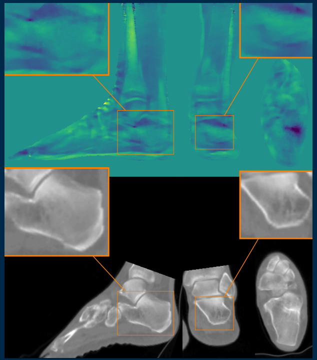
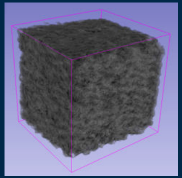
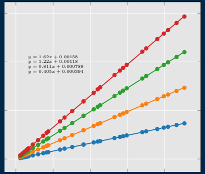
Klinikum rechts der Isar
Technische Universität München

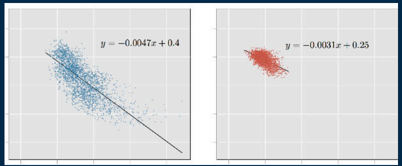
533 On the Sensitivity of Bone Marrow Magnetic Susceptibility and R2* on Trabecular Bone Microstructure

Maximilian N. Diefenbach[1], Anh Van[2], Jakob Meineke[3], Jan S. Kirschke[4], Benedikt Schwaiger[1], Thomas Baum[4], Alexandra Gersing[1], Dimitrios C. Karampinos[1]









Session: **Pitch: Conductivity, Relaxation, Water–Fat & Beyond**
Day/Date: **Tuesday, 19 June, 2018**
Session Time: **16:15**

[1]Department of Diagnostic & Interventional Radiology, Technical University of Munich, Munich, Germany
[2]Institute of Medical Engineering, Technical University of Munich, Garching, Germany
[3]Philips Research, Hamburg, Germany
[4]Section of Neuroradiology, Technical University of Munich, Germany

Declaration of Financial Interests or Relationships

Speaker Name: Maximilian N. Diefenbach

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

Company Name: Philips Healthcare
Type of Relationship: Grant Support

Introduction

Osteoporosis

commons.wikimedia.org/wiki/Category:Osteoporosis

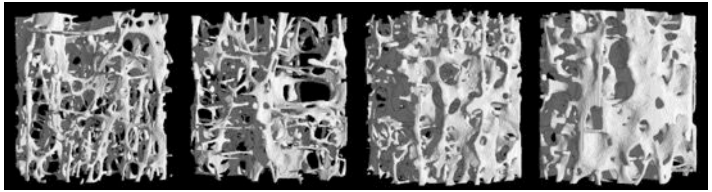
- bone weakness → fractures
- high prevalence

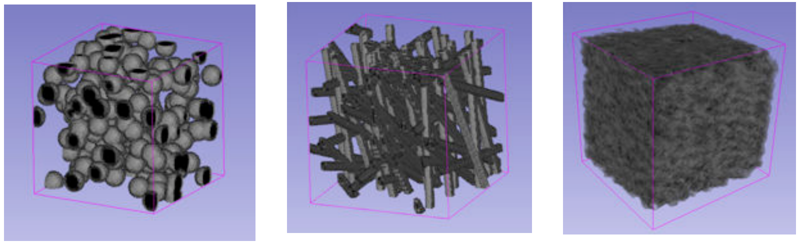
→strong need for **osteoporosis screening**

Quantitative Susceptibility Mapping (QSM)

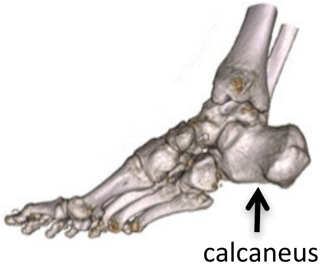
Methods/Results Outline

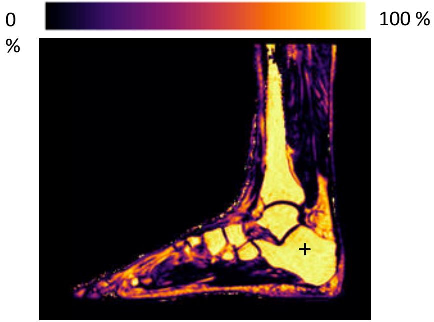
Numerical Simulations



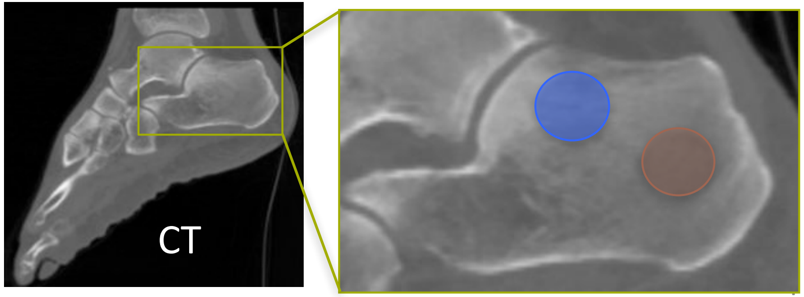


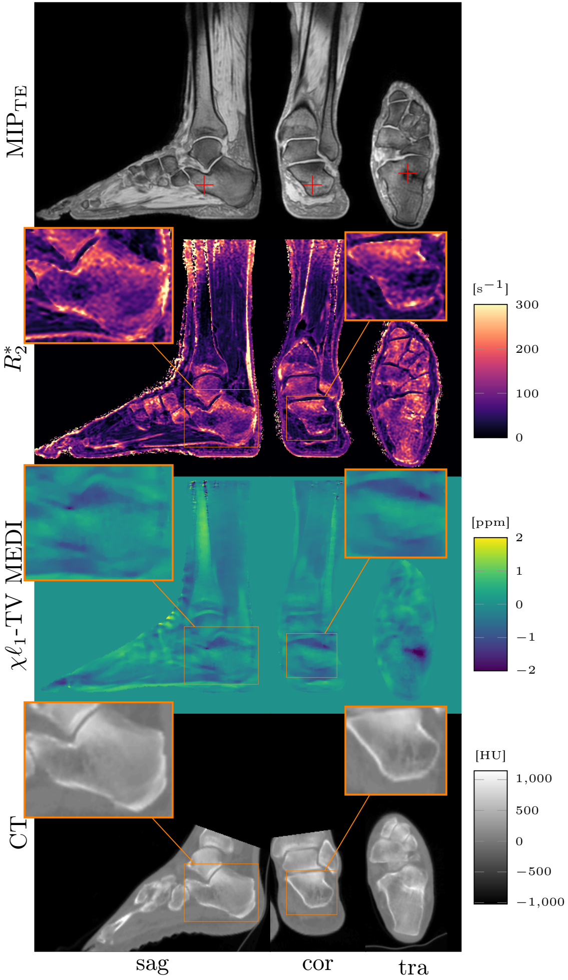
In vivo scans



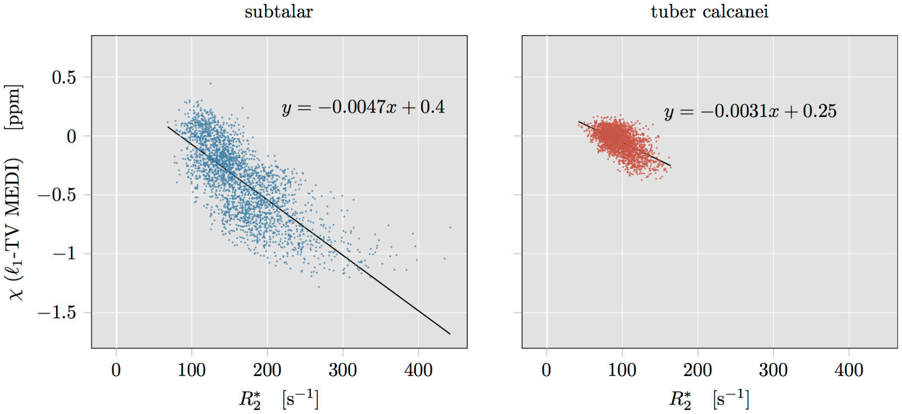


Fat Fraction



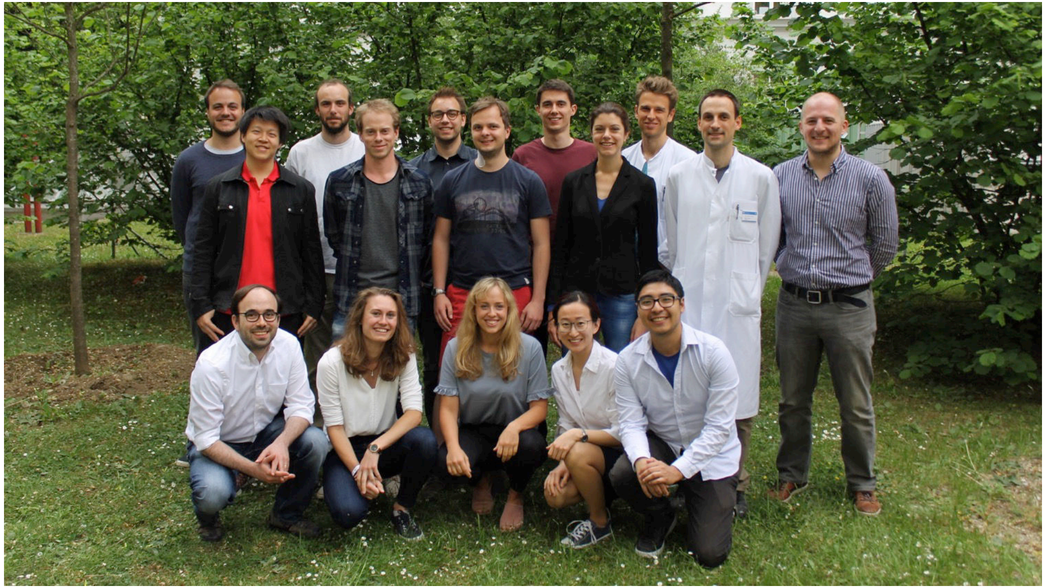


- **multi-parametric** results
- new **contrast sensitive** to the presence of trabecular bone
- combination of susceptibility–R2* parameters allows to extract **sub-voxel information** about **microstructure**



Session Time: 17:15

Plasma Number: 1



BMRR

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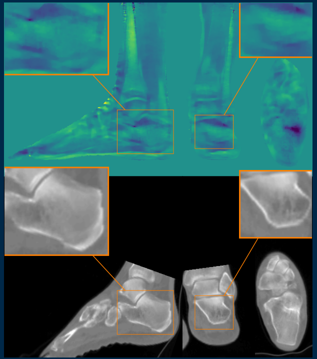

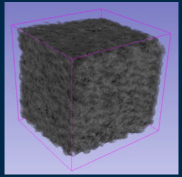

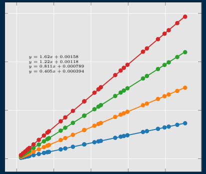

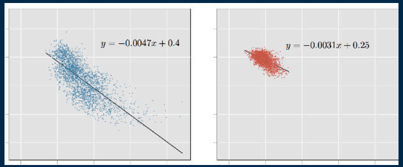

Session: **Poster: Conductivity, Relaxation, Water–Fat & Beyond**
Day/Date: **Tuesday, 19 June, 2018**
Session Time: **17:15**
Plasma Number: **1**

[1]Department of Diagnostic & Interventional Radiology, Technical University of Munich, Munich, Germany
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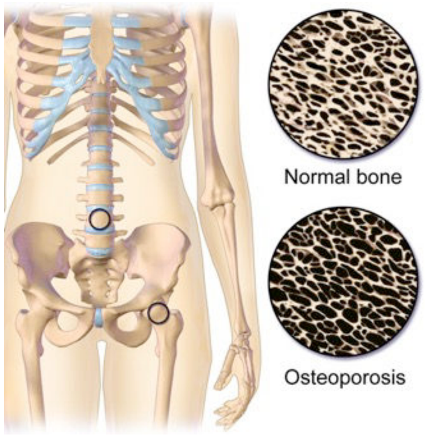
Introduction

Osteoporosis



*

- Definition: increased bone weakness → fractures

  →reduced individual quality-of-life

- High Prevalence: ~ 1 in 3 post-menopausal women in developed countries[1,2]

  →great economic burden on health care

- Treatement possible for early diagnosis

  →strong need for **osteoporosis screening**

[1] Wright et al. Journal of Bone and Mineral Research 29.11 (2014), pp. 2520–2526.
[2] Hernlund et al. Archives of Osteoporosis, 8(1-2), 136 (2013). doi:10.1007/s11657-013-0136-1

*/commons.wikimedia.org/wiki/Category:Osteoporosis

Introduction

Osteoporosis screening

- Dual-energy X-ray absorptiometry (DXA):
  measures areal bone mineral density (BMD)
  overlap of healthy and osteoporotic patients
  low accuracy in fracture prediction

Kling et al., J. Women's Health, 23(7), 563–572 (2014). doi: 10.1089/jwh.2013.4611

- Quantitative Computed Tomographgy (QCT):
  ionizing radiation

Damilakis et al., Europ Rad, 20(11), 2707–2714 (2010). doi: 10.1007/s00330-010-1845-0

- MRI-based techniques:
  - High-resolution imaging: slow, motion sensitive

    Song et al., JMRI, 7(2), 382–388 (1997). doi: 10.1002/jmri.1880070222
  - R2*-mapping: field strength and orientation dependent

    Wehrli et al., NMR Biomed, 19(7), 731–764 (2006). doi: 10.1002/nbm.1066
  - Quantitative Susceptibility Mapping (QSM)

    Wang et al., MRM, 73(1), 82–101 (2014). doi: 10.1002/mrm.25358

Introduction

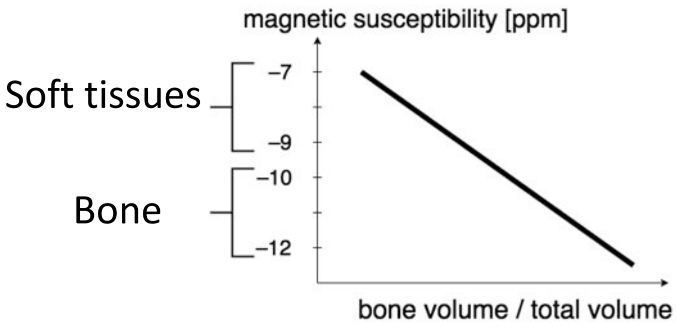
Quantitative Susceptibility Mapping (QSM)

- Method: GRE sequence → Magnetic-field mapping → Background Field Removal → Dipole Inversion

- Properties: more direct measurement of fundamental tissue magnetic susceptibility, incorporating B0 direction and strength as input (in contrast to voxel-wise R2* fit)

- Hypotheses:

1. QSM is sensitive to trabecular bone density



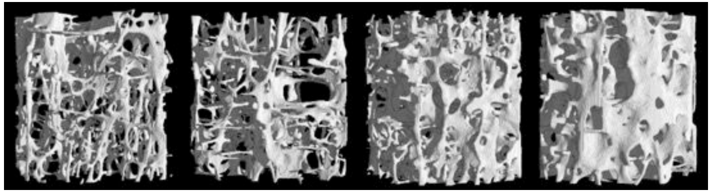
2. QSM can overcome limitations of other MR-based trabecular bone measurements

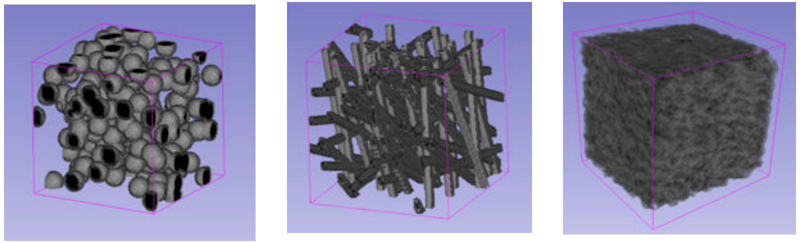
Purpose

To investigate the effect of trabecular bone architecture on gradient-echo-based multi-parametric mapping.

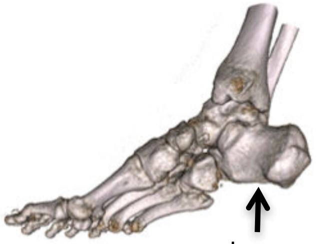
Methods/Results Outline

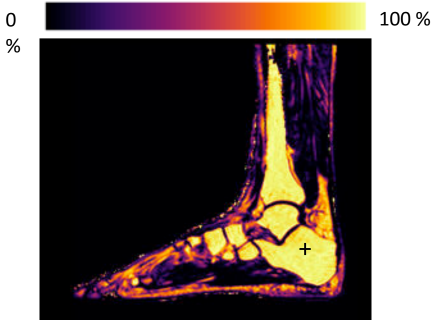
Numerical Simulations



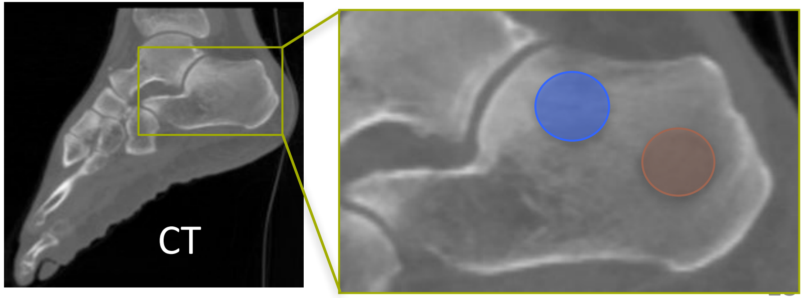


In vivo scans





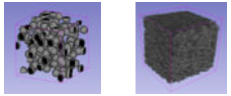
Fat Fraction



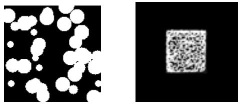
Methods

Numerical Simulations

1. Assume trabecular bone model

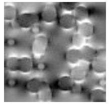


2. Construct susceptibility distribution



3. Forward simulation of magnetic field (relative difference field RDF)

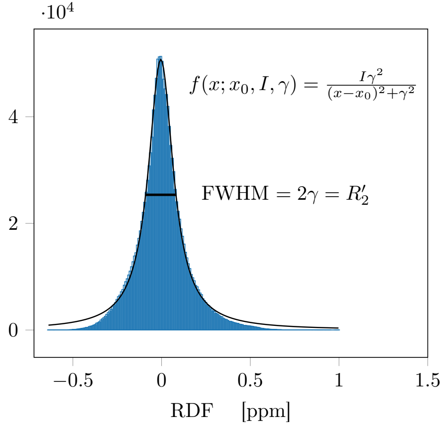
$$\mathrm{RDF} = F^{\dagger} D F \chi$$



Dipole kernel

Fourier transform

4. R2' measurement



5. Susceptibility measurement

$$\chi' = \underset{\chi}{\operatorname{argmin}} ||F^{\dagger} D F \chi - \mathrm{RDF}||_2^2 + \lambda ||\nabla \chi||_2^2$$

$\lambda = 0.8$ to suppress streaking

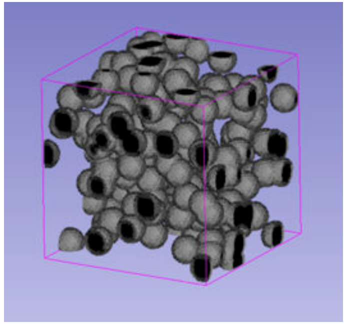
6. Monte-Carlo variations of the trabecular bone model with alternating bone volume to total volume (BV/TV)

Majumdar, MRM , 22(1), 101–110 (1991). doi: 10.1002/mrm.1910220111; Ford et al., MRM, 30(3), 373–379 (1993). doi: 10.1002/mrm.1910300316

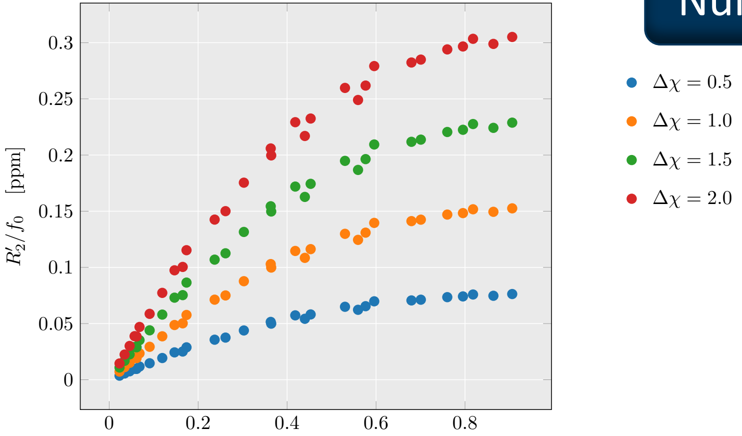
Results

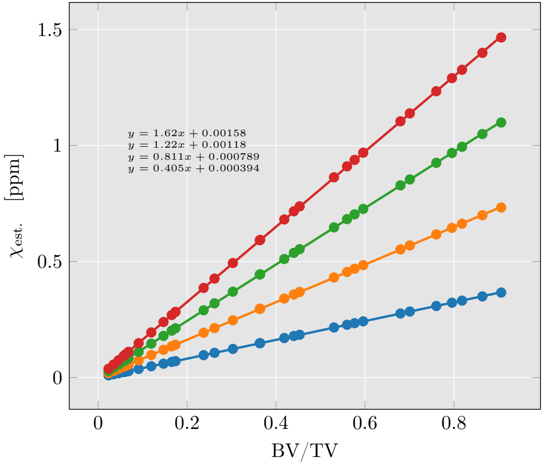
Numerical Simulations

Spherical Inclusions



$$\mathrm{ROI} = 128 \times 128 \times 128 \,\text{voxels}$$
$$\mathrm{FOV} = 384 \times 384 \times 384 \,\text{voxels}$$
$$N_{\text{inclusions}} = (100, 150, ..., 300)$$
$$r = (5, 10, 15, 20)$$
$$\Delta\chi = (0.5, 1.0, 1.5, 2.0)$$

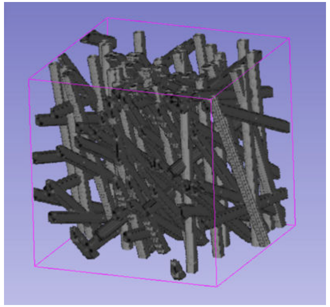




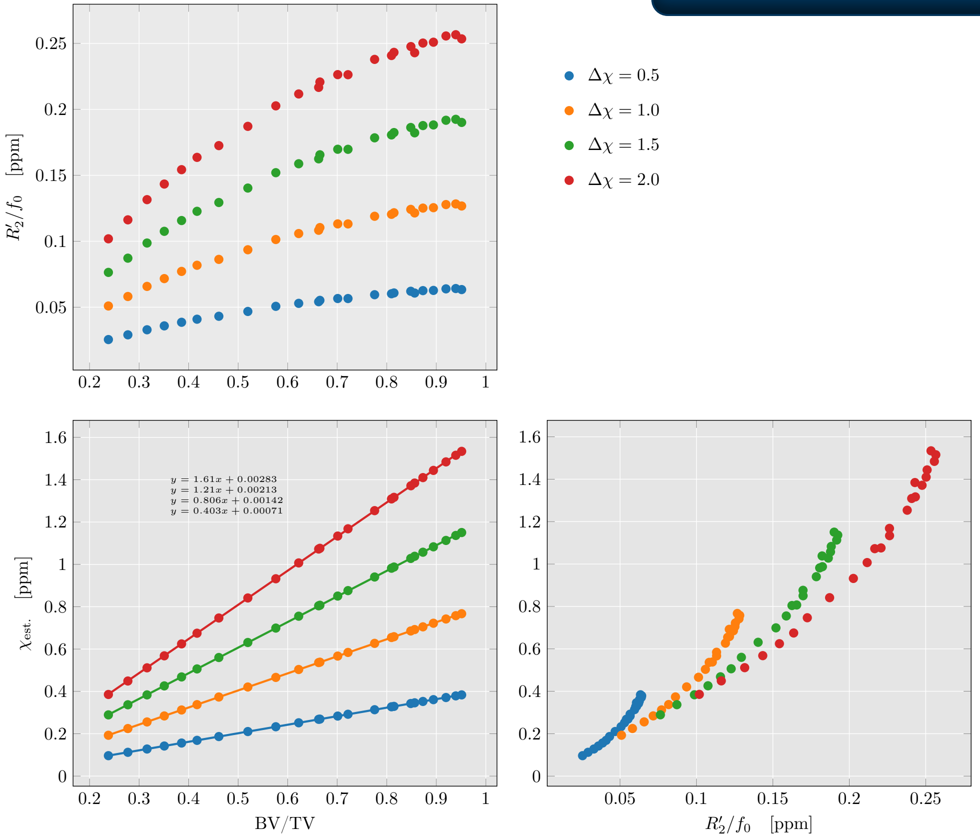
Results

Numerical Simulations

Cylindrical Inclusions

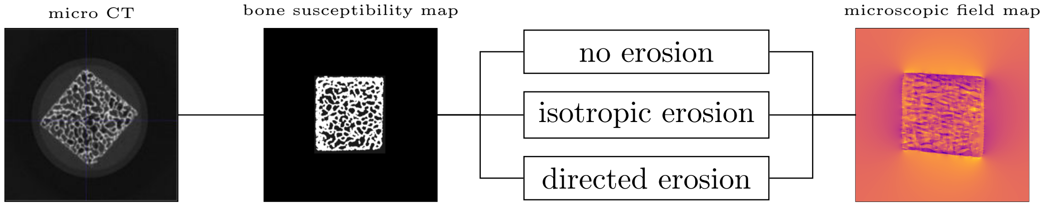


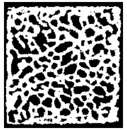
$$\mathrm{ROI} = 128 \times 128 \times 128\,\mathrm{voxels}$$
$$\mathrm{FOV} = 384 \times 384 \times 384\,\mathrm{voxels}$$
$$N_{\mathrm{inclusions}} = (100, 120, \ldots, 200)$$
$$r = (4, 6, 8, 10)$$
$$\Delta\chi = (0.5, 1.0, 1.5, 2.0)$$



Methods

Numerical Simulations





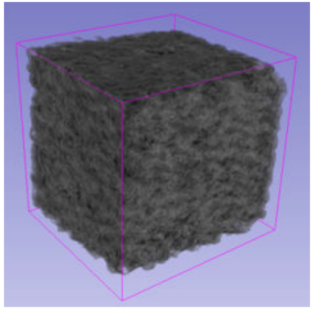
no erosion

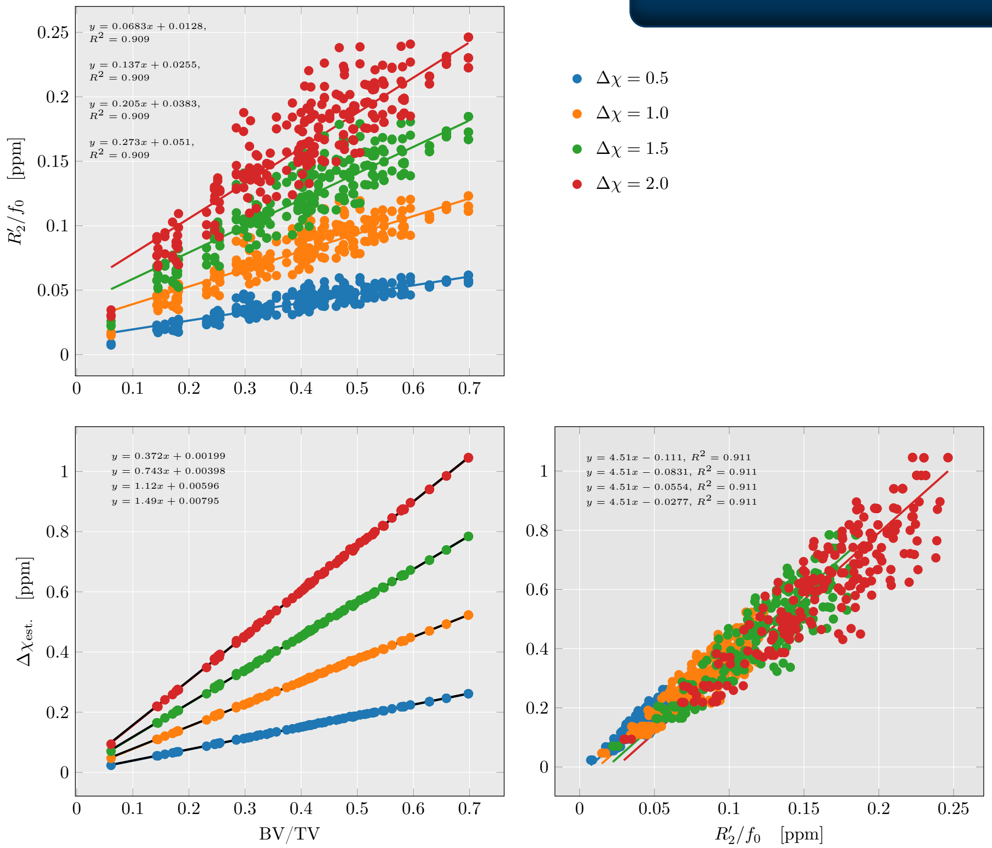
Diefenbach et al., ISMRM 2016, #677

Results

Numerical Simulations

Femoral trabecular bone

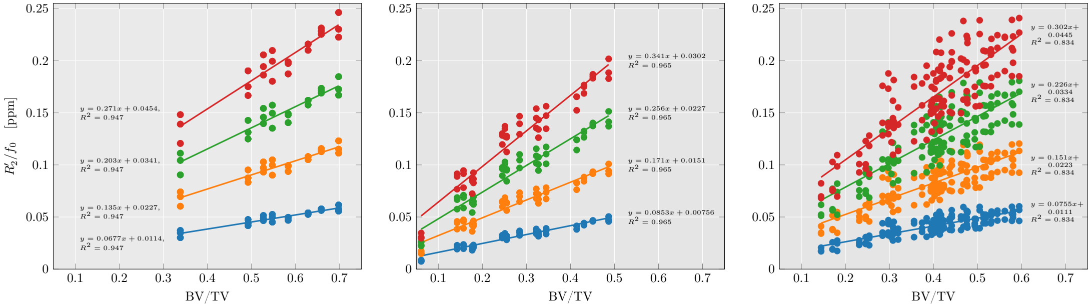




Results

Numerical Simulations

Femoral trabecular bone

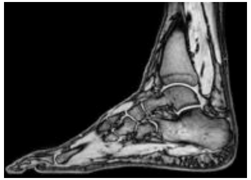


Methods

14 healthy volunteers + 2 patients

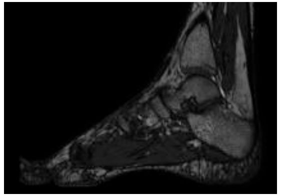
In vivo scans

Time-interleaved multi-gradient-echo sequence (TIMGRE)

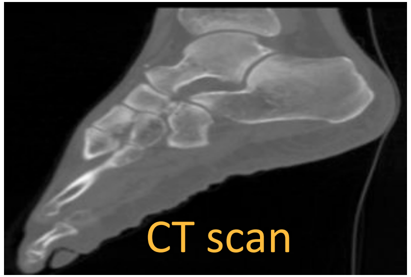


TIMGRE [10]	
Readout	Monopolar
Number of echoes	9 (3 interleaves à 3 echoes)
TE1/delta TE	1.7/0.9 ms
Voxel size	(1.5 x 1.5 x 1.5) mm^3
Flip angle	5°
Scan time	07:30.1 min:s
Bandwidth/pixel	1431.4 Hz

Balanced SSFP with 2 phase cycles



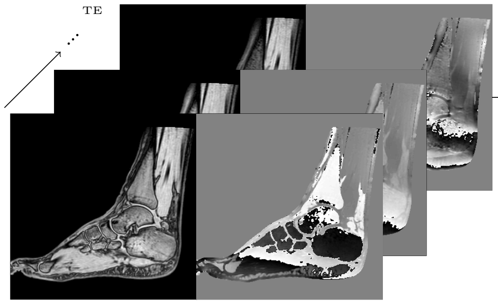
bSSFP	
TE	3.4 ms
Voxel size	(0.3 x 0.3 x 0.45) mm^3
Scan time	07:29.1 min:s
Bandwidth/pixel	233.9 Hz



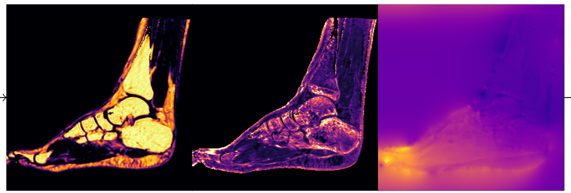
Methods

In vivo scans

Ruschke et al., MRM, 78(3), 984–996 (2016). doi: 10.1002/mrm.26485

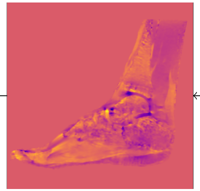


MR scan: TIMGRE sequence



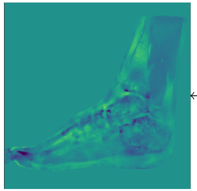
Field mapping: region-growing + IDEAL

Yu et al., MRM, 60(5), 1122–1134 (2008).
doi: 10.1002/mrm.21737;
Berglund et al., MRM, 63(6), 1659–1668 (2010).
doi: 10.1002/mrm.22385
Ren et al., J. Lipid Research, 49(9), 2055–2062 (2008).
doi: 10.1194/jlr.d800010-jlr200



Background field removal:
Laplacian boundary value method

Zhou et al., NMR Biomedicine, 27(3), 312–319 (2014). doi: 10.1002/nbm.3064

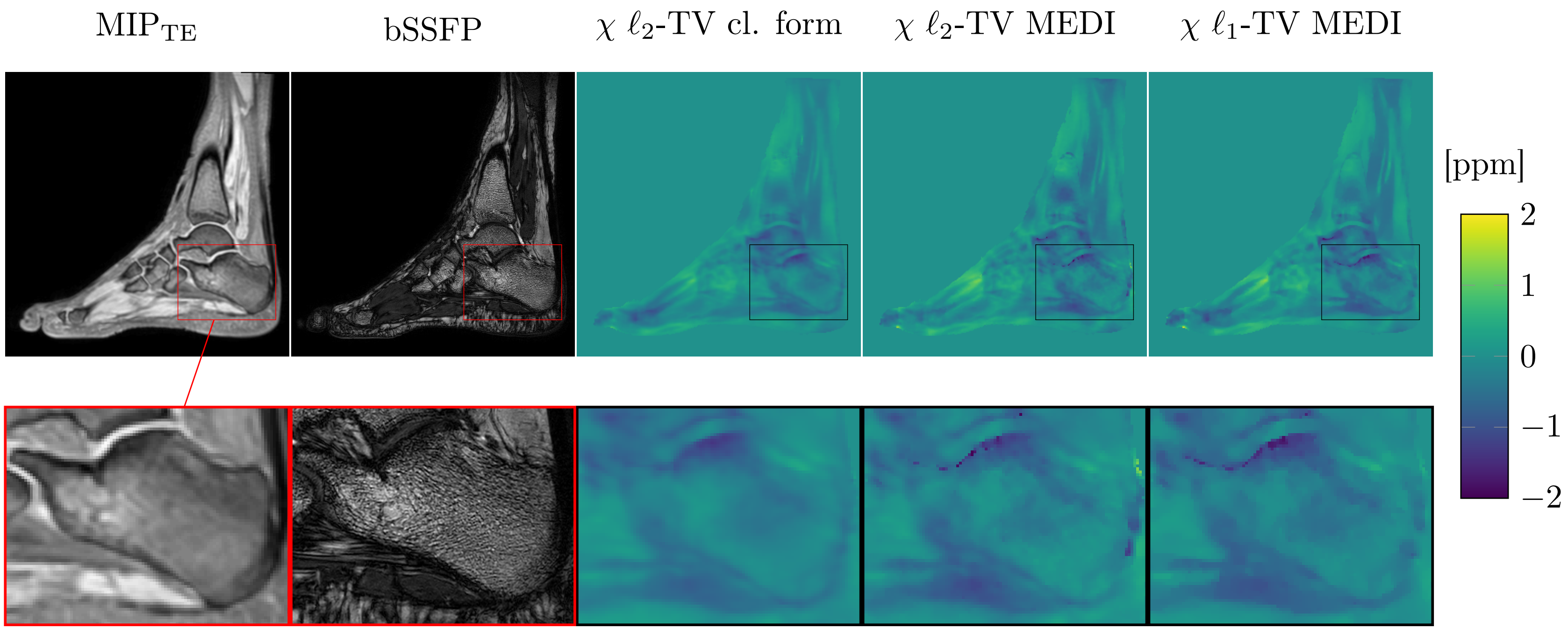


Dipole inversion:
(i) ℓ_2-TV closed-form solution, (ii) ℓ_2-TV morphology-enabled dipole inversion conjugate gradient solution, (iii) ℓ_1-TV morphology-enabled dipole inversion Nesterov's algorithm

Becker et al., SIAM J. Imaging Sci., 4(1), 1–39 (2011).
doi: /10.1137/090756855
Bilgic et al. JMRI, 40(1), 181–191 (2013).
doi: /10.1002/jmri.24365
Kressler et al., IEEE TMI, 29(2), 273–281 (2010).
doi: 10.1109/tmi.2009.2023787
Liu et al., IEEE TMI, 31(3), 816–824 (2012).
doi: 10.1109/tmi.2011.2182523

Results

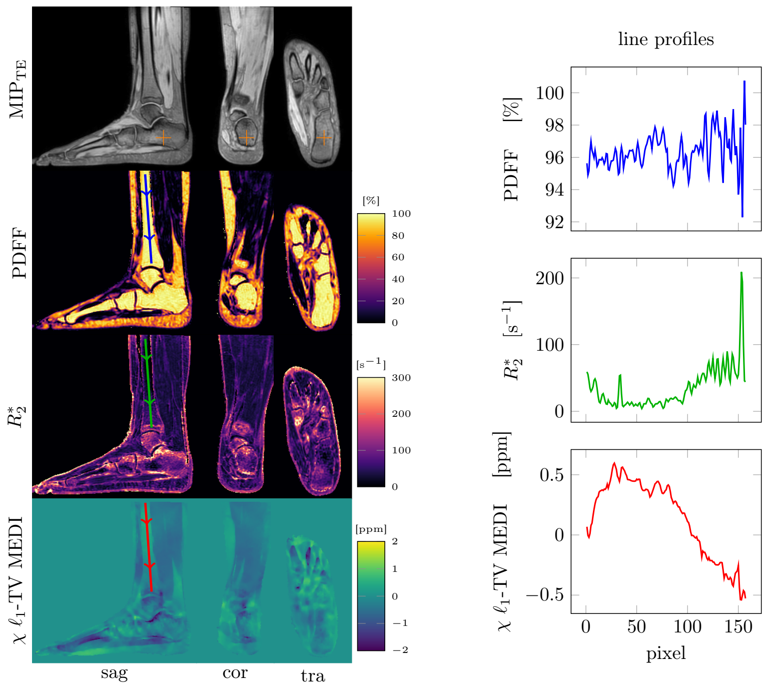
In vivo scans

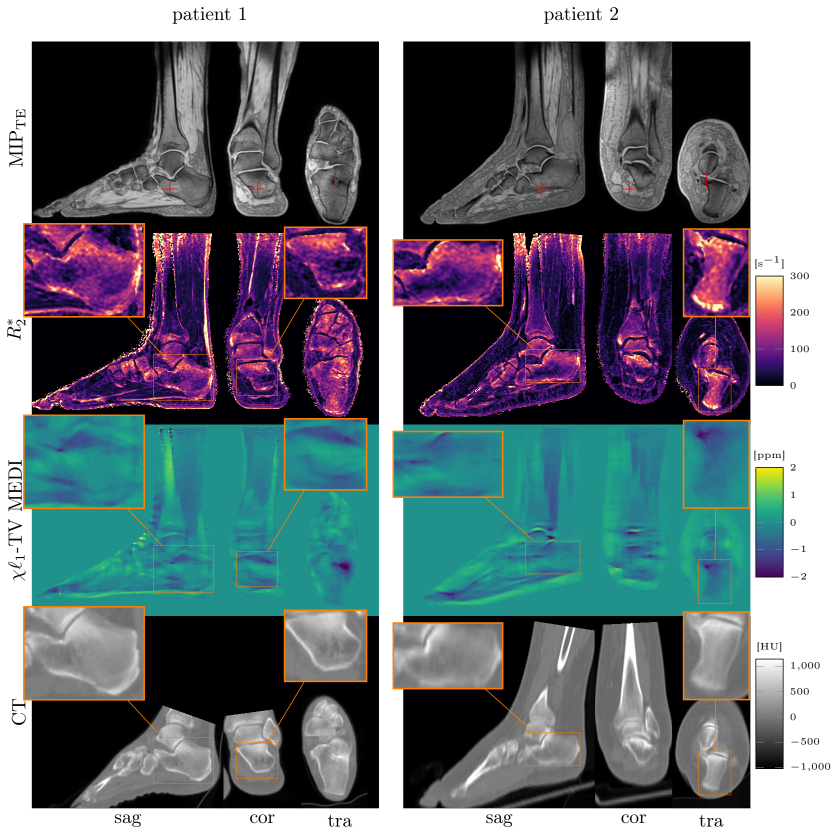


Diefenbach et al., ISMRM 2017, #850

Results

In vivo scans

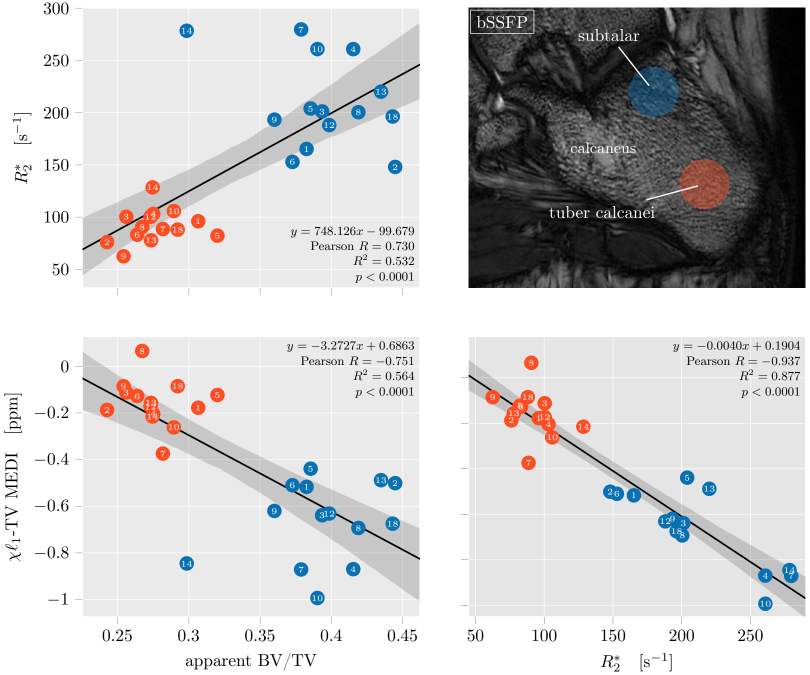




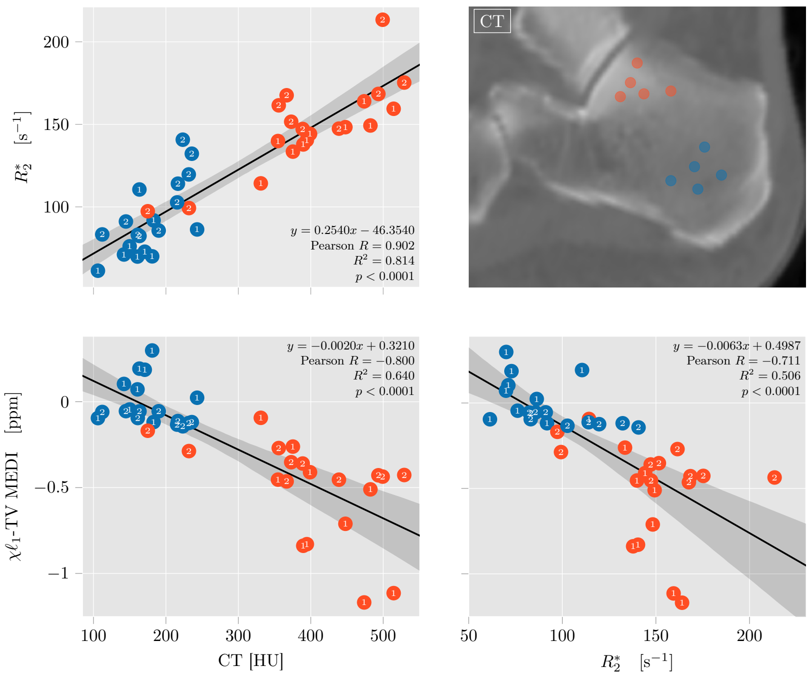
Results

In vivo scans

QSM – apparent BV/TV

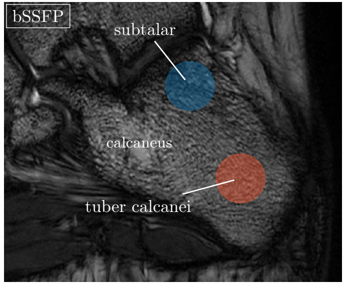


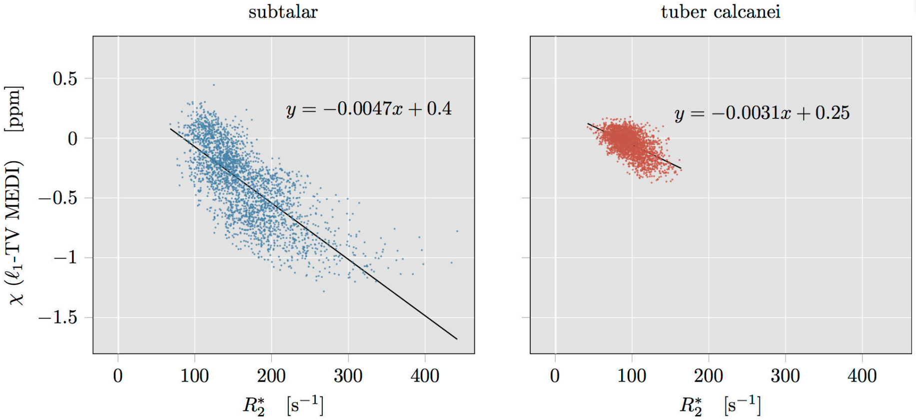
QSM – CT

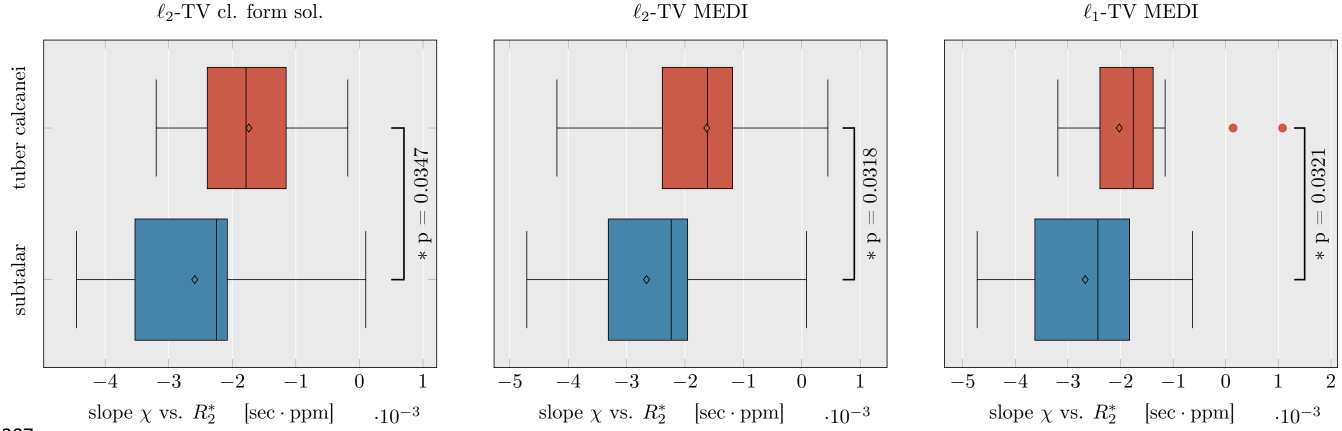


Results

In vivo scans

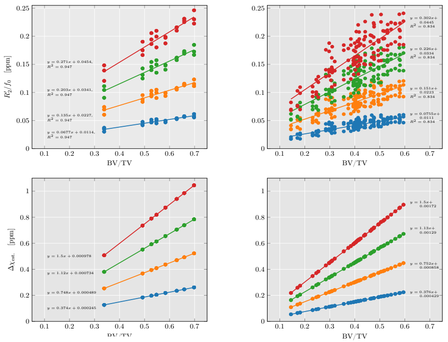






Taege et al., ISMRM 2017 #1207:
"Assessing the cellular distribution of iron in deep gray matter based on R2* and quantitative susceptibility mapping — application to healthy controls and patients with multiple sclerosis"

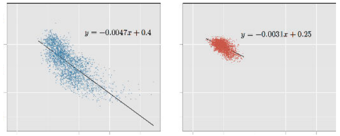
Discussion



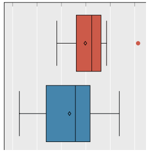
Theoretical advantage: QSM over R2’

Simulations show QSM more robust w.r.t.
voxel size (ratio inclusion size / ROI), B0 orientation,
anisotropic micro-stucture

Chi–R2’/R2* slope



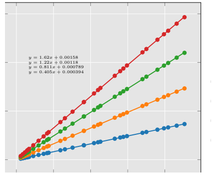
Simulations: chi–R2’ slopes differentiate microstructure orientation



In vivo: chi–R2’ slopes in subtalar and tuber calcanei ROIs confirm different slopes

True susceptibility of trabecular bone

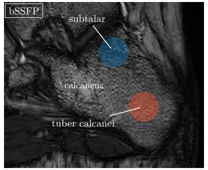
Broad range reported in literature.
Results indicate that susceptibility of trabeculae is closer to
values ~2 ppm and higher.



Discussion

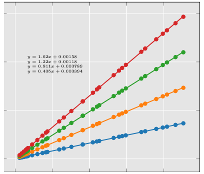
Limitations

- Difficulties in body QSM: signal voids, inter-subject referencing (lack of suited reference tissue)

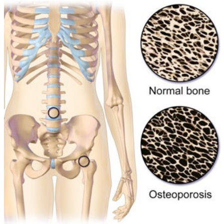


- Apparent BV/TV prone to trabecular thickening in gradient-echo images → overestimation

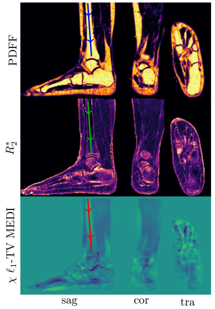
- Unknown true susceptibility →limited comparability of in vivo and simulation results



- Challenges for translation in major osteoporosis sites:
  more complex MR-signal evolution, breathing, background fields



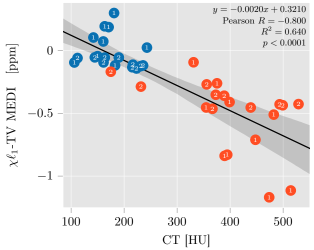
Discussion



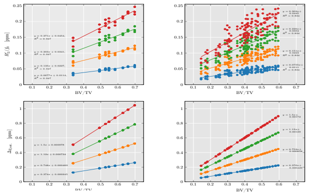
Summary

- The trabucular bone QSM pipeline results in **multi-parametric** quantitative maps

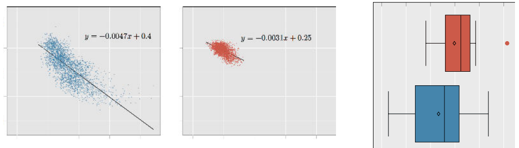
- QSM is **sensitive to trabecular bone density**!



- QSM appears to be **more robust** to measure trabecular density compared to R2* w.r.t. voxel size, field strength, B0 orientation, and anisotropic microstructures



- Combination of R2* and susceptibility can be used to extract **sub-voxel information about trabecular bone architecture**



Acknowledgements

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