Single Breath-hold Abdominal T₁ Mapping using 3-D Cartesian Sampling and Spatiotemporally Constrained Reconstruction

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Declaration of Financial Interests or Relationships

Speaker Name: Felix Lugauer

I have the following financial interest or relationship to disclose with regard to the subject matter of this presentation:

Company Name: Siemens Healthcare GmbH
Type of Relationship: Financial stipend
Motivation

Abdominal T₁ mapping

• Biomarker for functional analysis of, e.g. liver¹, kidney², pancreas³

Clinical practice

• 2-D Inversion recovery (IR)/Look-Locker (LL)
  + highly accurate
  − slow (single/few slice coverage)

• 3-D Variable Flip Angle (VFA)⁴
  + fast (large coverage)
  − B₁ bias (even with correction)

→ Fast and accurate 3-D IR/LL highly desirable

¹ Haimerl et al. PloS one 8(12):e85658, 2013
² Huang et al. JMRI 33(5):1241-1247, 2011
³ Tirkes et al. JMRI 45(4):1171-1176, 2017
State-of-the-Art

3-D Look-Locker\textsuperscript{5,6} \(\rightarrow\) minutes for 3-D T\textsubscript{1} map

+ accurate
+ large coverage
- relaxation delay (shortened by magn. prep.)

Recently: non-Cartesian breath-hold 3-D LL\textsuperscript{7}

Features: segmentation, higher acceleration, full relaxation assumption
+ breath-hold
- additional calibration scan (40s)

\textsuperscript{5} Henderson et al. MRI 17(8):1163-1171, 1999
\textsuperscript{6} Hui et al. NMR 26(11):1420-1430, 2013
\textsuperscript{7} Chen et al. MRM 75(4):1457-1465, 2016
3-D Cartesian Look-Locker

Aim: whole-liver $T_1$ mapping in self-contained single breath-hold (< 20s)

Hepatic $T_1$ range (field-strength, contrast enhancement): 0.3 - 1s

Requirements for LL acquisition:
- Acquisition long enough for high $T_1$ (2s)
- High temporal resolution for short $T_1$ (0.2s)

Exemplary 3-D matrix: $160 \times 100 \times 40$, $TR=2\text{ms} \rightarrow 40x\text{ acceleration factor (AF) needed}$

⇒ Combination of k-space segmentation (3-4x) and sparse sampling (10-14x)
3-D Acquisition Scheme

Divide k-space in $S$ segments and repeat: inversion – measure – wait

- Wait time for steady-state to reach (approx.) full relaxation\(^7\): 3 - 5s
Sparse Incoherent Sampling

Variable density (VD) incoherent sampling → Poisson disc

- Variable spatio-temporal incoherence ($\vartheta$) while maintaining Poisson property
  - Additional rule for potential sample $k$ at current TI $t$ using accumulated mask (AM):
    \[
    AM(k) \leq VD(k) t + 0.5(1 - \vartheta), \quad 0 \leq \vartheta \leq 1
    \]

Accumulated mask:

Random: $\vartheta = 0$
- Coverage/Duplicates: 52% / 33%

Temp. Inc.: $\vartheta = 0.8$
- Coverage/Duplicates: 64% / 18%
Segmentation and Reordering Strategy

Low gradient amplitude $\rightarrow$ minimize avg. distance between successive samples ($\bar{D}$)
High dynamic range for mapping $\rightarrow$ early sampling of k-space center

Segmentation:
- "Linear"
- "Onion"
- "Wedges"

Reordering:
- $\bar{D}$ per point (12x):
  - "Linear": 8.4
  - "Onion": 4.9
  - "Wedges": 4.5
Data Reconstruction

Joint Compressed Sensing reconstruction of all contrast images: 3-D+t
- Haar wavelet regularization in spatial and temporal domain
- Parallelization via decoupled 2-D+t reconstruction along readout after FFT

Phase-sensitive multi-step T₁ mapping⁸,⁹:

1. **Solve** 3-parameter model: \( M(A, B, T, t) = A - B e^{-t/T} \)
2. **Extract** \( M_0, T_1, \) FA, phase from \( A, B, T \) and **smooth** FA and phase map
3. **Solve** 2-parameter model \((M_0, T_1^*)\) using known FA and phase

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⁸ Deichmann MRM 54(1):20-27, 2005
⁹ Barral et al. MRM 64(4):1057-1067, 2010
Evaluation

Comparison against reference 2-D LL
- ROI analysis

Data
- NIST phantom data
- 8 Volunteers

Scanner
- Siemens MAGNETOM Skyra (3T)/Aera (1.5T)

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3-D setup 1.5T (3T):
FA = 3-5, TR=1.9ms, TE=0.9, #TI=12, AF=12(10)
4(3) segments, wait time = 3(4.5)s
Voxel size: 2.2x2.2x6mm³
Scan time: ~19s for 30 slices

2-D setup:
FA=8, TR=2.9ms, TE=1.6, #TI=16, AF=PAT2
Pixel size: 1.9 x 1.9 mm² (8mm thickness)
Scan time: ~3.8s per slice

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10 Keenan ISMRM #3290, 2016
Results: NIST Phantom at 3T

- High agreement with nominal values and reference 2-D LL

RMSE/Avg. STD: 3.9% / 8.3ms

RMSE/Avg. STD: 4.1% / 24.5ms
Quantitative Results: In-vivo

Assessment of mean hepatic $T_1$:
- Multiple ROIs in matching 2-D/3-D slices
- 8 volunteers (4 x 1.5T, 4 x 3T)

→ High agreement with reference 2-D LL
  Average ROI Std. deviation [ms] (1.5/3T)
  2-D: 50.2 / 34.8
  3-D: 42.0 / 39.9
Results: Qualitative Comparison at 1.5T

- **Six-fold** gain of volumetric data in breath-hold (slightly lower resolution)
- Fully scanner integrated reconstruction
  - < 5min on CPU
  - < 3min on GPU

Proposed 3-D acquisition (30 slices in 19s)

Reference 2-D (2 slices in 8s)
Discussion

Optimal configuration field-strength dependent
• Lower temporal resolution @3T → less AF → 3 segments sufficient

Challenges of segmented PSF
• Motion sensitivity: bigger issue than with e.g., 2-D multi-slice
• Scan efficiency (long delay at 3T)
  • Undercutting delay → inconsistent magnetization → artifacts possible

→ Magnetization preparation (lower $B_1$ robustness)
Summary

Accurate whole-liver T₁ mapping

- First application of single breath-hold Cartesian Look-Locker
- Features: segmentation, spatiotemporal sparsity and through-time regularized iterative reconstruction
- Highly accurate for phantom and volunteer data