Advances in Quantitative MRI: Acquisition, Estimation, and Applications

by

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ABSTRACT

**Advances in Quantitative MRI:
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We show that it is possible to get approximate solutions to analytically intractable equations using iterative methods. Thus we show that the author could pass an undergraduate class in numerical analysis. In addition, a unique extension to Brent's method is proposed that results in slight improvements in convergence.

CHAPTER 1

Introduction

{c,intro}

Magnetic resonance imaging (MRI) is a non-invasive tool that has earned widespread clinical adoption due (among other factors) to its potential for excellent soft tissue contrast, its avoidance of ionizing radiation, and its flexibility to characterize many physical phenomena. Despite its numerous advantages, MRI requires highly specialized hardware, ongoing liquid-helium cooling of its superconducting main magnet, and comparably long scan times. For these reasons, MRI is (somewhat inherently) expensive relative to other medical imaging modalities. Accordingly, one broad initiative recently advocated by the MR community is to increase the *value* of MRI examinations.

Two reasonable measures of an acquisition's value are its sensitivity to a given disorder and its specificity in distinguishing it from others. The field of *pathology* seeks to ascribe physical processes to disorders of interest with high sensitivity and specificity. The field of *quantitative MRI* (QMRI) seeks to build MRI biomarkers that measurably describe such physical processes and thereby provide indirect information about the onset and progression of underlying conditions.

QMRI poses several challenges beyond those of commonplace anatomical MRI and thus remains yet to be widely adopted clinically. For example, latent parameter "maps" that describe relevant physical processes are often related to the received MR signal through complicated, highly nonlinear relationships. Furthermore, practical MR pulse sequences produce signals that are usually functions of not only desired but also nuisance parameters. Scan repetition is often necessary for accurate estimation of multiple desired and nuisance parameters, which can increase scan times. Mitigating these challenges (and likely others) is essential to furthering widespread clinical adoption of QMRI techniques.

1.1 Thesis Overview

{s,intro,over}

In this thesis, we seek to build a systematic framework towards QMRI. We borrow tools from optimization, statistics, and machine learning to construct time-efficient workflows for quantifiably characterizing physical processes of interest. We apply this framework to challenging QMRI problems that are motivated by pathological studies. Our goal is to introduce tools that aid in identifying clinical tasks for which QMRI should (or should not) be part of a targeted, high-value MRI examination.

We consider two distinct subproblems in our framework. Questions in *acquisition design* (Chapters 4,6) ask how to assemble fast collections of scans that yield data rich in information about physical processes of interest. Questions in *parameter estimation* (Chapters 3,5) ask how to quickly and reliably quantify parameters associated with these relevant physical processes. The overall framework seeks to first design fast and informative scans based on the application, and to then accurately and precisely estimate application-specific parameters of interest.

1.2 Thesis Organization

{s,intro,org}

The main body of this thesis is organized as follows:

- Chapter 2 reviews relevant background MR material about DESS,SPGR,blahblah...
- Chapter 3 discusses methods for MRI parameter estimation from likelihood models and applies these methods for model-based MR relaxometry, (*i.e.*, estimation of relaxation parameters T_1, T_2), of interest for many neurological applications. It derives some content (especially regarding applications) from conference papers [1, 2].
- Chapter 4 introduces a minimax optimization approach to aid robust and application-specific MR scan selection and optimization for precise latent parameter estimation. It optimizes several practical acquisitions and uses the likelihood-based estimation techniques introduced in Chapter 3 to assess the utility of scan optimization through simulations, phantom studies, and *in vivo* experiments. It derives content mainly from journal paper [3] and conference paper [4].
- Chapter 5 describes MRI parameter estimation using kernel ridge regression. It derives content from conference paper [5].
- Chapter 6 introduces a multi-compartmental model for relevant MR pulse sequences and proposes a new acquisition useful for myelin water fraction estimation, of in-

terest in white matter disorders. It applies kernel-based MR parameter estimation to estimate myelin water fraction, in simulations and *in vivo* experiments. It derives some content from conference paper [6].

- Chapter 7 presents some relatively immature ideas on steady-state radiofrequency (RF) pulse design as well as associated challenges. This work is presently unpublished and may offer avenues for further development.

- Chapter 8 summarizes several items of possible future work (on both short- and long-term timescales) and presents a timeline for completion of this thesis.

The appendices are organized as follows:

- Appendix A proposes an algorithm for combining multiple MRI datasets (as is necessary for many parameter estimation problems), when each dataset is acquired using multiple receiver coils.

- Appendix B presents an analysis of DESS in the presence of diffusion, shows that neglecting diffusive effects during T_2 estimation from DESS can cause significant bias, and suggests acquisition modifications for mitigating this bias.

CHAPTER 2

Background

{c,bkgrd}

CHAPTER 3

MRI Parameter Estimation from Likelihood Models

{c,relax}

CHAPTER 4

Optimizing MR Scan Design for Model-Based Relaxometry

{c,scn-dsgn}

CHAPTER 5

MRI Parameter Estimation via Kernel Regression

{c,krr}

CHAPTER 6

Myelin Water Fraction Estimation from Steady-State Sequences

{c,mwf}

CHAPTER 7

Steady-State RF Pulse Design

{c,ss-rf}

CHAPTER 8

Future Work

{c,future}

APPENDIX A

Coil Data Combination from Multiple Datasets

{a,cc-multi}

APPENDIX B

DESS in the Presence of Diffusion

{a,dess-diff}

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