem of imaging articular cartilage to general analysis and design of rapid imaging methods that may have multiple applications. This section summarizes some possible future directions for the work described in the previous chapters, organized by topic.

7.1.1 Driven Equilibrium Cartilage Imaging

This work has shown that DEFT imaging has the potential to be a very useful clinical imaging method for knee imaging. Although clinical testing is the logical next step, there are a few technical improvements that could be investigated.

- Clinical evaluations of DEFT for diagnosing both cartilage disorders and other common knee ailments such as ligament tears and meniscal tears would be very useful. Clinical comparisons between DEFT and other methods must be
performed if DEFT is to replace other methods in a general MR exam of joints such as the knee.

- The three-dimensional (EPI) imaging sequence should be made more robust for patient scans. The addition of line-by-line phase correction rather than the current correction would help considerably to improve the EPI phase correction. Currently the images are artifact-free about 80% of the time.

- The striated appearance of cartilage has been shown to correlate with cartilage structure. 3D DEFT is possibly one of the best options for visualizing this structure in vivo. More investigation on the effect of imaging technique (gradient-echo and spin-echo imaging) as well as parameters such as echo time could be useful in correlating the striated appearance to the physiology.

- The partial-k-space acquisitions in three-dimensional DEFT imaging offer some options to reduce echo times using asymmetrically placed refocussing pulses. Further investigation of this could reduce scan times or further enhance the signal from cartilage.

### 7.1.2 Steady-State Analysis and Transient Reduction

The analysis of steady-state imaging sequences presented is useful for providing an intuitive view of magnetization dynamics. The reduction of the transient response of steady-state sequences has many practical uses, once implemented robustly. In both areas, there are many interesting research directions.

- The eigenvector analysis of transient response and steady-state response of magnetization to periodic excitations provides some intuition. The significance of the real-valued eigenvector, which closely corresponds to the effective axis of periodic rotations, could be studied more. This could lead to more understanding of how to create arbitrary steady states for different applications.
• $\mathbf{B}_1$ variations adversely affect the catalyzation scheme proposed here. For practical implementation, it would be essential to re-examine the sequence design to reduce the sensitivity to $\mathbf{B}_1$.

• For multiple-pass steady-state methods, where different steady states are created, it would be useful to be able to catalyze the transition from one steady state to another. Similarly, being able to “undo” the steady state could be useful, as has been shown in [81].

• The current design of the catalyzing sequence forces the resulting pulses to be discretized. For several reasons it may be desirable to use continuous pulses with lower amplitude.

• The catalyzing sequence presented is not spatially-selective. However, for some applications it would be necessary to investigate slice-selective catalyzation.

### 7.1.3 Short-Readout Spiral Imaging

Imaging using spiral readout trajectories with high-performance gradients has been studied briefly. There are several improvements that could be made to the gradient design as well as possible applications of the methods discussed.

• The current design used a constant-slew-rate-limit model rather than a voltage-limit model. Small reductions in readout times could be achieved by using a circuit model in the gradient design.

• The three-dimensional stack-of-spirals trajectory offers many possible variations to improve aliasing characteristics. The individual planes could be rotated slightly with respect to each other, and/or the phase-encode could be incremented with each spiral interleaf. Additionally variable-density approaches could be added, as suggested in [103,104].
• The slab-selective excitation could be shortened in time, resulting in even shorter readout trajectories and shorter repetition times that would improve off-resonance characteristics in SSFP imaging.

• Imaging of nuclei with constant flow may be improved both by nulling first moments of the spiral readouts [95] and by using a different phase encode order such as a centric ordering.

• The SSFP spiral imaging could lend itself very well to contrast-enhanced imaging, since fluid is bright on SSFP images.

• Short readouts are assumed to have better off-resonance properties than longer readouts. However it would be simple and useful to compare images acquired using different length readouts.

• For many applications, implementation of some kind of fat suppression technique would be very useful, as has been suggested already [71, 80, 101].