T1/T2/T2* Mapping

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MR Relaxometry in Clinical Practice

Liver
• T2 (R2=1/T2)
• T2* (R2*=1/T2*)
• T1

Heart
• T1
• T2
• T2*

Knee
• T2
• T1ρ

Technique and Quality Assurance
R2 Relaxometry for Liver Iron Concentration (LIC)

- FerriScan is FDA-approved and commercially available for 1.5 T scanners
- FerriScan has been calibrated and validated against liver biopsy across scanners

1.5 T MRI data is securely transmitted to the Resonance Health Service Centre

Liver Iron Concentration Report available for secure download by Radiology Centre within target time of 2 business days

Patient referred for 10 min MRI scan at a validated Radiology Centre

FerriScan analysis and quality checks performed

https://www.resonancehealth.com/

R2 Relaxometry Acquisition

Five Single Spin Echo Sequences
- TR/TE = 1000/6, 9, 12, 15, 18 ms
- Pixel size = 1.6x1.6 mm²
- Slice thickness = 5–6 mm; 11 slices
- Free-breathing (2min/scan)

Bi-exponential Signal Decay Model \( \rightarrow R_{2\text{ fast}} \) & \( \rightarrow R_{2\text{ slow}} \) \( \rightarrow R_{2\text{ mean}} \)

Internal Control within FOV
- A 1000 mL saline bag (long T2 reference)
- To correct the instrumental gain drift and signal intensity variations

**R2-based Liver Iron Concentration**

**R2–LIC Calibration Curve**
(105 pts; LIC: 0.3–42.7 mg/g)


**R2–MRI Technical Verification and Limitations**

**FerriScan Phantom Pack**
MnCl₂ solutions with R2 values relevant to the measurements from *in vivo* liver

- Main limitations of FerriScan:
  - Long scan time (10–20 min)
  - Limited anatomic coverage
  - Motion artifacts
  - Extra cost of FerriScan service (fee per scan)
**R2*—Based Liver Iron Quantification**

- The 2D or 3D multi-echo gradient echo sequence can provide the full liver coverage within a single breath-hold
- R2* postprocessing is available on most 1.5T and 3T scanners
- R2*—LIC relationship: \( LIC = a \cdot R_2^* + b \) (universal calibration & diagnostic cutoffs under investigation)

![R2* maps](image)

**Hernando D, JMRI 2014;40: 1003**

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**Confounder of R2* Iron Quantification: Liver Fat**

- Multi-echo Dixon-based gradient echo sequence with the multipeak fat spectral model can simultaneously quantify
  - Proton-density fat fraction (PDFF) for liver fat
  - R2* for liver iron

![Fat Fraction Map](image)

T1 Relaxometry in Liver MRI

- T1 is shortened by liver iron, but the effect is less than T2 and T2*
- T1 increases in liver fibrosis and inflammation due to the increase of extracellular fluid
- LiverMultiScan – iron corrected T1 mapping (cT1) as a fibro-inflammation biomarker
  - T1 mapping by Shortened Modified Look Locker Inversion (ShMOLLI)
  - T2* mapping by multi-echo spoiled gradient-echo imaging (or T2* DIXON imaging)

MR Relaxometry for Myocardial Tissue Characterization

- Non-invasive quantification of tissue alterations
- Changes in T1, T2 and T2* are associated with multiple diseases
Modified Look-Locker IR (MOLLI) for T1 mapping

- Non-selective inversion recovery (IR) for T1-weighting
- ECG-triggered images acquired using a single-shot bSSFP sequence at end-diastole during breath-hold
- 3 sets of data acquired with increasing inversion time (TI)
- Data sets merged according to the effective TI to compute the apparent T1* → T1

\[ S = A - B \cdot e^{-1/T_1} \]
\[ T_1 = T_1^* \cdot (B/A - 1) \]


T1 and Extracellular Volume (ECV) Mapping

- ShMOLLI (Shortened MOLLI)
- SASHA (Saturation Recovery Single-shot Acquisition)
- SAPPHIRE (Saturation Pulse Prepared Heart Rate Independent Inversion Recovery)
- SASHA & SAPPHIRE – higher accuracy of T1 mapping
- MOLLI & ShMOLLI – higher precision of T1 mapping

\[ ECV(\%) = \frac{1}{post T_{1,myo}} - \frac{1}{native T_{1,myo}} \times \frac{1}{post T_{1,blood}} - \frac{1}{native T_{1,blood}} \times (100 - Hct) \]

**T1 Mapping and ECV Standardization (T1MES) Phantom**

- 9 NiCl$_2$-doped agarose vials
- Representing clinically relevant T1 and T2 values of
  - blood and myocardium
  - pre- and post-contrast
  - 1.5 and 3T

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**T2 Mapping to Detect Myocardial Inflammation/Edema**

- Gradient and spin echo (GRASE) sequence
- Fast or Turbo spin echo (FSE or TSE) sequence

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**Cardiac T2* Mapping for Iron and Hemorrhage at 1.5T**

- Multi-echo gradient echo sequence with 8 TEs (2–18 ms)
- **Black-blood** sequence with double inversion recovery provides better myocardium blood contrast
- Myocardial T2* analysis restricted to the **septum** to avoid susceptibility artifact

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**MRI-based Compositional Imaging of Cartilage**

- In osteoarthritis (OA), cartilage degeneration starts with
  - Dehydration
  - Loss of proteoglycan
  - Thinning and disruption of collagen
- Increase of **T2** and **T1ρ**

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*Triadyaksa P, et al. JMRI 2020;52:1340*

*Li and Majumdar. JMRI 2013;38:991*
**T2 Mapping of Knee Cartilage**

- Multi-echo spin-echo (MESE) sequence
  - TR = 2700 ms
  - TE = 10, 20, 30, 40, 50, 60, 70 ms
  - Slice thickness = 3 mm
  - Pixel size = 0.313 x 0.446 mm²
- High spatial resolution images and T2 maps
  - Elevated cartilage T2 values were associated with knee pain in the early phase of osteoarthritis

_Baum T, et al. Arthritis Care Res (Hoboken) 2012;64:248_

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**T1ρ Relaxation Time and Spin-lock (SL) Technique**

- T1ρ is the spin-lattice relaxation time in the rotating frame

\[ S(TSL) = S_0 \cdot e^{-TSL/T1\rho} \]

_Wang and Regatte. JMRI 2015;41:586_
**QIBA Profile for MRI-based Compositional Imaging of Knee Cartilage**

- **A 3D $T_1\rho$ and $T_2$ sequence** recommended, available as a research prototype at 3.0 T by GE, Siemens and Philips
  - Magnetization-prepared Angle-modulated Partitioned k-space SPGR Snapshots (MAPSS)
- Calibration phantom being developed for standardization
  - $T1$: 300 – 1200 ms; $T1\rho$ & $T2$: 15 – 105 ms

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**Magnetic Resonance Fingerprinting (MRF)**

- Voxel-based signal evolution is acquired using pseudo-random variation of imaging parameters at every repetition
- Dictionary of theoretical signal evolution is generated for all possible tissue properties, based on the Bloch equation unique to the signal acquisition
- Pattern matching to find the nearest match, then the corresponding MR parameters are assigned to that voxel

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*Poorman, et al. JMRI 2020;51:675*
Deep Learning Increases Efficiency of MR Relaxometry

Following network training, average T2 map reconstruction ~2.1 sec for each patient

Summary

- MR relaxometry provides both visualization and quantification of the disease process in vivo
- Quantitative MR measurements enable inter- and intra-patient comparability, specific clinical diagnosis and treatment monitoring
- Robust clinical utility of MR relaxometry requires rigorous technical validation and quality assurance procedures
Thank You!

- Takeshi Yokoo, MD, PhD
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Quantitative MRI Phantoms for Multiparametric MRI

- **Set I:** Peanut butter oil
  - PDFF: 0%, 10%, 20%, 30%, 40%

- **Set II:** MnCl$_2$ and iron microspheres
  - $R_2^*$: 50, 100, 200, 400, 600 s$^{-1}$

- **Set III:** NiCl$_2$
  - $T_1$: 500, 750, 1000, 1250, 1500 ms

**Quality Assurance**
- Clinical Applications
- Multicenter Clinical Trials

*Zhao R, et al. MRM 2021;85:734*
MRF Validation Using the NIST/ISMRM MR System Phantom

NiCl₂-doped spheres for T1 mapping (20 – 1900 ms, 3T at 20°C)
MnCl₂-doped spheres for T2 mapping (5 – 550 ms, 3T at 20°C)

Jiang Y, et al. MRM 2017;78:1458
Ma D, et al. JMRI 2019;49:1333