UKD Universitätsklinikum Düsseldorf

hhu Heinrich Heine Universität Düsseldorf

Quantitative Susceptibility Mapping (QSM) of the kidney – Technical challenge and potential diagnostic value

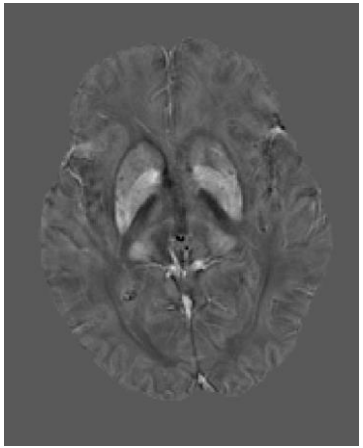
Eric Bechler
Department of Diagnostic and Interventional Radiology
University Hospital Düsseldorf, Germany
Eric.Bechler@med.uni-duesseldorf.de

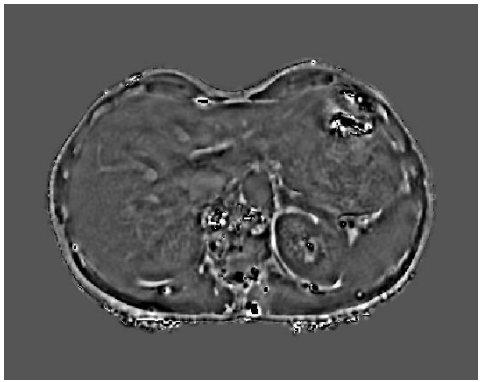
Disclosure

I have no actual or potential conflict of interest in relation to this presentation.

Motivation – Why Quantitative Susceptibility Mapping (QSM)?

- Quantitative Susceptibility Mapping (QSM) estimates the magnetic susceptibility of the underlying tissue
- Susceptibility χ is an intrinsic property of materials (including tissue) that determines how the material will behave in an external magnetic field
- Mostly applied in neuroimaging to examine iron uptake in brain nuclei for various diseases[1,2]
- Potentially useful tool to study and evaluate diseases in the kidney
  - Inflammation and fibrosis in the kidney[3]
  - Structural changes of the kidney[3]





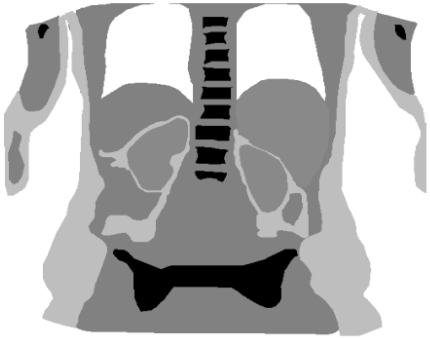
1. Li DTH. et al., *NeuroImage Clin.*, 2018
2. Zivadinov R. et al., *Radiology,* 2018
3. Xie L. et al., *Am. J. Physiol. Renal Physiol.,* 2013

From susceptibility to MRI phase – forward model

susceptibility distribution χ(r)

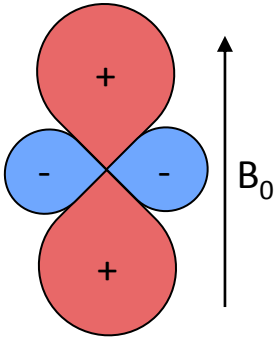
Modified from Bechler E. et al. MRM 2019

inverse problem

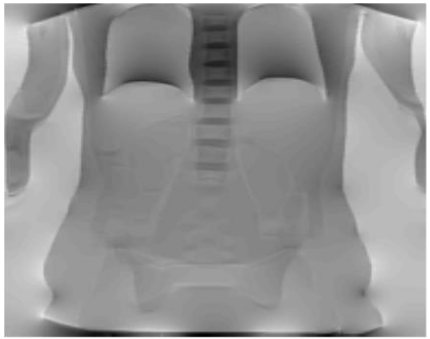


⊗

dipole field d(r)

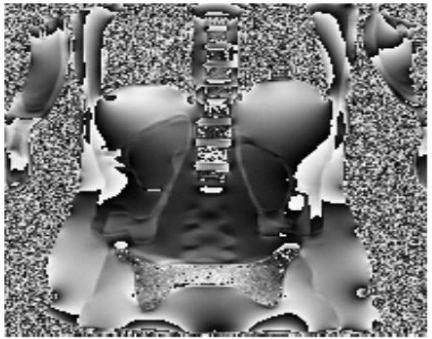


field perturbation ΔB(r)



$$\Delta B(r) = B_0 \times [\chi(r) \otimes d(r)]$$

MRI phase image Δφ



$$\Delta\varphi(r) = \gamma \times TE \times \Delta B(r)$$

$$\Delta\varphi(r) = \gamma \times TE \times B_0 \times [\chi(r) \otimes d(r)]$$

How do we measure susceptibility with MRI

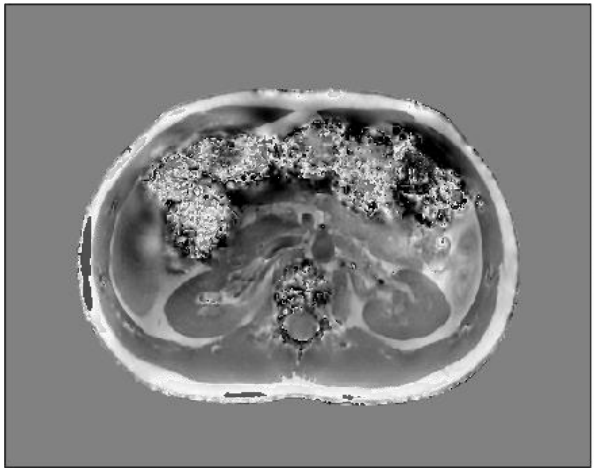
- Gradient Echo (GRE) – Phase data (2D/3D, single- or multi-echo)

- **Phase unwrapping** to eliminate cyclic nature of the phase

- Remove contributions to magnetic field perturbations from outside the ROI (**Background field removal**)

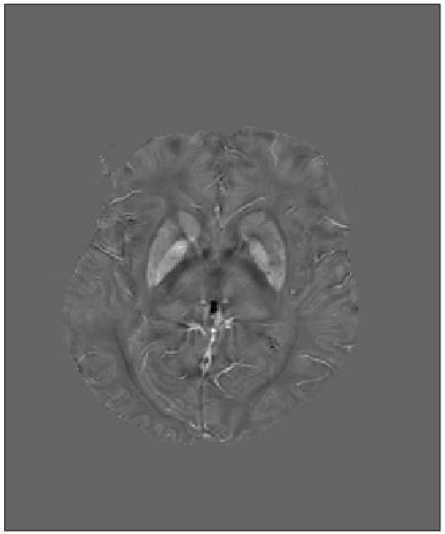
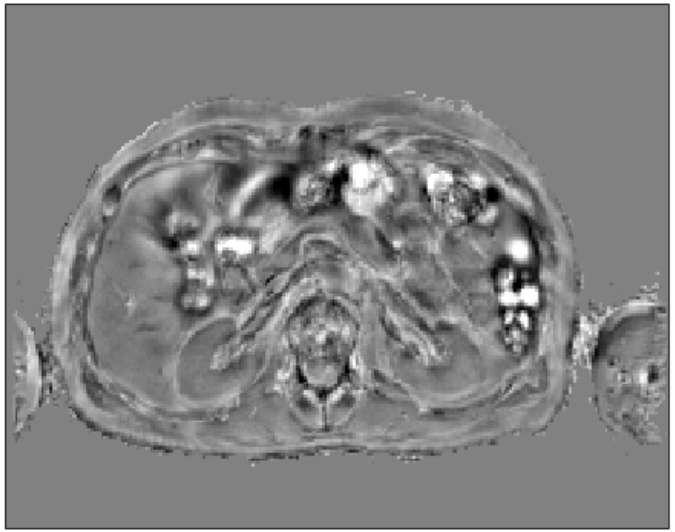
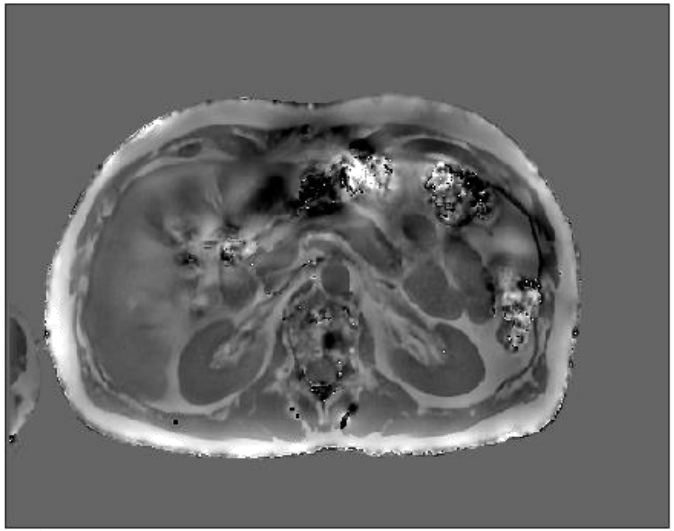
- **Solve the ill-posed inverse problem** to generate the susceptibility map

$$\chi(\mathrm{r}) = \mathrm{FT}^{-1}[\mathrm{FT}\left(\frac{\Delta\varphi(r)}{\gamma \times B_0 \times TE}\right) \times \left(\frac{1}{D(k)}\right)]$$



Algorithms and Software

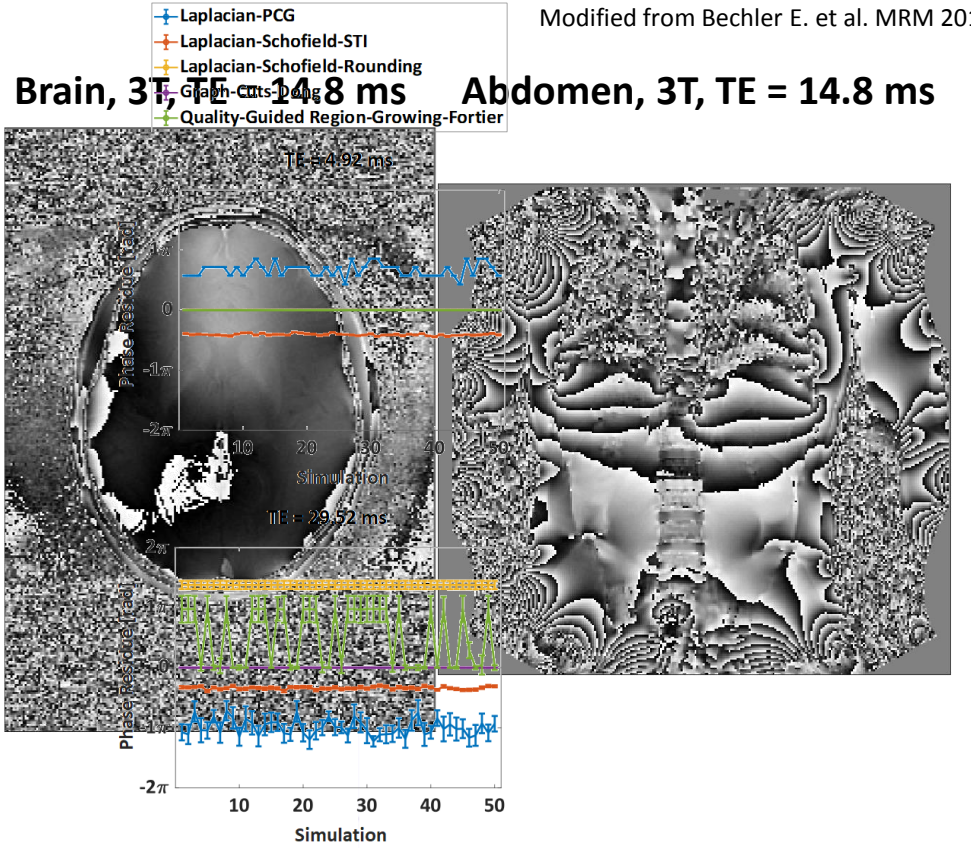
- There is a variety of algorithms and software to calculate the susceptibility maps
  - STI Suite (https://people.eecs.berkeley.edu/~chunlei.liu/software.html)
  - MEDI Toolbox (http://pre.weill.cornell.edu/mri/pages/qsm.html)
- But all of them are optimized for brain imaging

Technical challenges – Phase unwrapping

- Increased amount of phase wraps in the abdomen due to air and fat
- Not every phase unwrapping algorithm is able to deal with the increased amount of wraps
- Recent simulations suggest that algorithms based on the **graph-cuts** method should be preferred

Modified from Bechler E. et al. MRM 2019

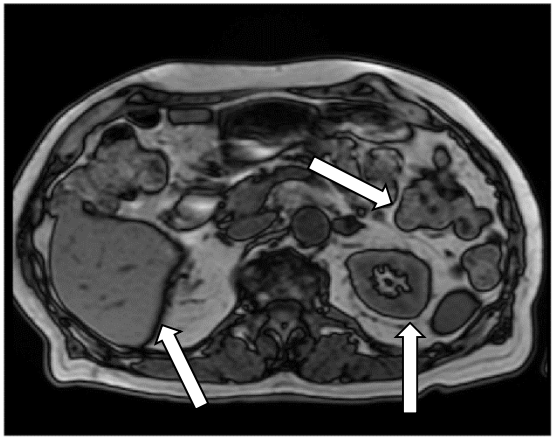


Technical challenges – chemical shift of fat

- Chemical shift caused by fatty tissue affects the phase signal and further the QSM quantification

➔ Chemical shift effects have to be removed before accurate susceptibility maps can be calculated

- Two options:
  - Measure data in-phase (TE_1 = 2.2 ms, TE_2 = 4.4 ms etc. for 3T)
  - Use SPURS[4] to simultaneously unwrap the data and remove the chemical shift effect (graph-cuts based method, needs at least 3 echoes)



4. Dong J. et al., *IEEE Trans. Med. Imaging,* 2015

Technical challenges – background field removal

- Large changes in susceptibility (compared to the brain):
  - Fat ~ 0.85 ppm
  - Bones ~ -2.5 ppm
  - Lungs (air) ~ 9.4 ppm
  - Water (soft tissue) ~ 0 ppm

- So far no algorithm was able to restore the correct values

➔ It still remains an open question for QSM with large changes in susceptibility

IPR-QSM after background phase removal only	Cubic dipole outside phantom	Air around phantom
PDF	7.9 ± 1.8	6.4 ± 2.0
LBV	7.8 ± 1.6	6.8 ± 2.0
V-SHARP	4.8 ± 2.6	4.7 ± 3.5

Fortier V. et al. MRM 2017

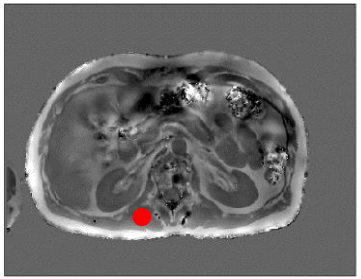
	Liver (ppm)	Kidney (ppm)	Fat (ppm)
True reference	0.23	0.23	0.85
V-SHARP-based reference	0.0 ± 0.01	−0.02 ± 0.01	0.25 ± 0.03
LBV-based reference	0.17 ± 0.00	0.06 ± 0.02	0.65 ± 0.10

Bechler E. et al. MRM 2019

Technical challenges – Susceptibility reference

- **When comparing susceptibility values it is important to specify the reference**

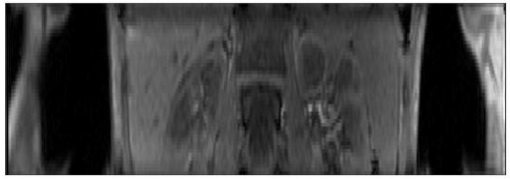
- Reference tissue should have a homogenous susceptibility and not be affected by the studied disease
  - Paravertebral muscle tissue
  - Urea in the bladder (if not effected by the disease)



- STAR-QSM (STI-Suite) automatically references to the mean susceptibility
  - Results heavily depend on the amount of fat and air
  - You can still use STAR-QSM, but you **need** to reference to something else afterwards

Technical challenges – breath-hold (1)

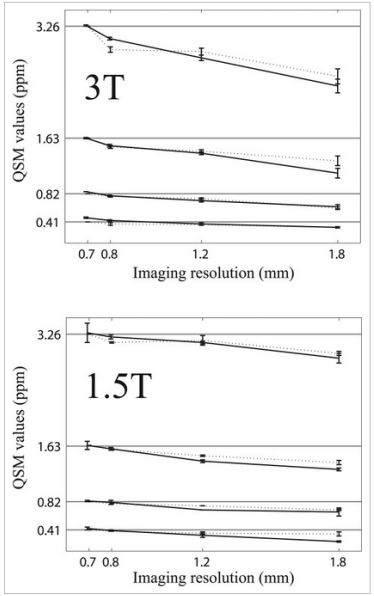
- QSM of the kidneys is heavily limited by respiratory motions



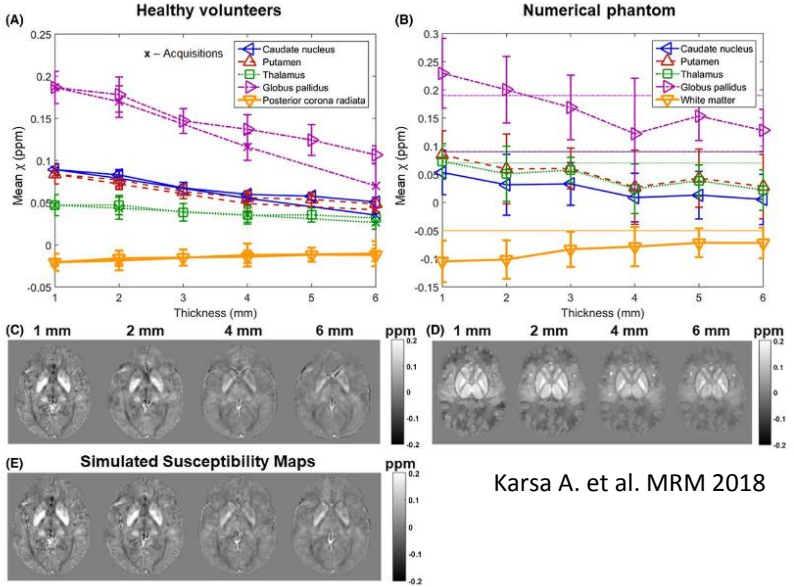
- Multiple echoes have to be acquired in one breath-hold (20-30s)

➔ Limited resolution

➔ Underestimated Susceptibility



Zhou D. et al. MRM 2016



Karsa A. et al. MRM 2018

Technical challenges – breath-hold (2)

- Respiratory gating
  - Often only single echo acquisitions possible
  - Extends measuring time
  - Coregistration needed
- Interleaved acquisition (between breath-holds)
  - Possible shifts between slices
- Acquire multiple single-echo scans
  - Coregistration needed
  - Extends measuring time
  - Higher TEs still require long breath-holds

https://www.redbull.com/us-en/freediver-heart-rate-37-bpm-video

In summary

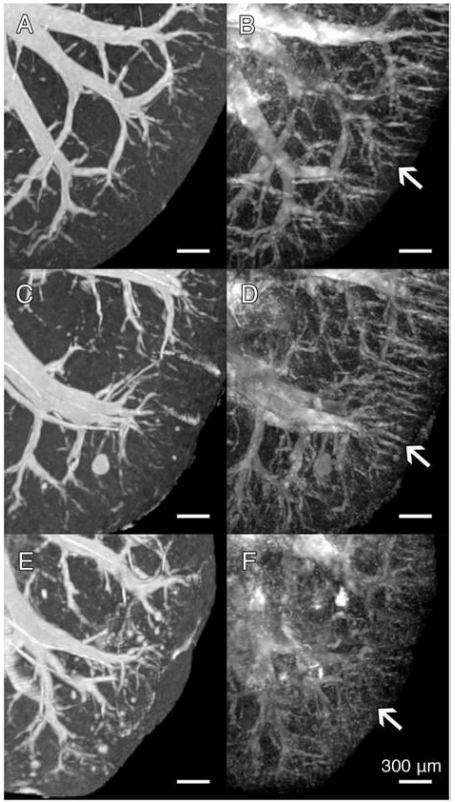
- Relevant aspects of QSM post-processing:
  - Use a graph-cuts based unwrapping (e.g. SPURS)
  - Minimize the influence of the chemical shift of fat
  - Use one of the more robust background field removal techniques (e.g. LBV)
    - open ended question, no ‘perfect‘ algorithm
  - Reference your susceptibility to make it comparable

- Relevant aspects of QSM data acquisitions:
  - Respiratory motions ➔ low image resolution ➔ underestimated susceptibility
    - No promising solutions yet

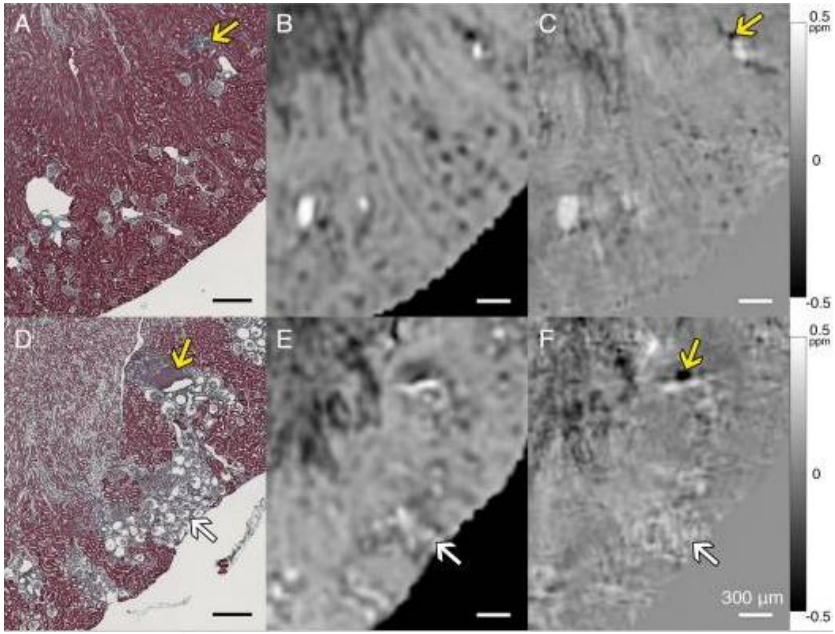
- Why should we still try to measure QSM of the kidney?

Diagnostic value (1)

- QSM can be used to detect fibrosis
- Well defined structures and vessels in the outer cortical region
- Ex vivo study with high resolution (9.4 T system)



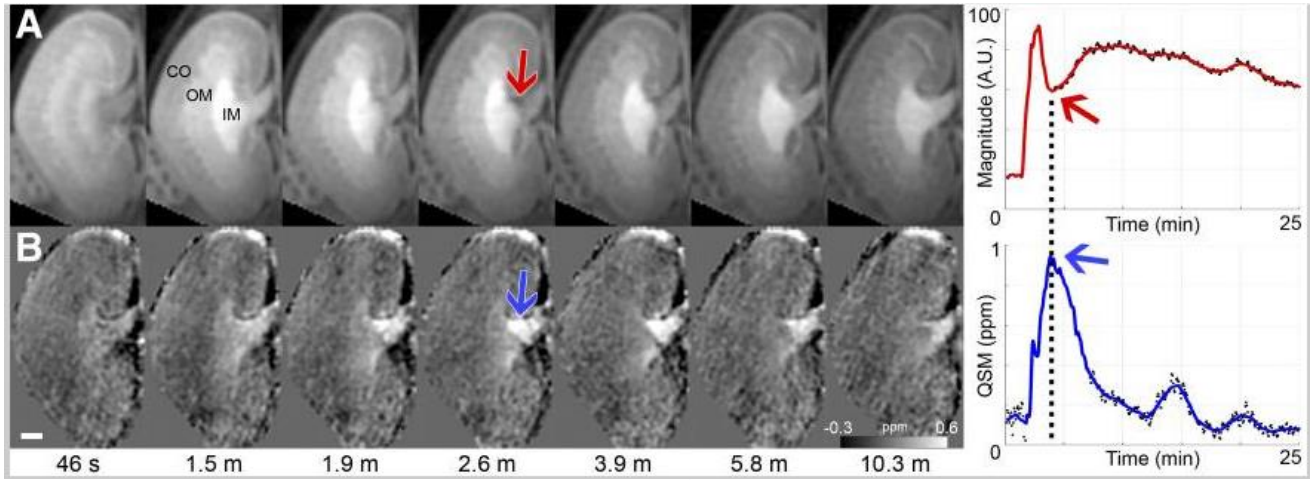
Xie L. et al. NMR Biomed. 2013



Diagnostic value (2)

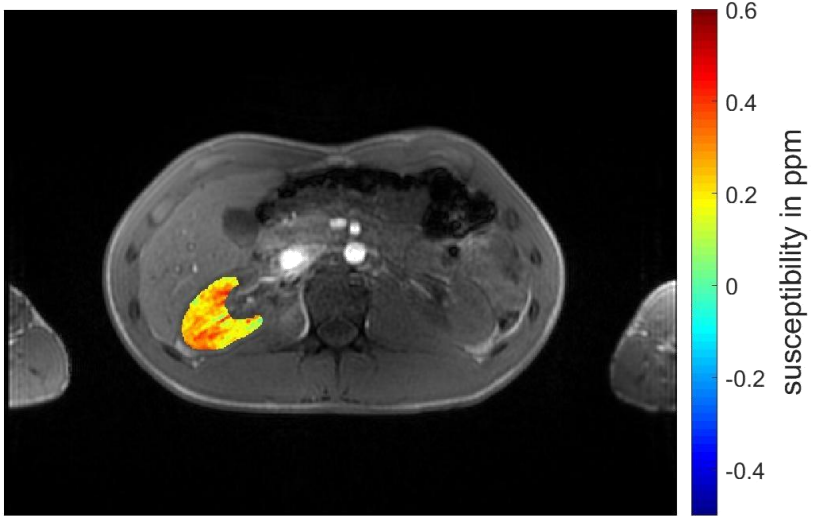
- Dynamic contrast - enhanced QSM
- QSM can overcome the T2* blooming effect
- Gd concentration from the renal artery to the inner medulla quantifiable
- In vivo study

Xie L. et al. NMR Biomed. 2016

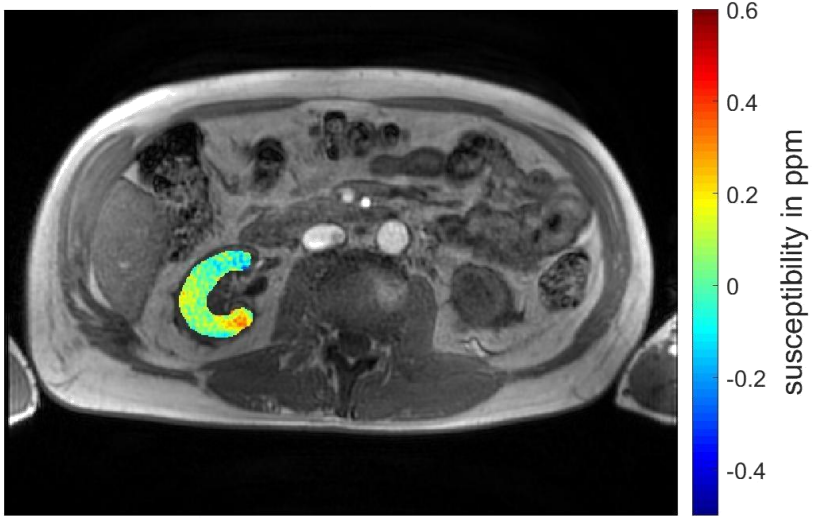


Diagnostic value (3)

Healthy control



Patient with kidney failure (GFR = 23)



Thank you very much for your attention!