Single Breath-hold Abdominal T_1 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 T_1 mapping

- Biomarker for functional analysis of, e.g. liver[1], kidney[2], pancreas[3]

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)
  - – B_1 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
[4] Deoni, JMRI, 26(4):1106-1111, 2007

State-of-the-Art

3-D Look-Locker[5,6] → minutes for 3-D T_1 map

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

Recently: non-Cartesian breath-hold 3-D LL[7]

Features: segmentation, higher acceleration, full relaxation assumption

- \+ breath-hold
- – additional calibration scan (40s)

[5] Henderson et al. MRI 17(8):1163-1171, 1999
[6] Hui et al. NMR 26(11):1420-1430, 2013
[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

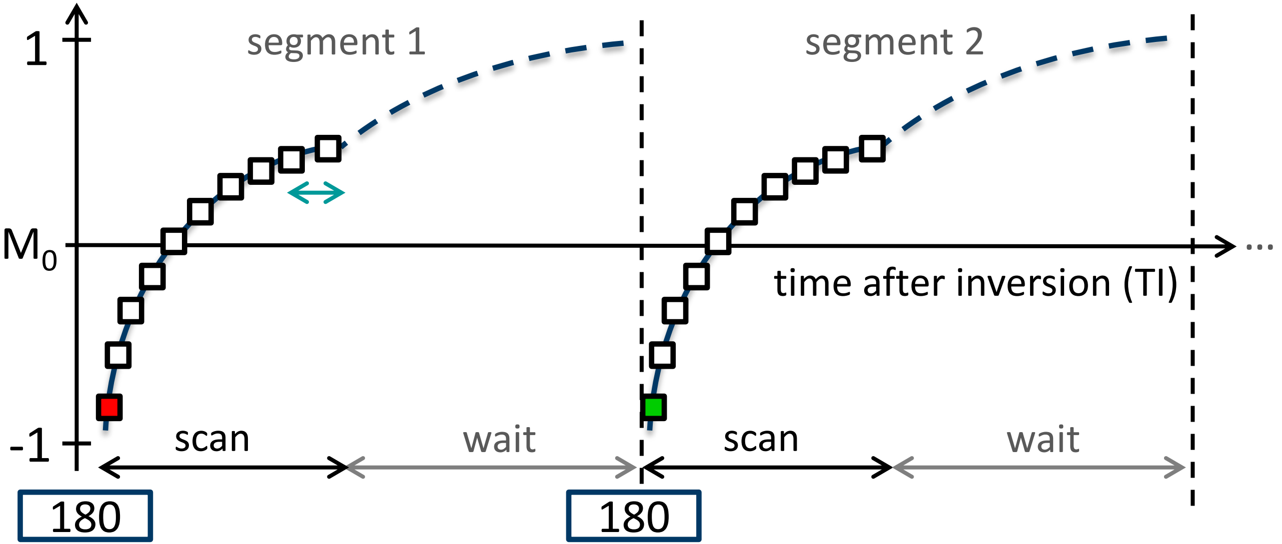
Requirements for LL acquisition:

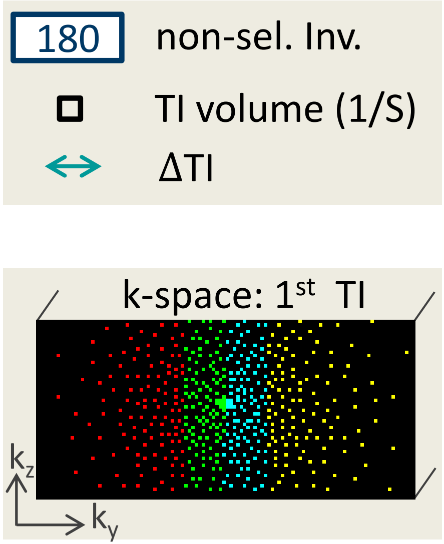
- Acquisition long enough for high T_1 (2s)
- High temporal resolution for short T_1 (0.2s)

Exemplary 3-D matrix: *160x100x40, TR=2ms* → *40x 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

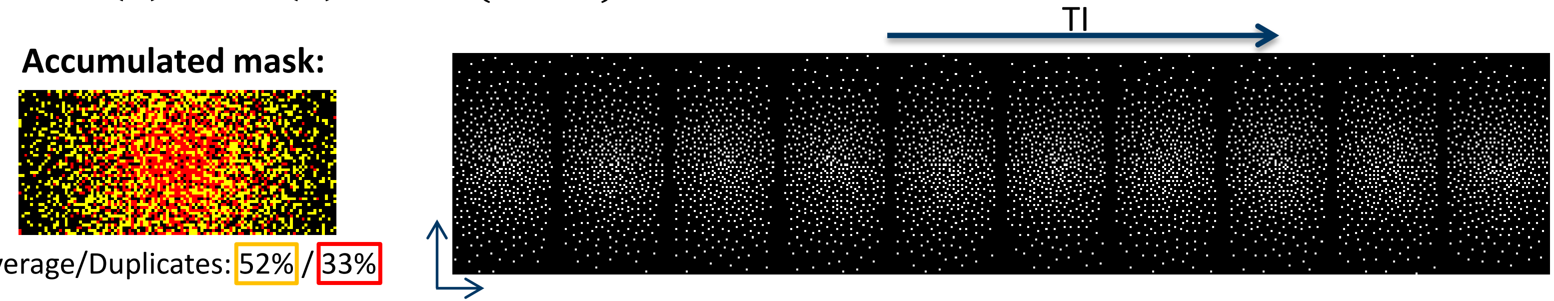
Variable density (VD) incoherent sampling → Poisson disc

- Variable spatio-temporal incoherence (ϑ) while maintaining Poisson property
  - Additional rule for potential sample $\boldsymbol{k}$ at current TI t using accumulated mask (AM):

$$AM(\boldsymbol{k}) \leq VD(\boldsymbol{k})\, t + 0.5(1 - \vartheta), \quad 0 \leq \vartheta \leq 1$$

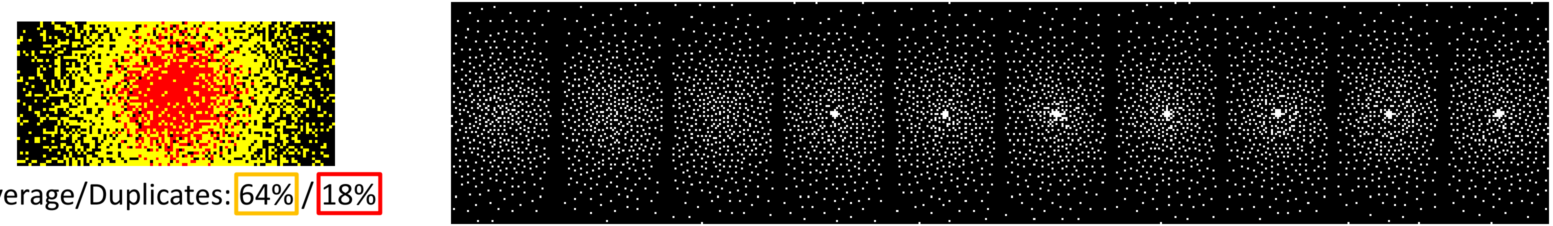
Accumulated mask:

Random: $\vartheta = 0$



Coverage/Duplicates: 52% / 33%

Temp. Inc.: $\vartheta = 0.8$



Coverage/Duplicates: 64% / 18%

Segmentation and Reordering Strategy

Low gradient amplitude → minimize avg. distance between successive samples ($\bar{D}$)

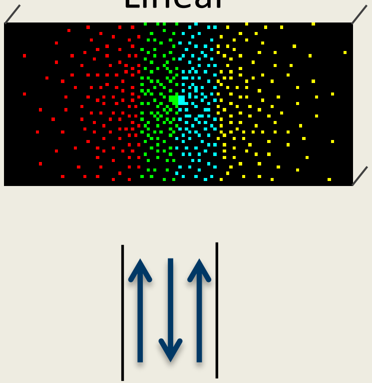
High dynamic range for mapping → early sampling of k-space center

Segmentation:

Reordering:

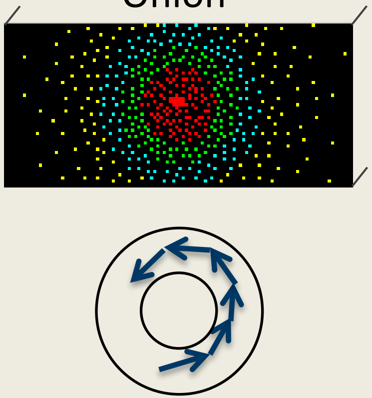
$\bar{D}$ per point (12x):

"Linear"



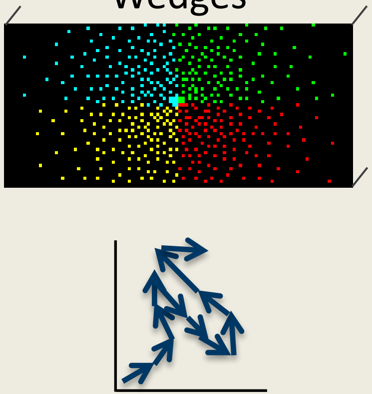
8.4

"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 T_1 mapping[8,9]:

1. Solve 3-parameter model: $M(\boldsymbol{A}, \boldsymbol{B}, \boldsymbol{T}, t) = \boldsymbol{A} - \boldsymbol{B} e^{-t/\boldsymbol{T}}$
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

[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[12]
- 8 Volunteers

Scanner

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

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: 2.2x2.2x6mm^3

Scan time: ~19s for 30 slices

2-D setup:

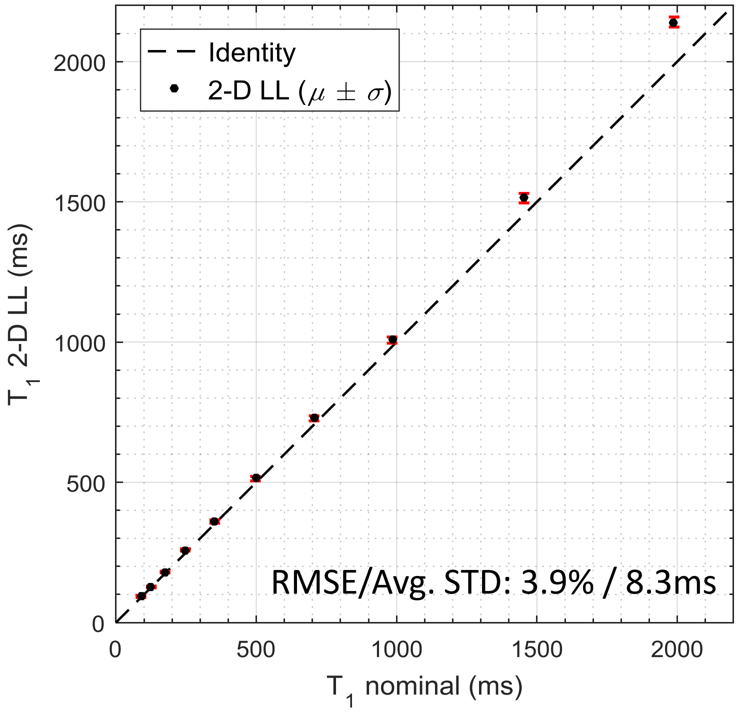
FA=8, TR=2.9ms, TE=1.6, #TI=16, **AF=PAT2**

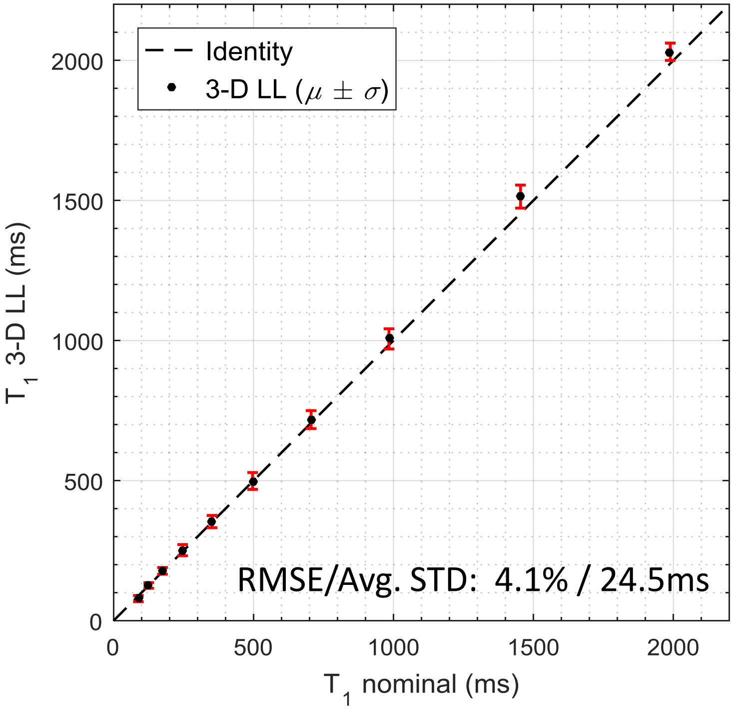
Pixel size: 1.9 x 1.9 mm^2 (8mm thickness)

Scan time: ~3.8s per slice

[10] Keenan ISMRM #3290, 2016

Results: NIST Phantom at 3T





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

Quantitative Results: In-vivo

Assessment of mean hepatic T_1:

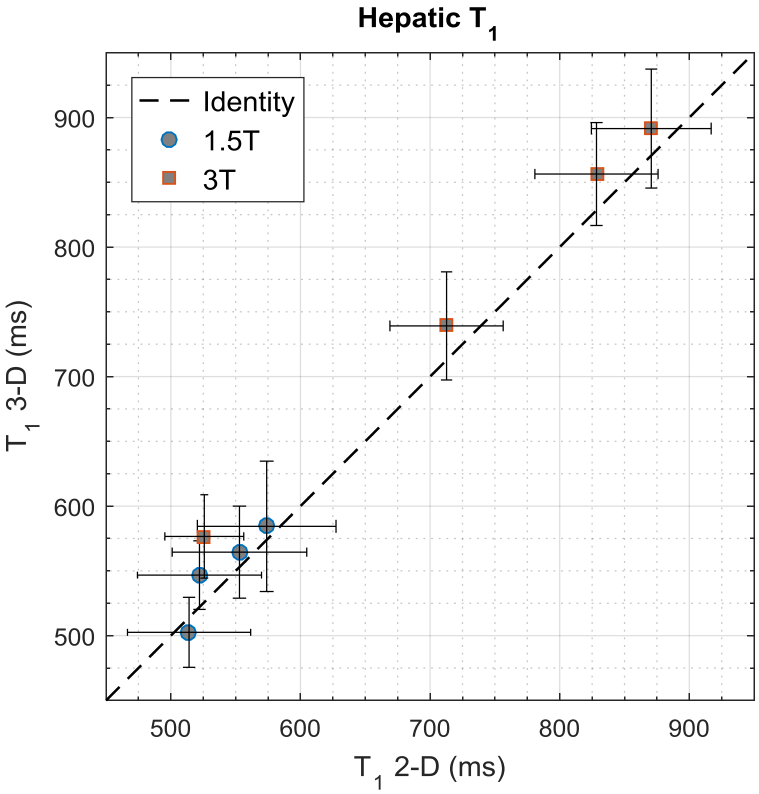
- Multiple ROIs in matching 2-D/3-D slices
- 8 volunteers (4 x 1.5T, 4 x 3T)

→ High agreement with reference 2-D LL

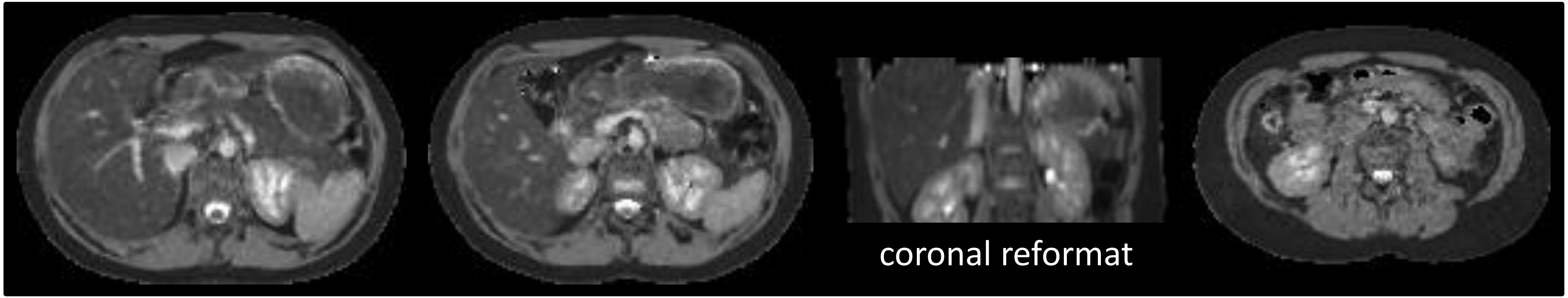
Average ROI Std. deviation [ms] (1.5/3T)

2-D: **50.2** / 34.8

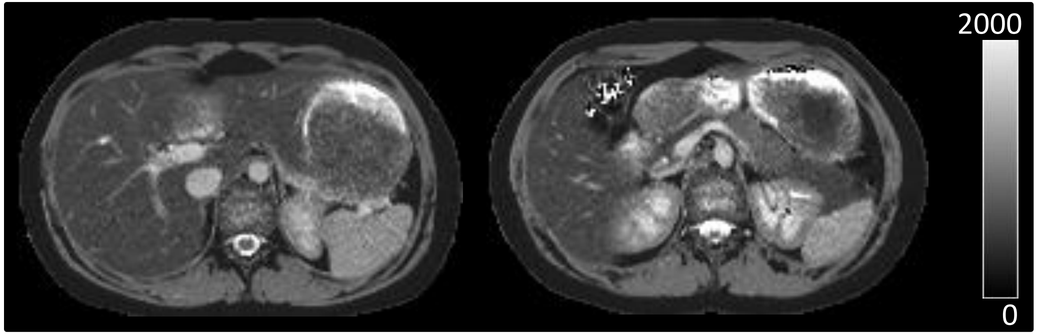
3-D: 42.0 / 39.9



Results: Qualitative Comparison at 1.5T



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



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

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

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 T_1 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