Study and development of advanced quantitative Magnetic Resonance Imaging techniques for subvoxel quantification

Candidate: Matteo Cencini

Supervisor: Prof. Michela Tosetti

Pre-thesis discussion

Pisa, 22/10/2018

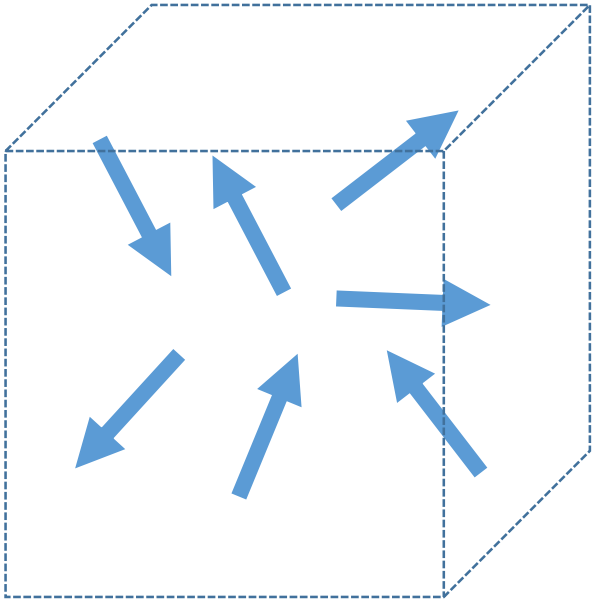
Magnetic Resonance Imaging

Versatile imaging technique based on the interaction of nuclear spins within the human body with magnetic fields

- ✓ It is non invasive! (non-ionizing radiation)
- − Still qualitative, quantitative imaging is not routinely used in clinic
- − Most quantitative techniques assume one tissue per voxel

How does it work?

Spin $\boldsymbol{J} \neq 0 \Rightarrow \boldsymbol{\mu} = \gamma \boldsymbol{J}$



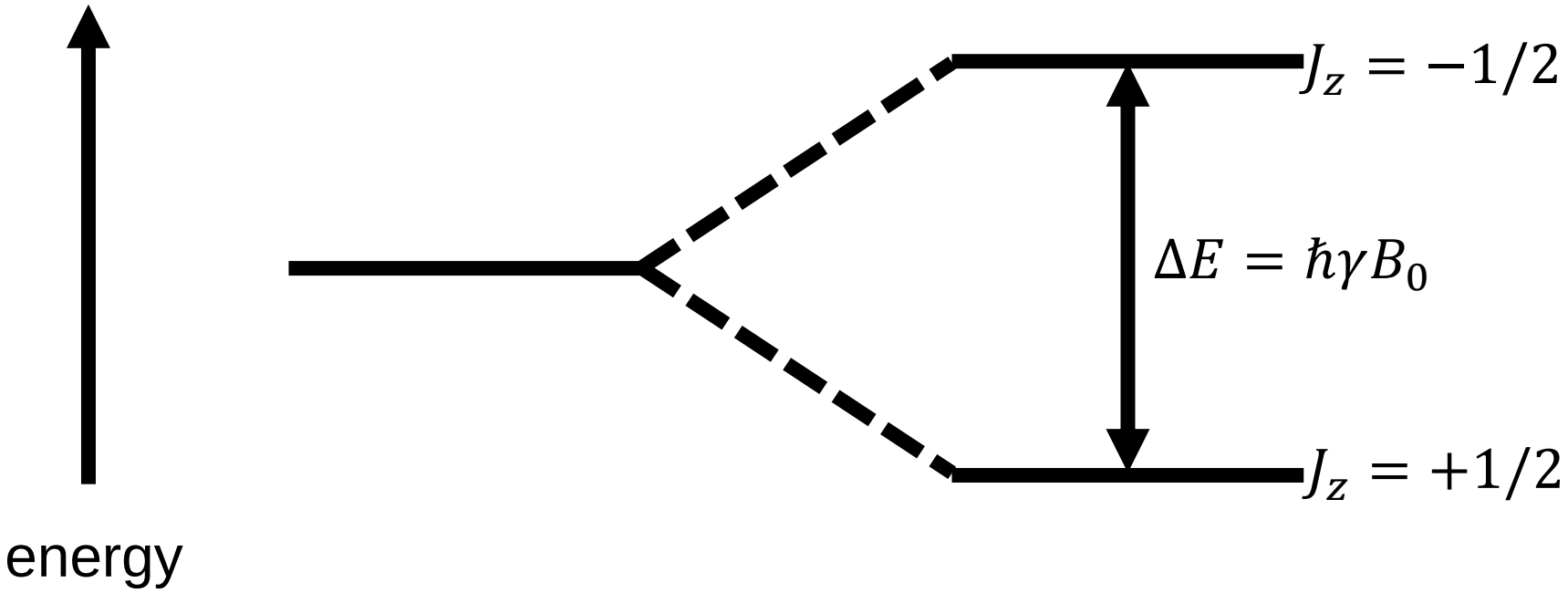
Spin ensemble

$$\sum_{i} \boldsymbol{\mu_i} = 0$$

How does it work?

$J = 1/2$

$\frac{N_{+1/2}}{N_{-1/2}} = \exp(-\frac{\Delta E}{kT})$ Boltzmann distribution



Zeeman Effect

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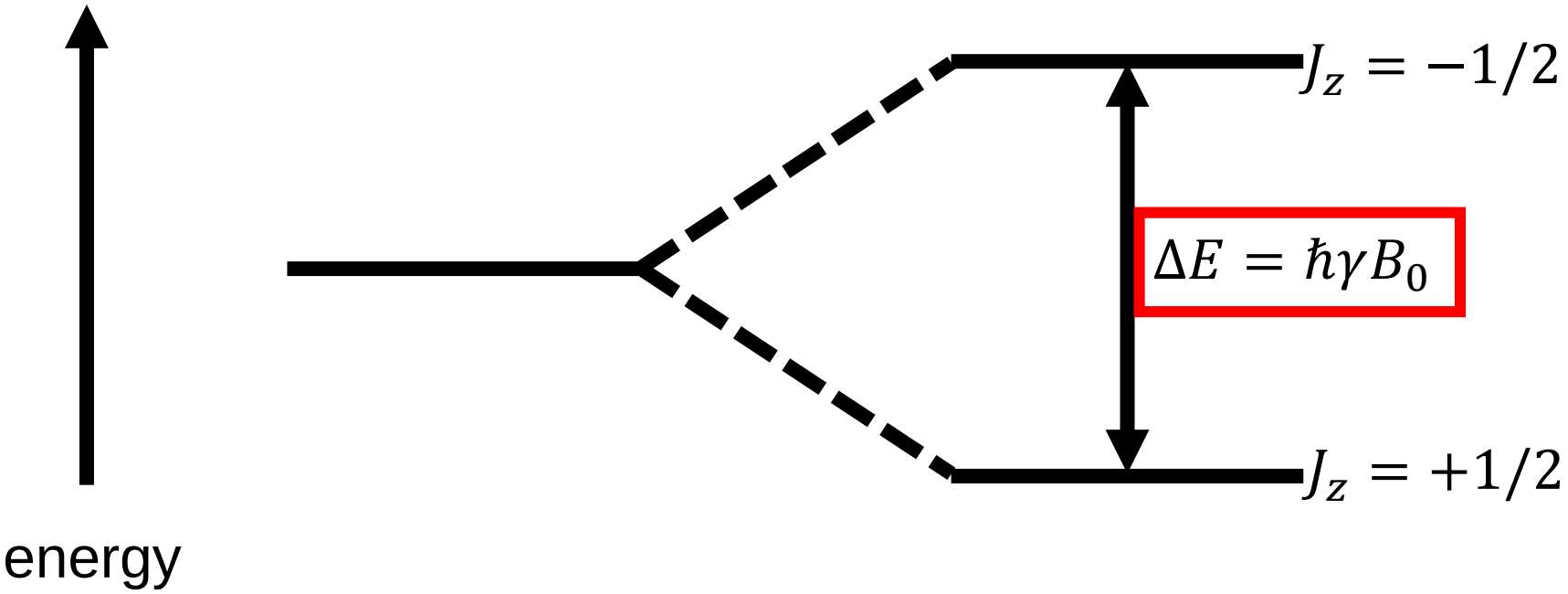
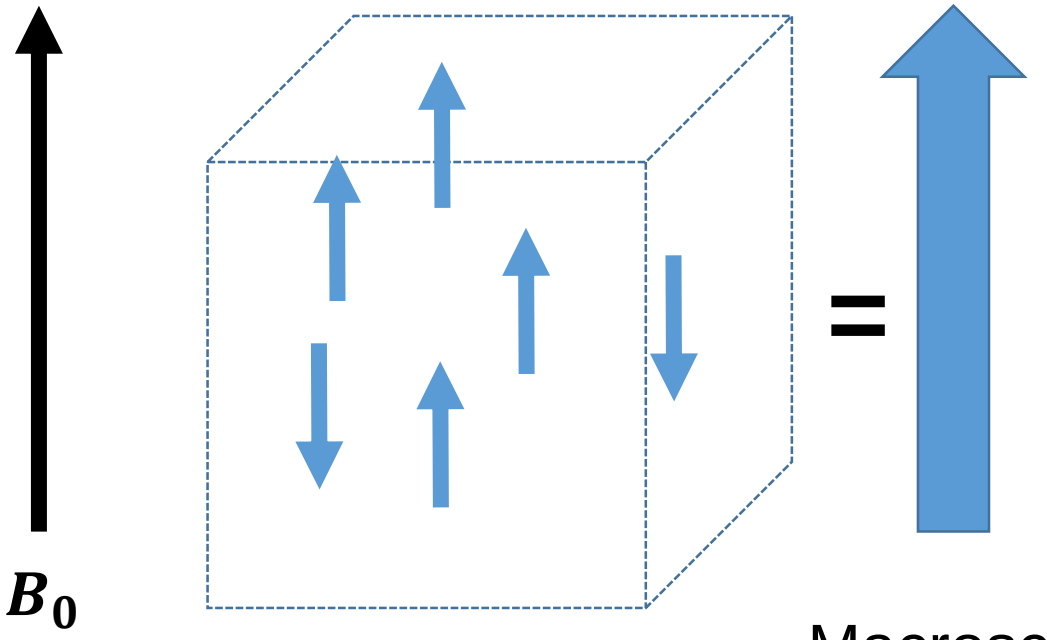


Zeeman Effect

How does it work?

Precess around B0 with frequency
$\omega_0 = \gamma B_0$ (Larmor Frequency)



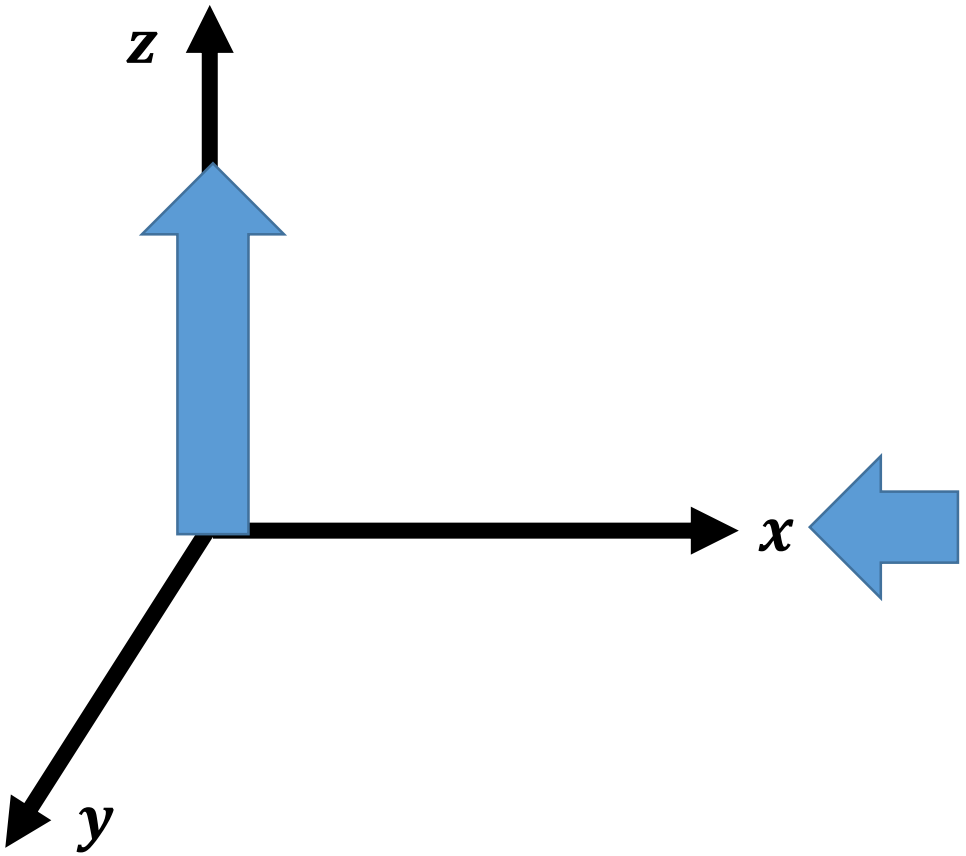
$$\sum_i \boldsymbol{\mu_i} = \boldsymbol{m_0}$$

Spin ensemble

Macroscopic magnetization

How does it work?

$$\boldsymbol{B_0} = \mathrm{B}_0\hat{\boldsymbol{z}}$$



$\boldsymbol{B_1}(t)$ radiofrequency field pulse

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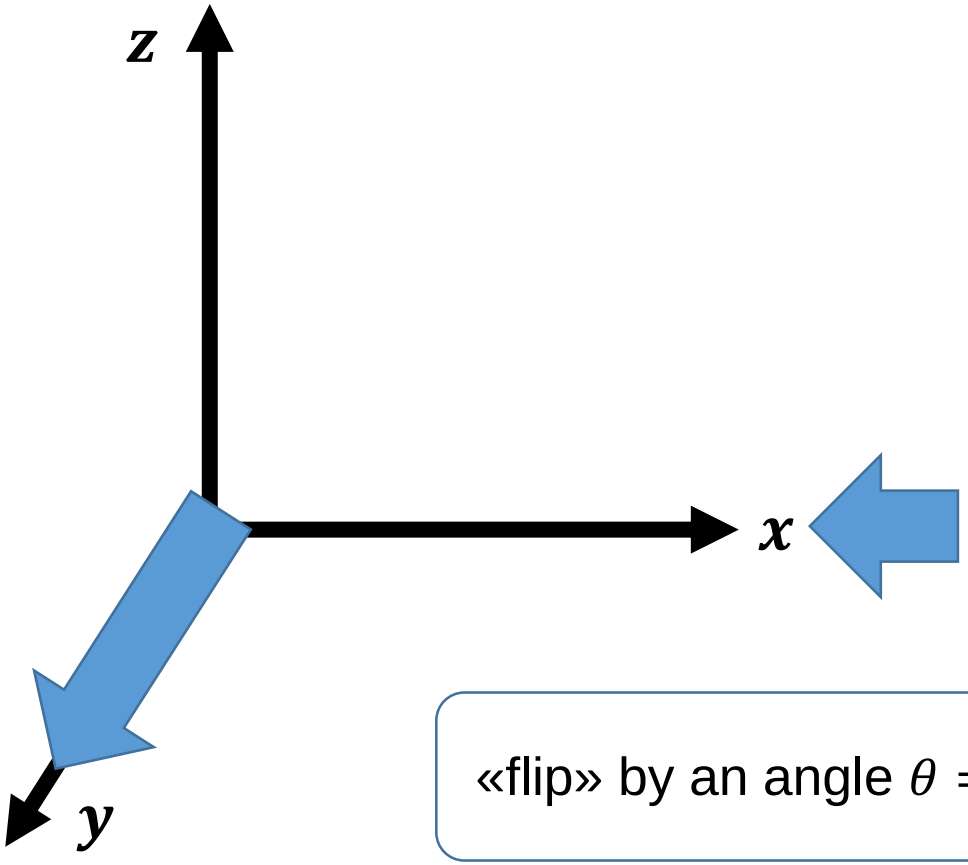

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«flip» by an angle $\theta = \gamma \int_0^\tau B_1(t)dt$ (flip angle)

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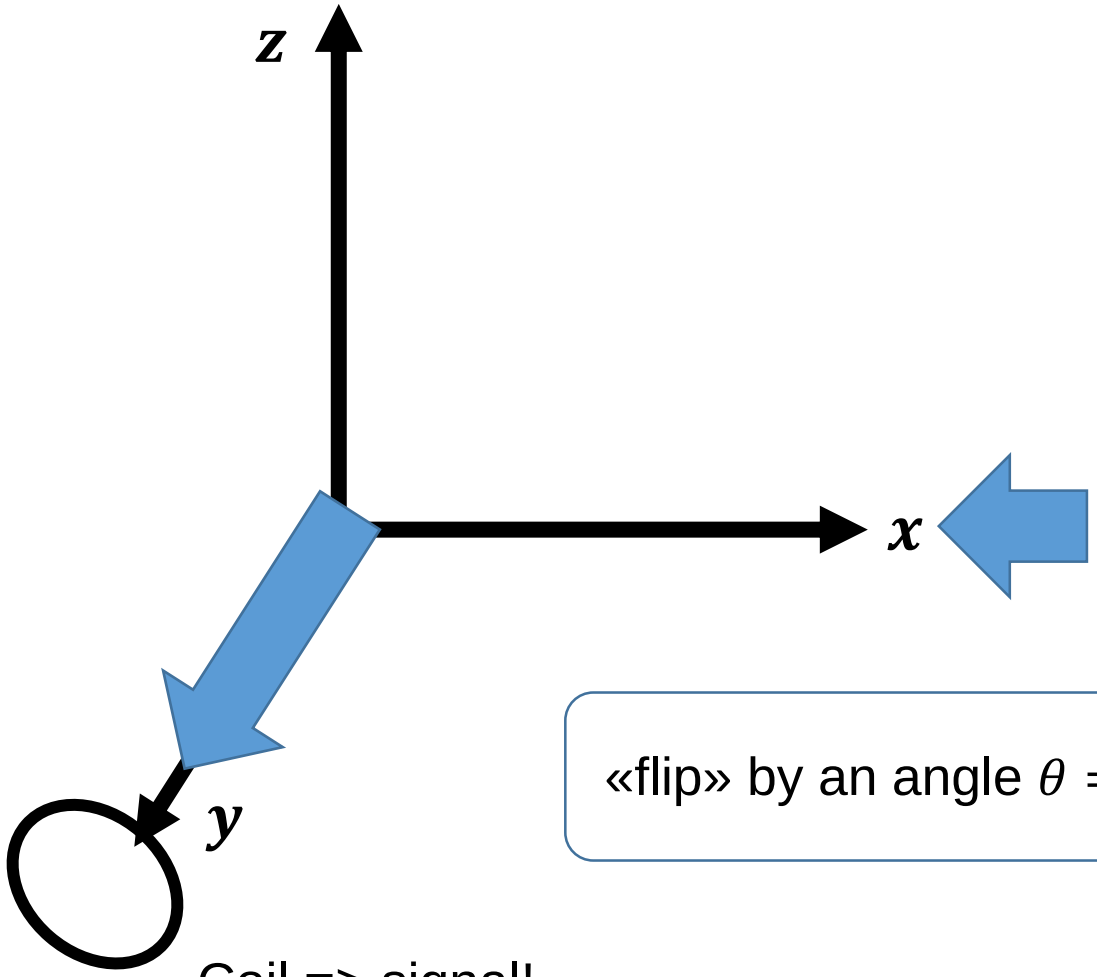

$\boldsymbol{B_1}(t)$ radiofrequency field pulse

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Coil => signal!

Why not quantitative?

After excitation: relaxation!

- **Spin-lattice relaxation:** exchange of energy with the environment
- **Spin-spin relaxation:** dephasing of the spins on transverse plane (no energy loss)

Bloch Equation

$$\frac{\partial \boldsymbol{m}}{\partial t} = \gamma \boldsymbol{m} \times \boldsymbol{B_0} + \frac{1}{T_1}(m_0 - m_z)\hat{z} + \frac{1}{T_2}\boldsymbol{m}_\perp$$

- **T1**: spin-lattice relaxation time
- **T2**: spin-spin relaxation time

$$s = s(t; T1, T2, B, \dots)$$

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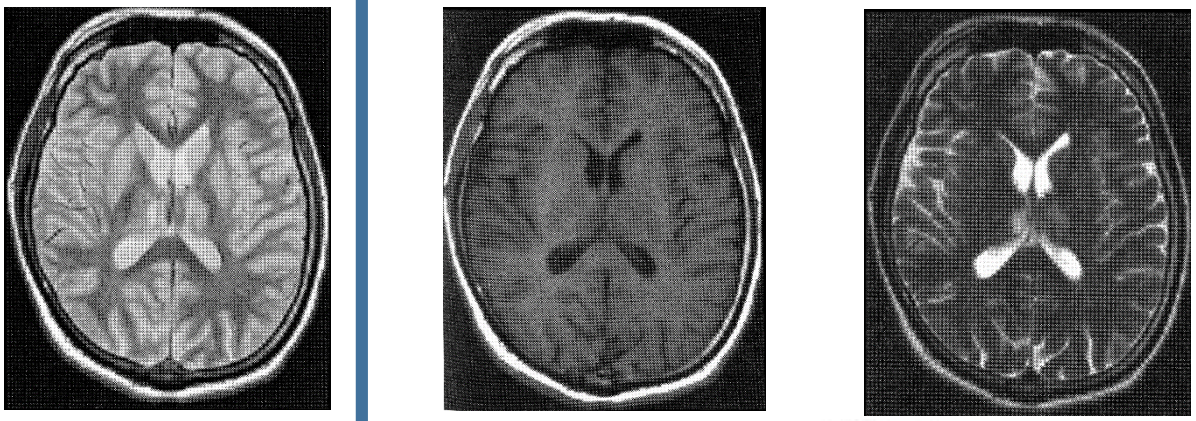
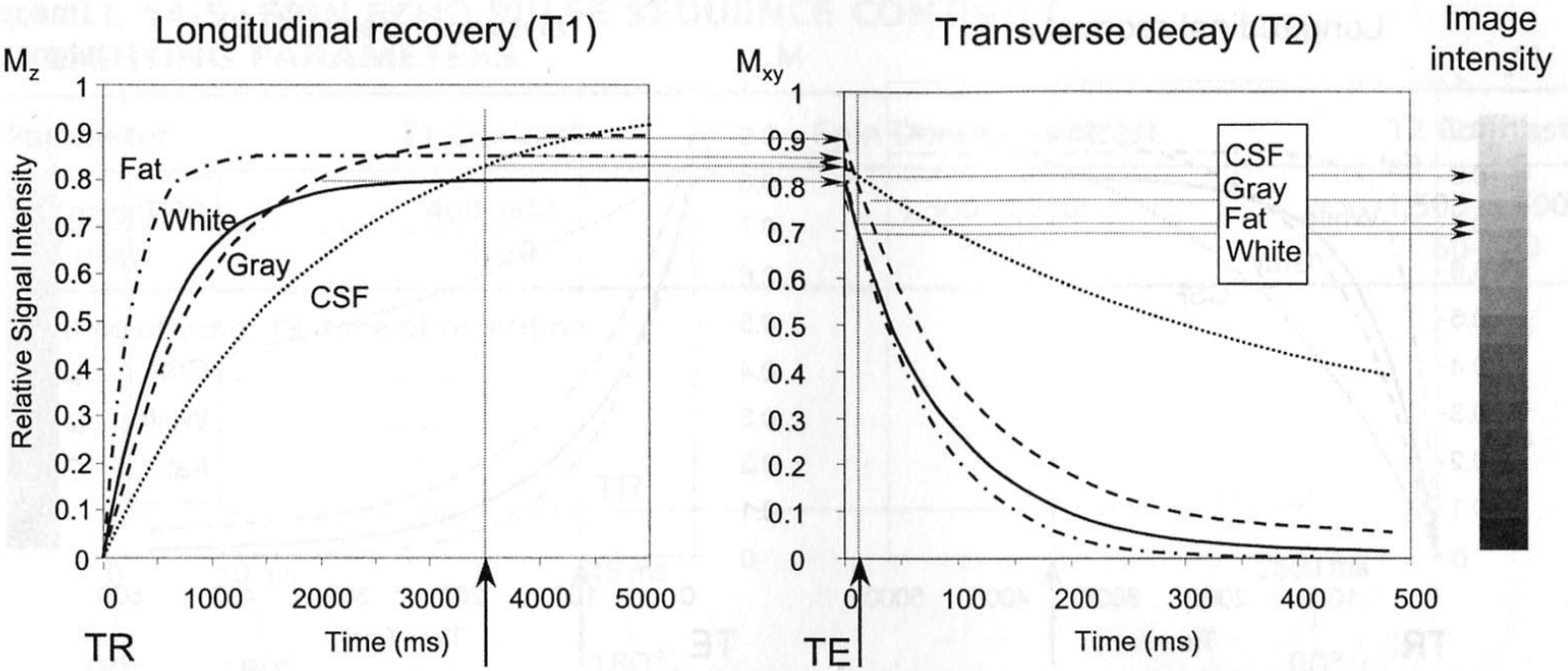


TR: repetition time

TE: echo time



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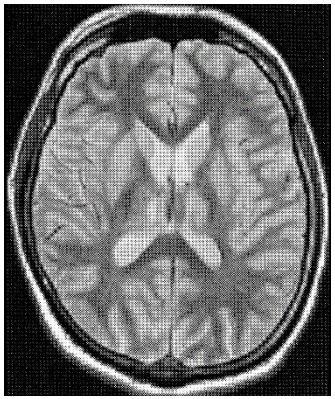

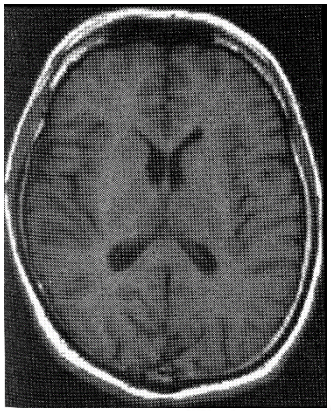

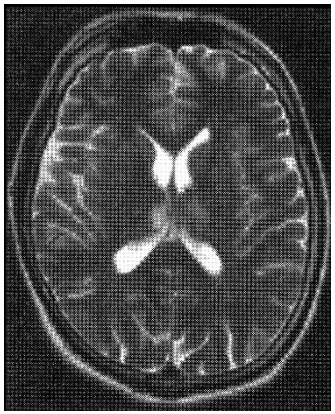

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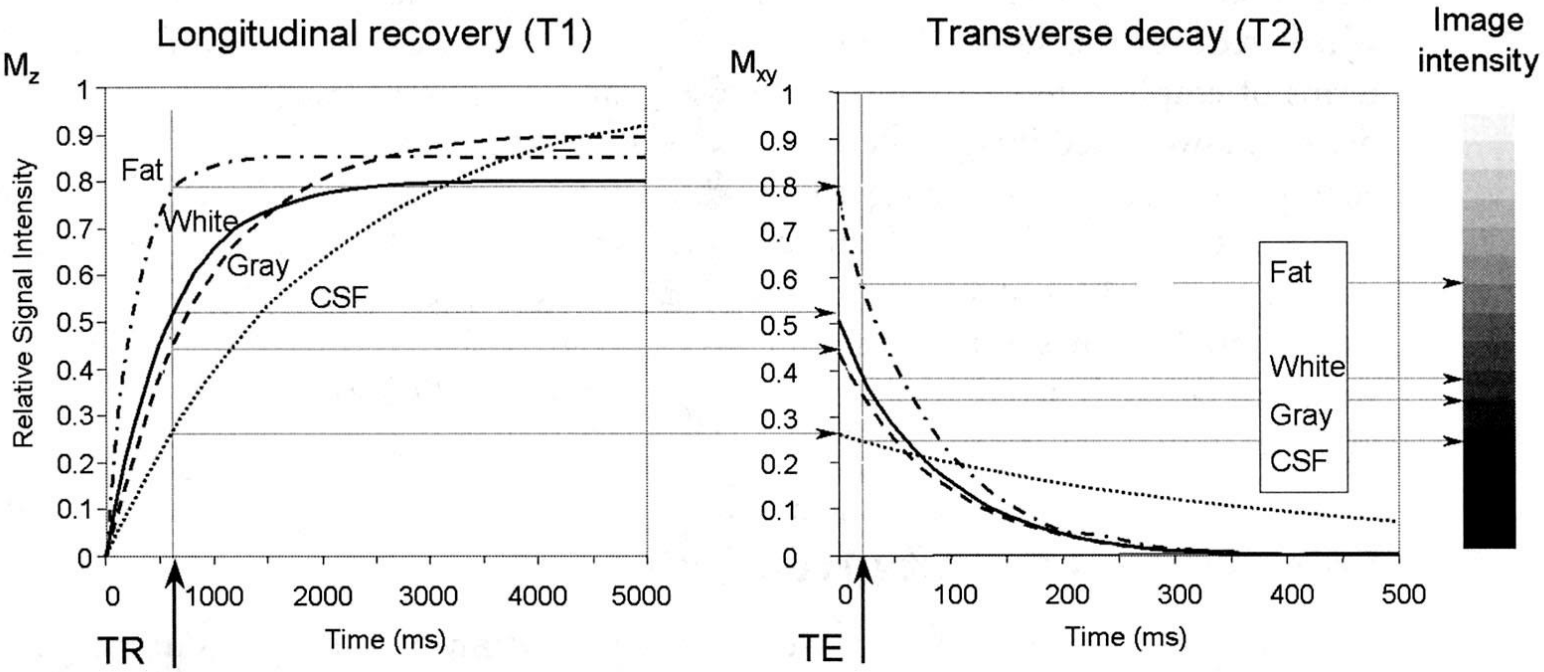

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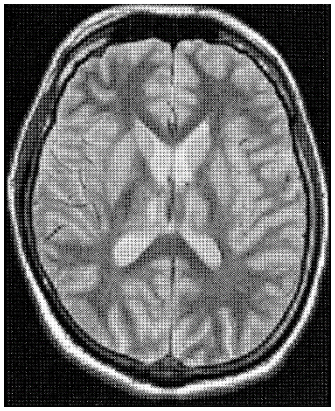

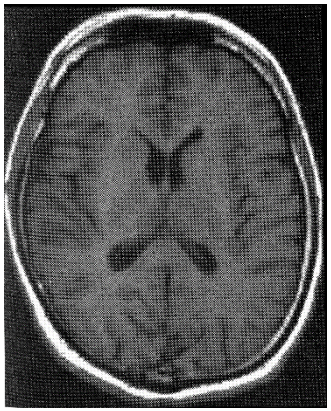

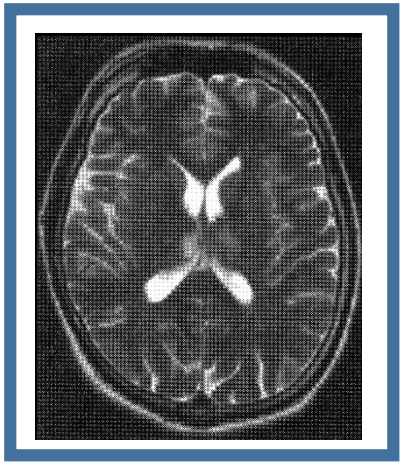

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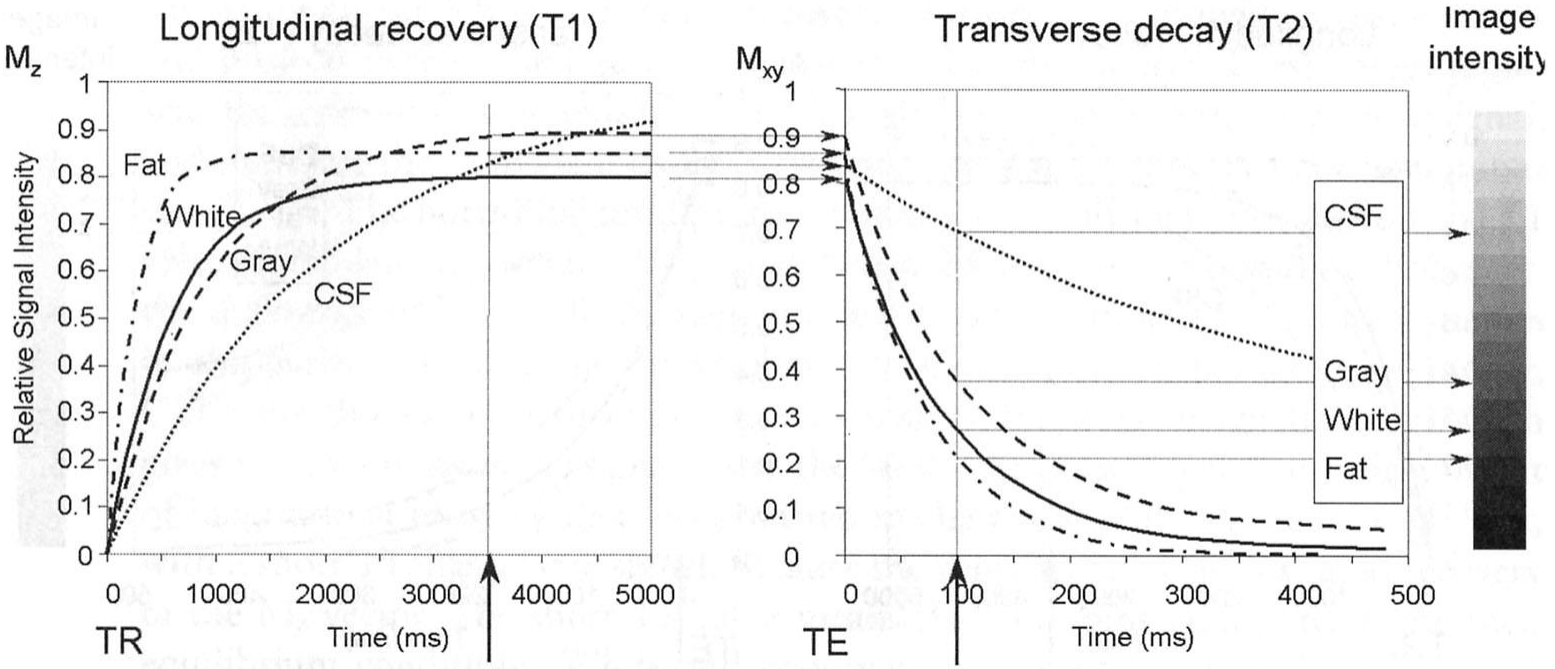
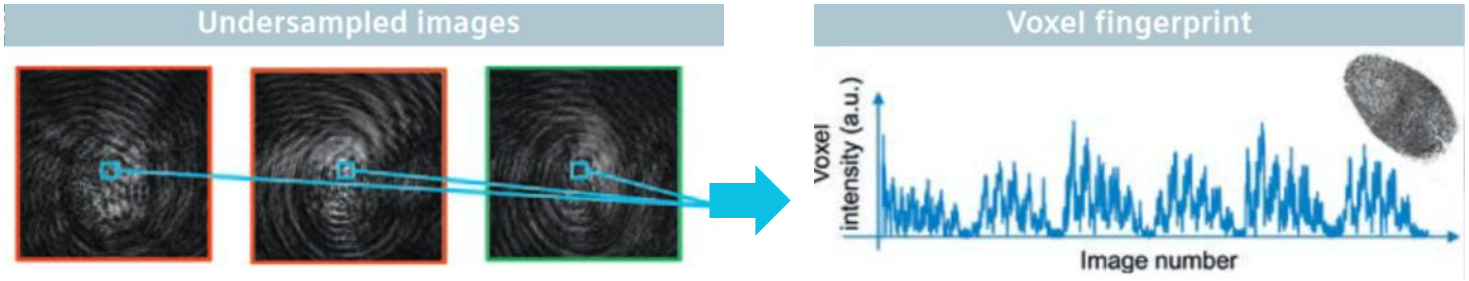


Magnetic Resonance Fingerprinting (D Ma *et al. Nature*, 2013)



Coppo et al. (2016)

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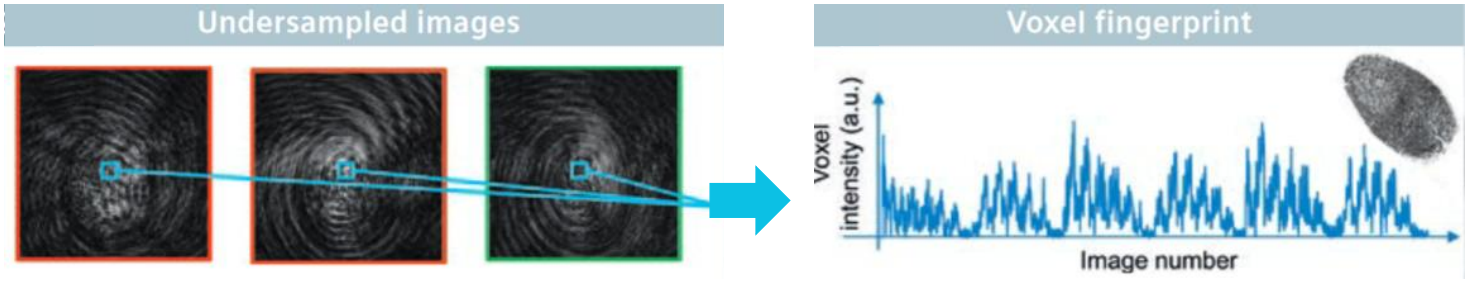

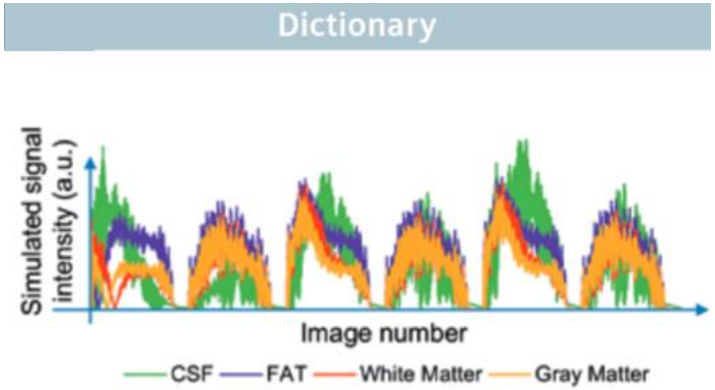

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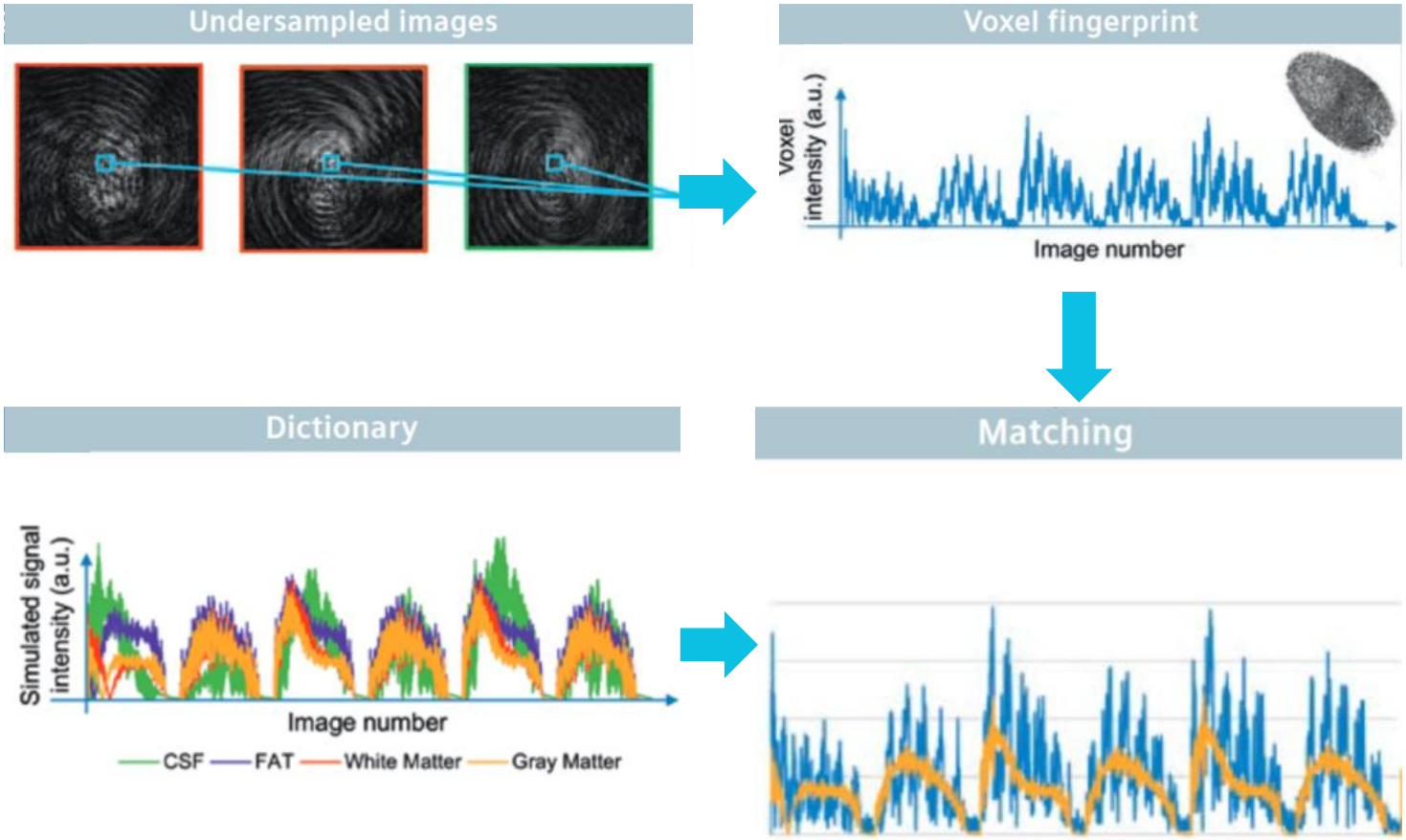

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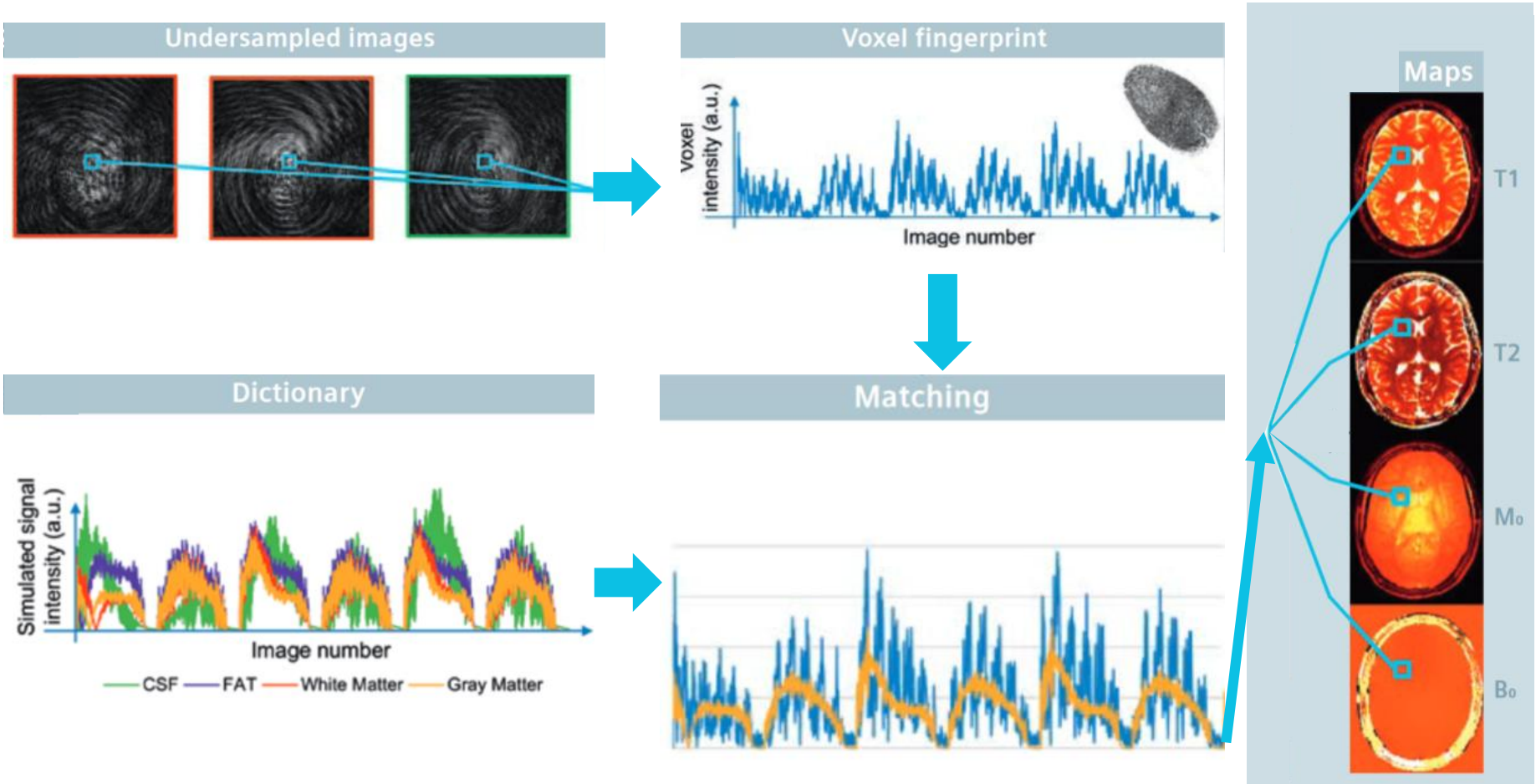

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Magnetic Resonance Fingerprinting: matching

For each acquired signal $\hat{x}$:

1. Find $\max|D' \cdot \hat{x}^T|$

D' = normalized dictionary

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For each acquired signal $\hat{x}$:

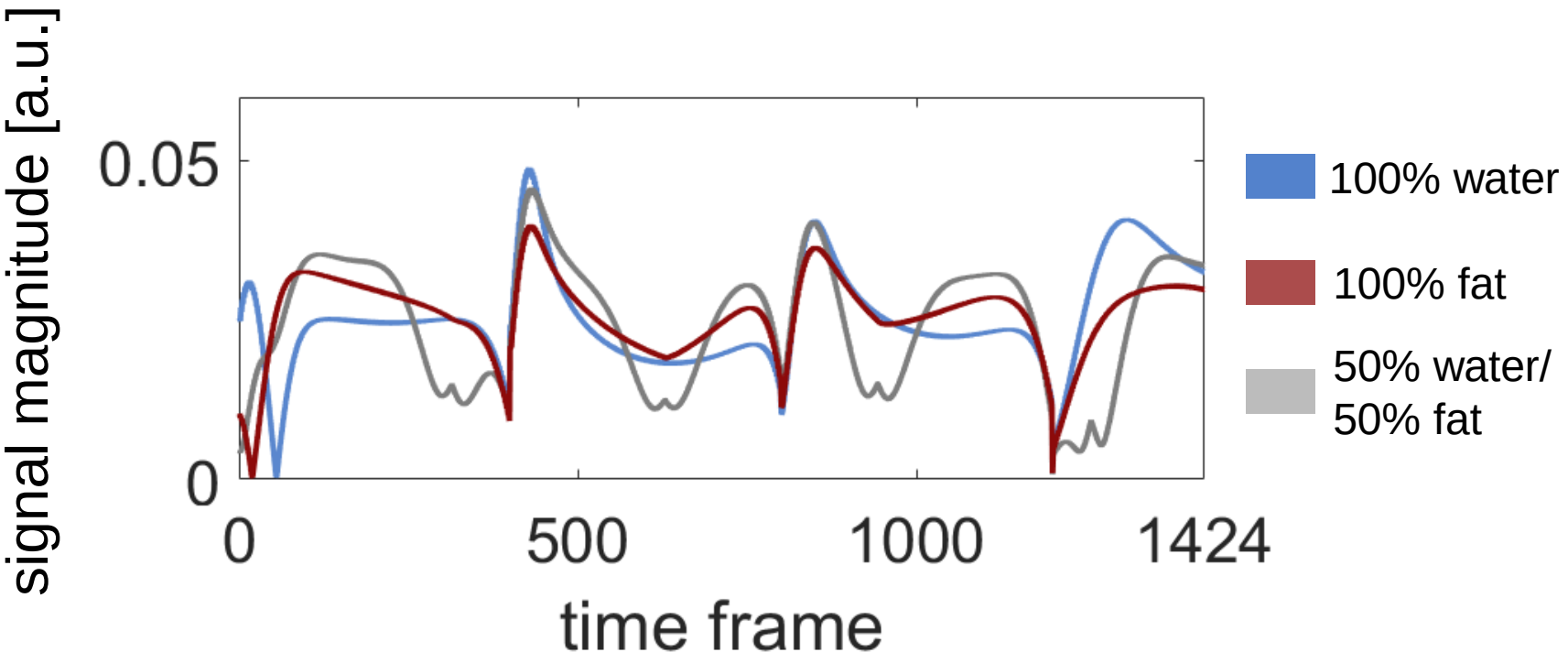
1. Find $\max|D' \cdot \hat{x}^T|$ D' = normalized dictionary
2. Find corresponding parameters (T1,T2,…)
3. Calculate PD as $PD = \max|D' \cdot \hat{x}^T| / |D|$

Magnetic Resonance Fingerprinting: matching

	Number of patterns in the dictionary	Intel® Xeon® processor E5-2600 v4 (48 cpu)	NVIDIA Tesla K80 GPU
1. MR Relaxation times only	250 000 (each 10 complex singles)	615 s	340 s
2. Adding fat fraction estimations	3 186 414 (each 30 complex singles)	6.5 hours	3 hours
3. Adding two blood perfusion parameters	3 e8 (each 30 complex singles)	27 days (estimated)	14 days (estimated)
4. Adding diffusion tensor estimations	1.56 e10 (each 10 complex singles)	3.5 years (estimated)	1.5 years (estimated)

Benchmark values (time per each exam) for reconstructing 3D MR Fingerprinting on a brain using a 128x128x128 image matrix

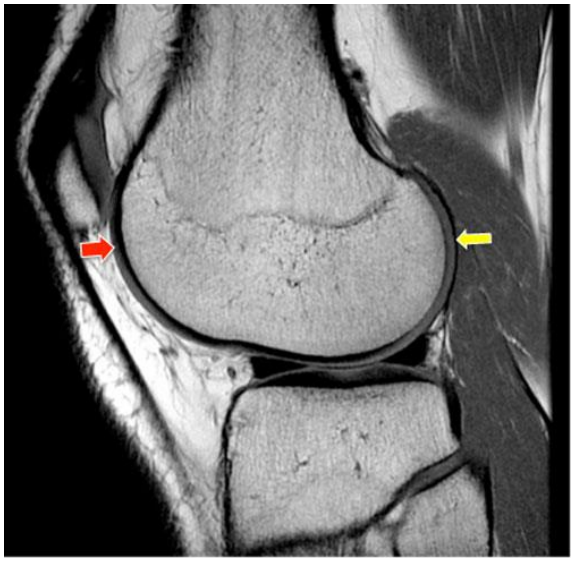
Magnetic Resonance Fingerprinting: multicomponent



My work: fat water separation

Problems due to fat presence:

- Brighter than water (short T1)
- Displacement in the image (different chemical shift, i.e. different resonant frequency)



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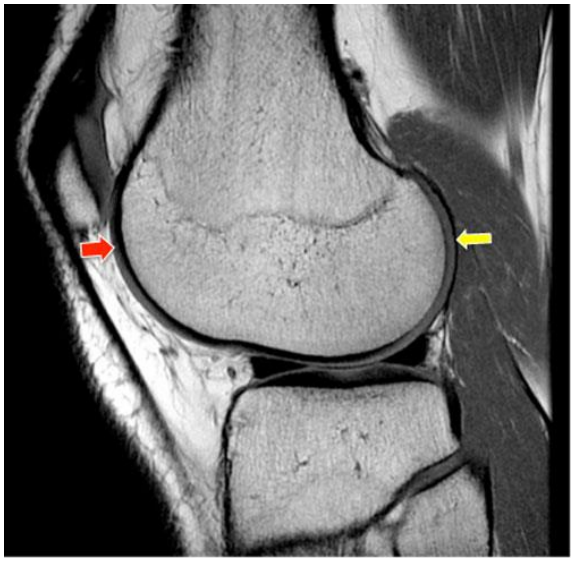


source: mriquestion.com

Fat quantification: can offer useful diagnostic information (e.g. liver diseases)

Conventional fat-water imaging

Conventional Fat suppression

T1 based:

+ Fast and efficient suppression
- No fat quantification

Chemical shift based:

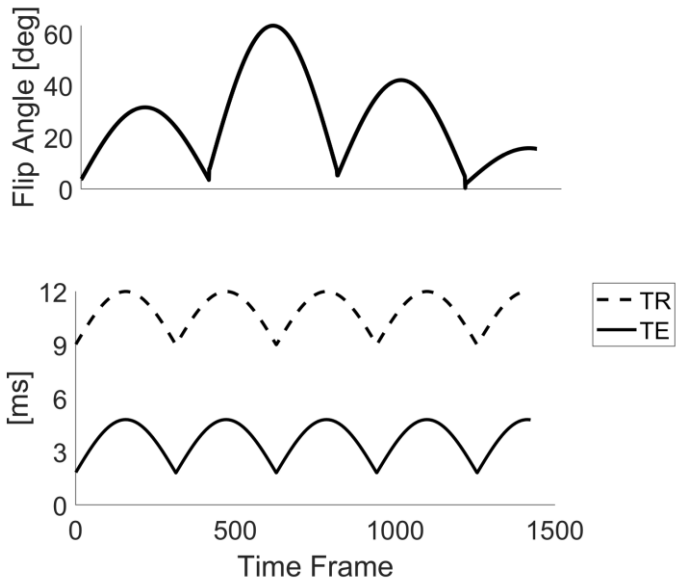
+ Allow fat quantification
- Increased acquisition time

Acquisition pattern

Acquisition:

- Inversion pulse => add T1 sensitivity
- Variable TE/TR (TE/TR min: 1.8/9 ms; TE/TR max: 4.8/12 ms) => add chemical shift sensitivity

Acquisition Time: 16s per slice



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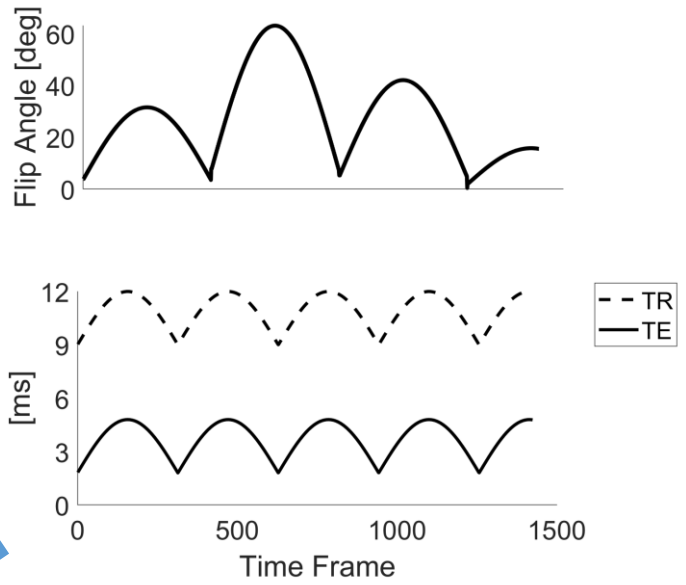
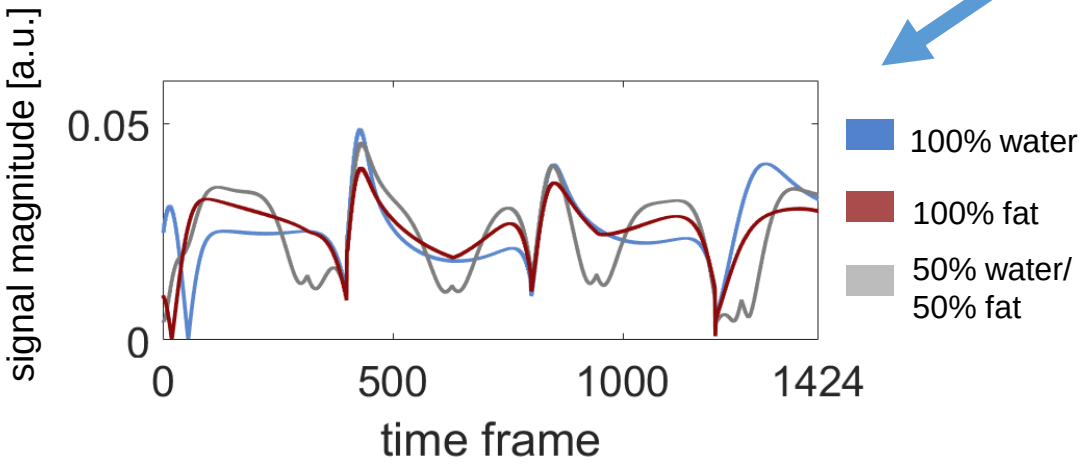
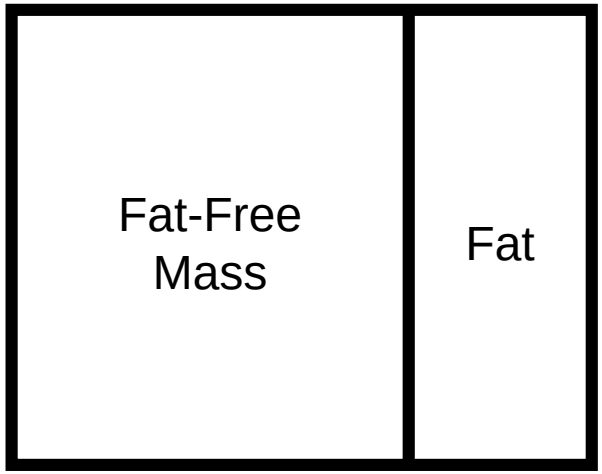




Signal model



Simple two component model

Dictionary Creation:

1. Pure water dictionary $D_w(T_1w, B_1, \Delta f)$
2. Pure fat dictionary $D_f(T_1f, B_1, \Delta f + 220\ Hz)$
3. Linear combinations $D = (1 - ff)D_w + ffD_f$

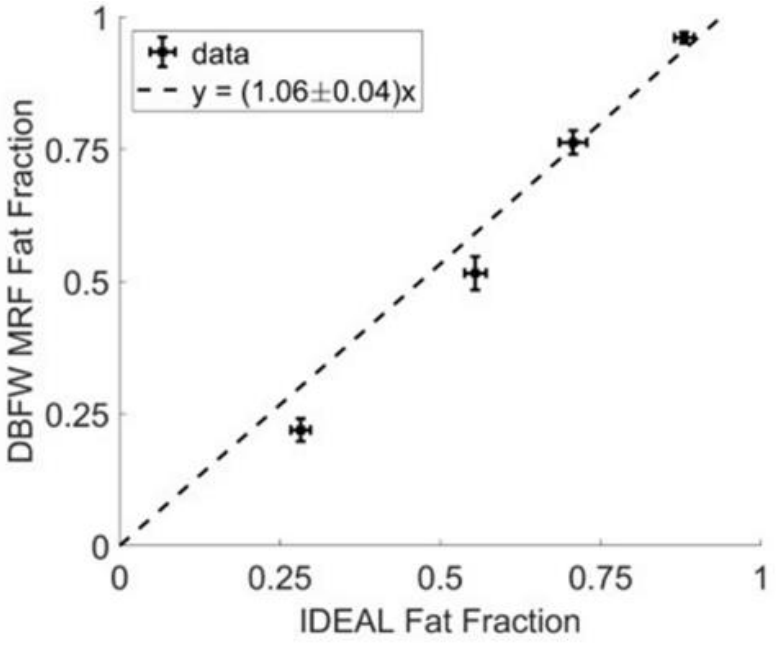
ff: fat fraction

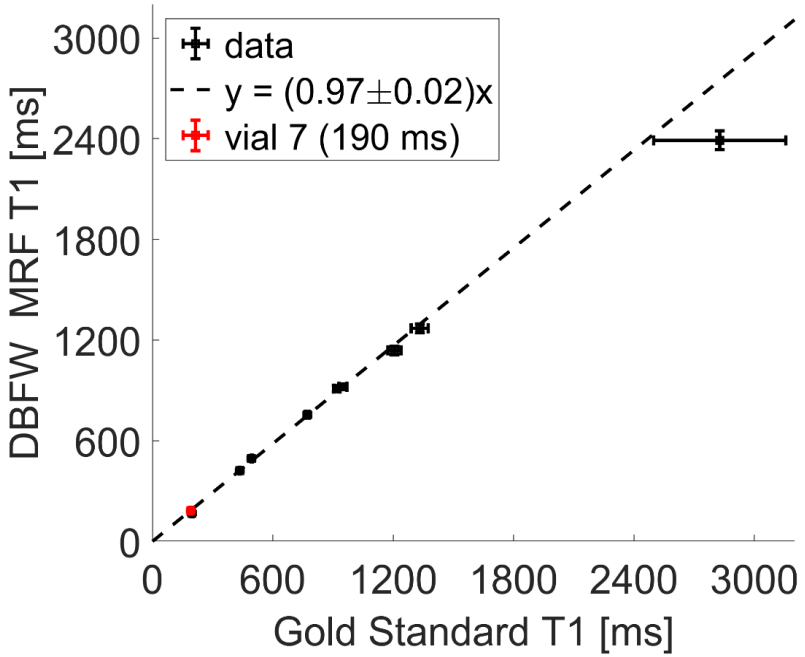
Validation studies

- **In-Vitro**: Vials filled with fat-water mixtures at different concentration (0%, 25%, 50%, 80%, 100%) + agarose gel with different T1

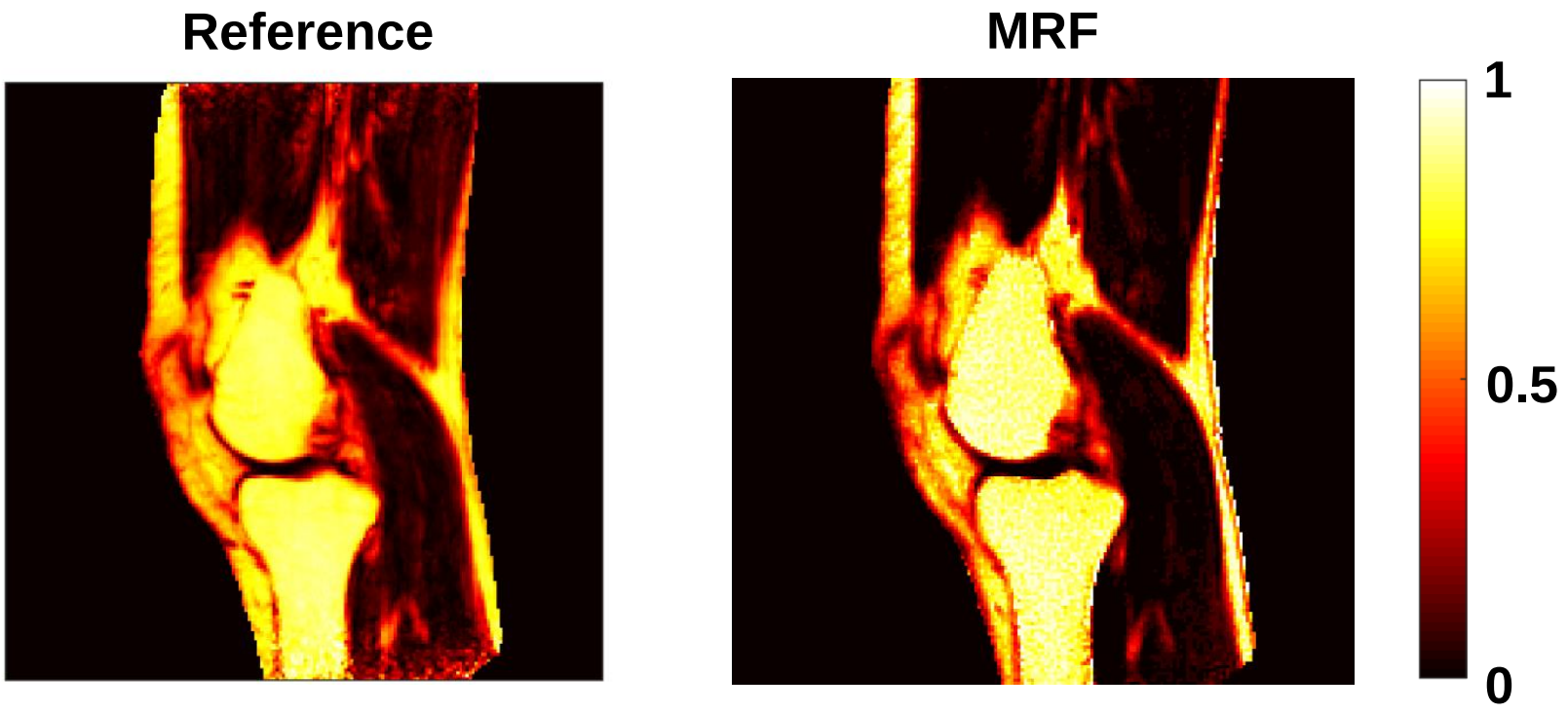
- **In-Vivo**: Knee joint of a healthy human volunteer

Results: phantom



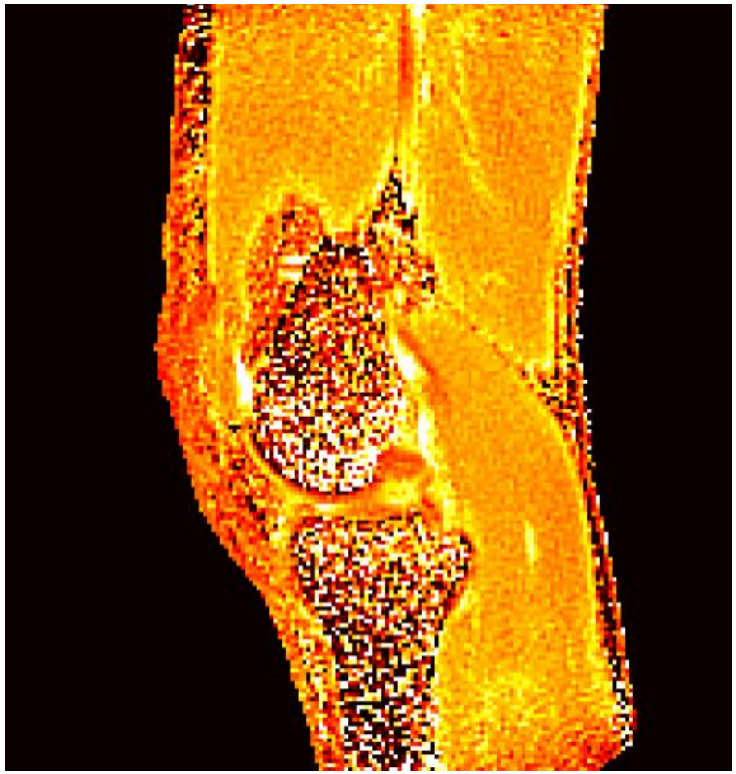


Results: in vivo fat fraction

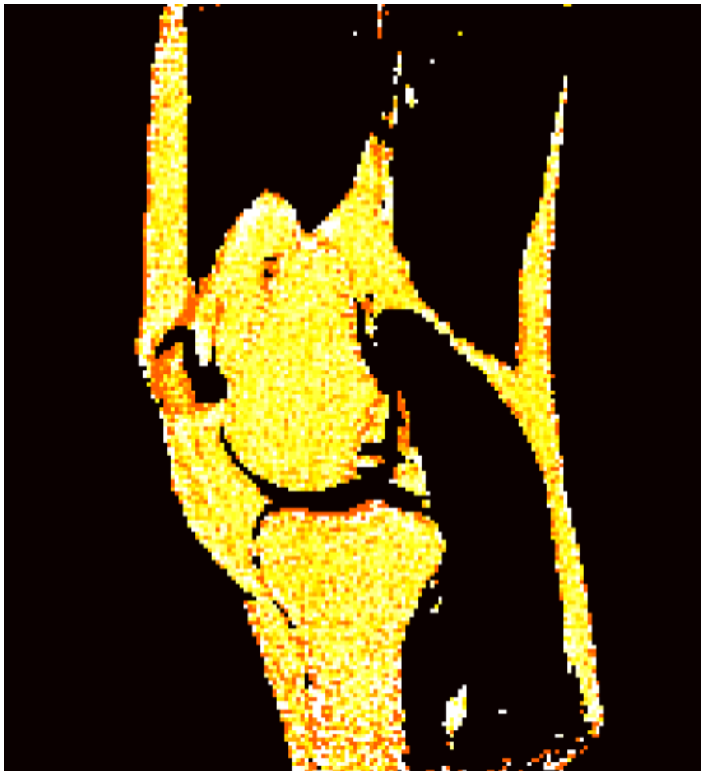


Results: in vivo T1

Water T1 [ms]



Fat T1 [ms]

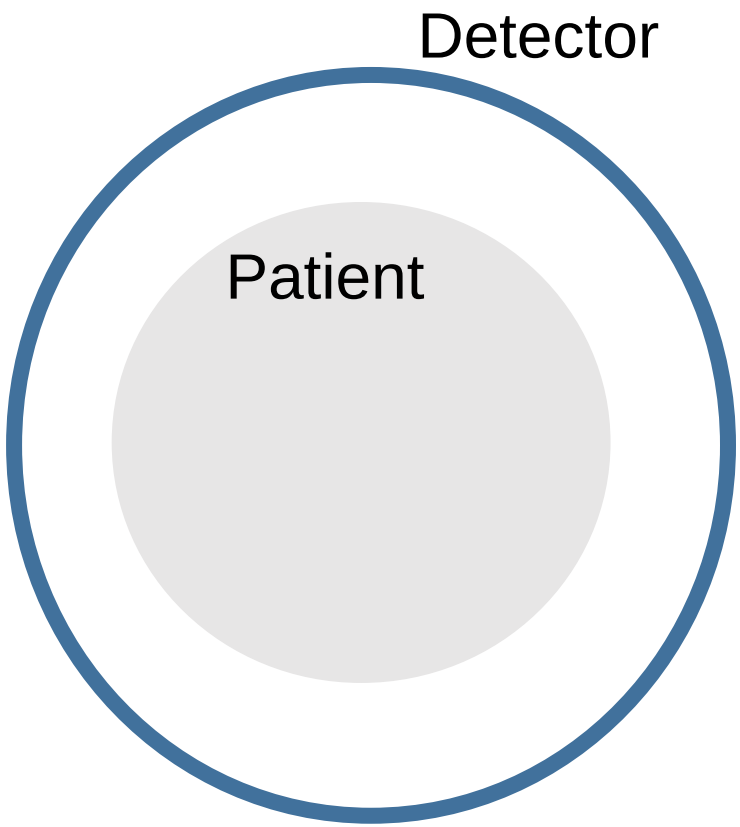


Fat water: conclusions

- Consistent Fat Fraction and T1 maps in 16s/slice

- Combine T1-based and chemical shift-based fat water separation approach => more robust!

My work: PET attenuation correction



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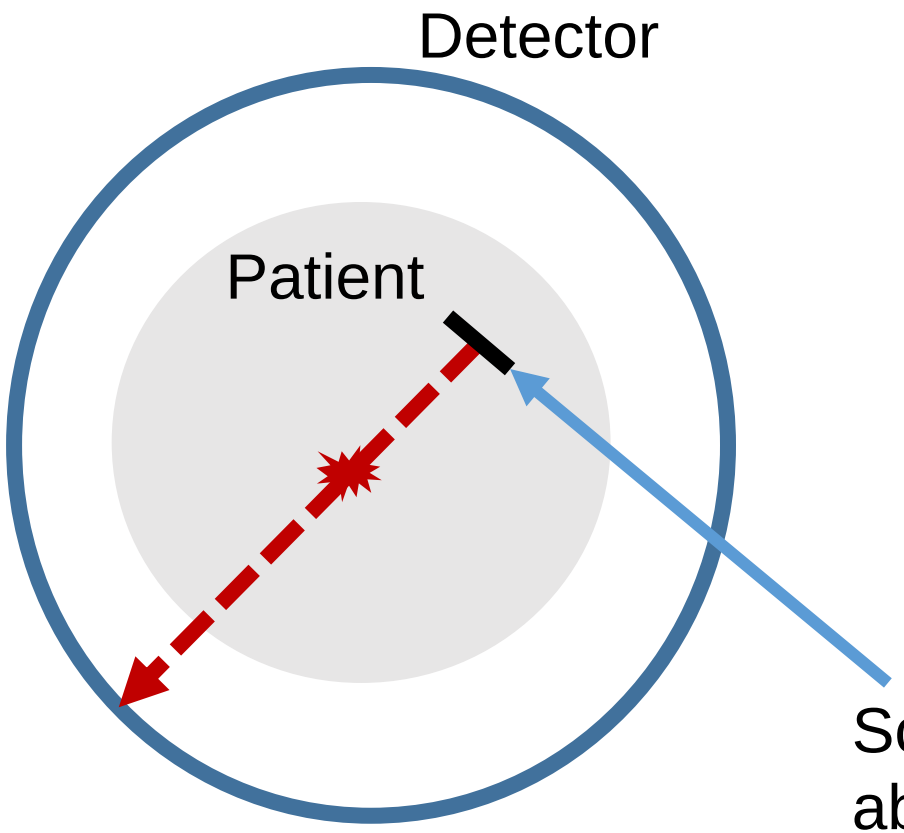

$$I = I_0 \exp(-\int \mu(x)dx)$$

Underestimation of tracer uptake!

Scattering or absorption of 511 KeV photon

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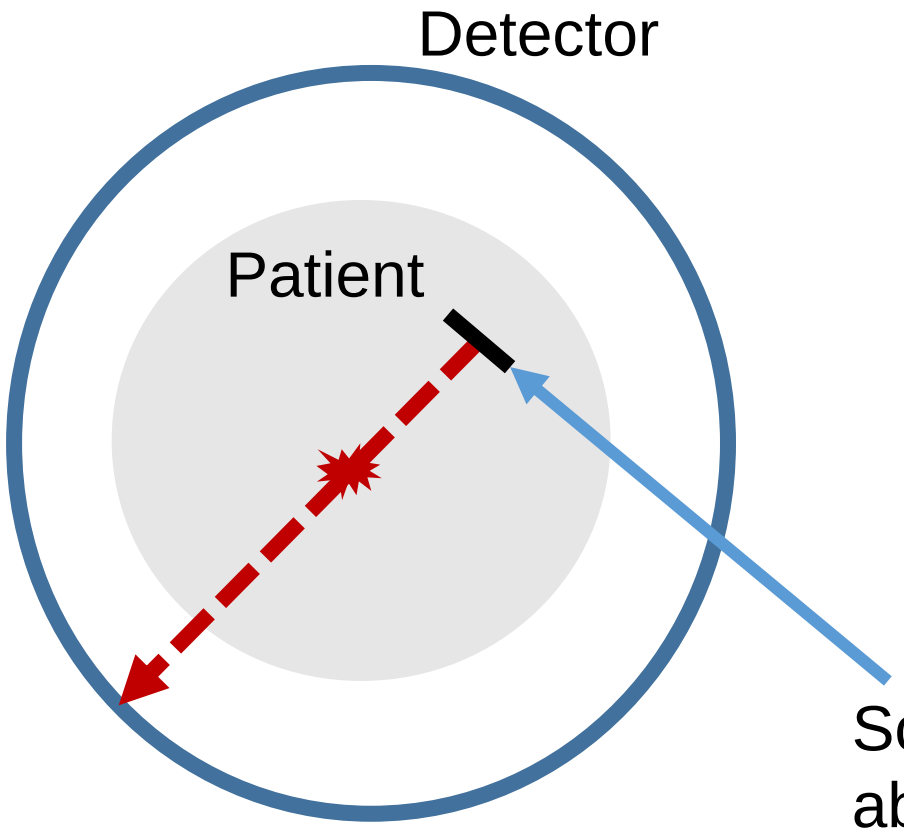

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Underestimation of tracer uptake!

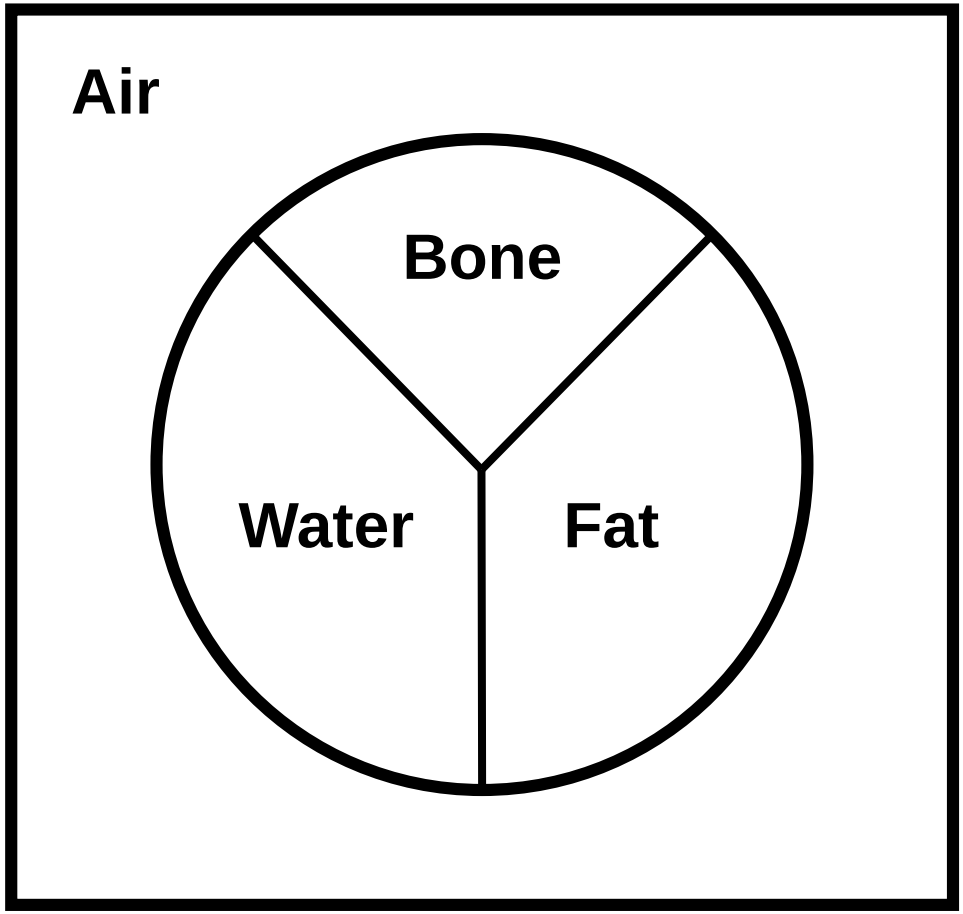
Scattering or absorption of 511 KeV photon

Conventional AC

- **PET/CT:** photon attenuation is readily estimated from CT Hounsfield units

- **PET/MRI:** attenuation correction rely on MRI segmentations: anatomic models => **not subject specific** OR ultra-short echo times (UTE) to separate the short T2 in bone from longer T2 in soft tissues + Dixon techniques => bone, fat and water maps => **require multiple acquisitions at high resolution**!!!

Signal model



Tissue properties:

- **Water**: relatively long T1 and T2; on resonance
- **Fat**: short T1; ~3.5 ppm chemical shift
- **Bone**: ultra-short T2

Air properties:

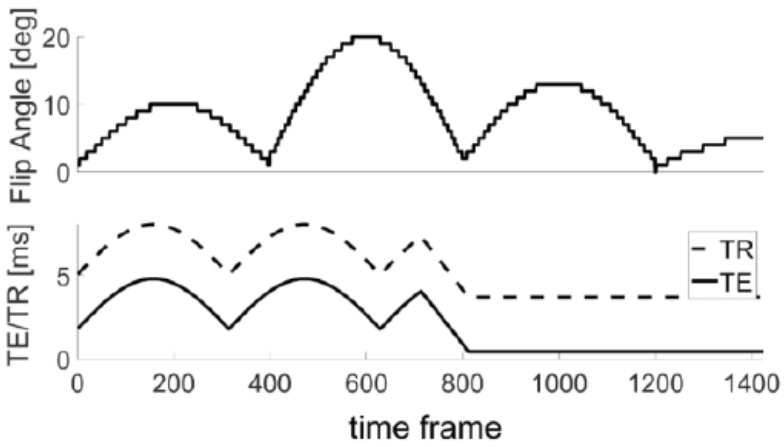
- Totally incoherent signal (low correlation with each dictionary entry!)

Acquisition pattern

Acquisition pattern:

- UTE + Variable TR/TE

  (TE min: 400μs; TE max: 4.8 ms)



MR Scanner: GE HDxt 1.5T

3D acquisition

Resolution: 4mm isotropic

Acquisition time: 123s

Dictionary

MRF

Dictionary: simulations for a many different T1s,T2s and ΔB0s

ARISTOMRAC

Dictionary: simulation for 3 pools (water, fat, bone each with sparse T1, T2, ΔB0 values); many combinations of these tissues according to many different weightings

Air: classified by threshold on the matching cost function

Validation studies

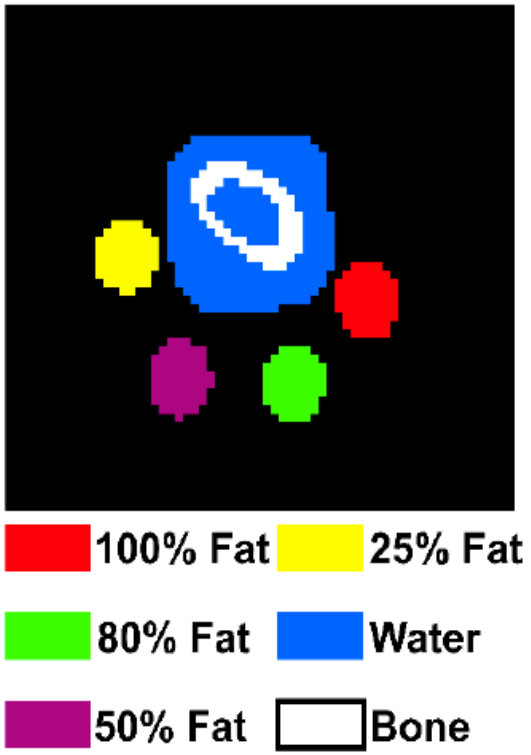
Phantom:

- Bovine bone in a 0.6% agar gel.
- Four oil-water emulsions (nominal concentrations: 25%, 50%, 80%, 100%

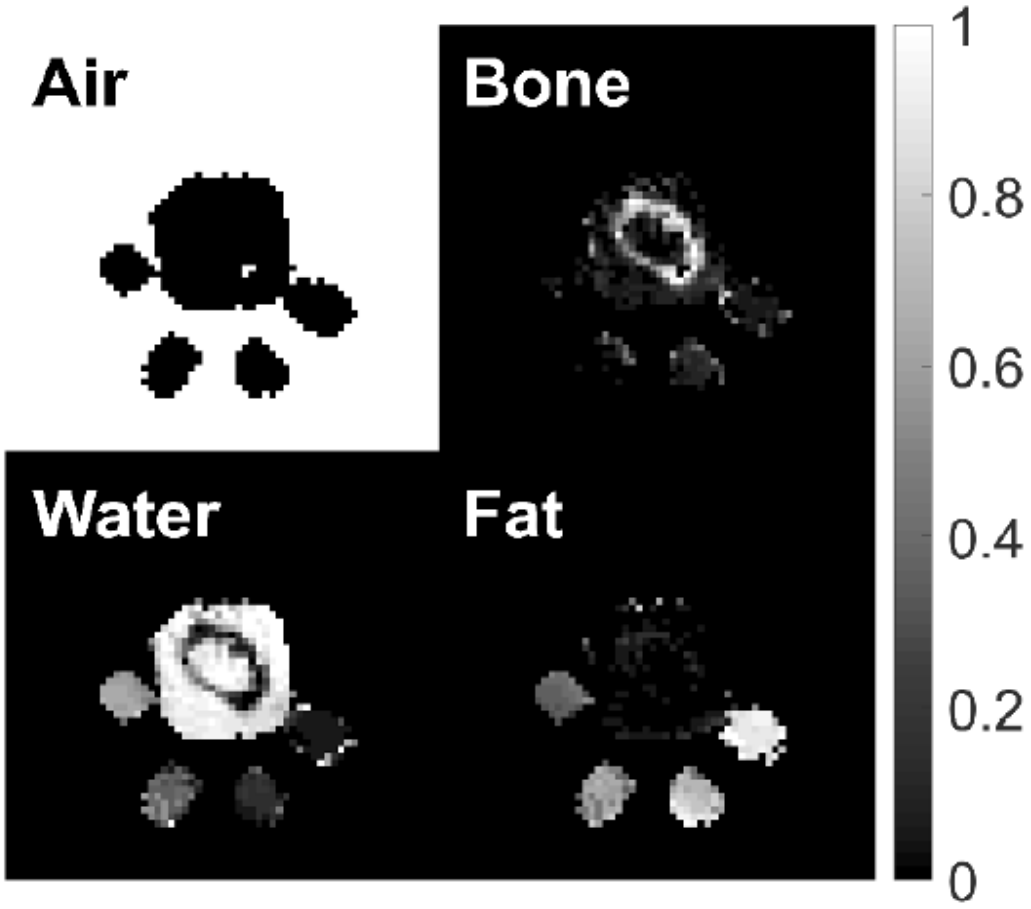
Ground truth maps:

segmentation/classification of a high resolution T1 image + resampling to 4mm isotropic

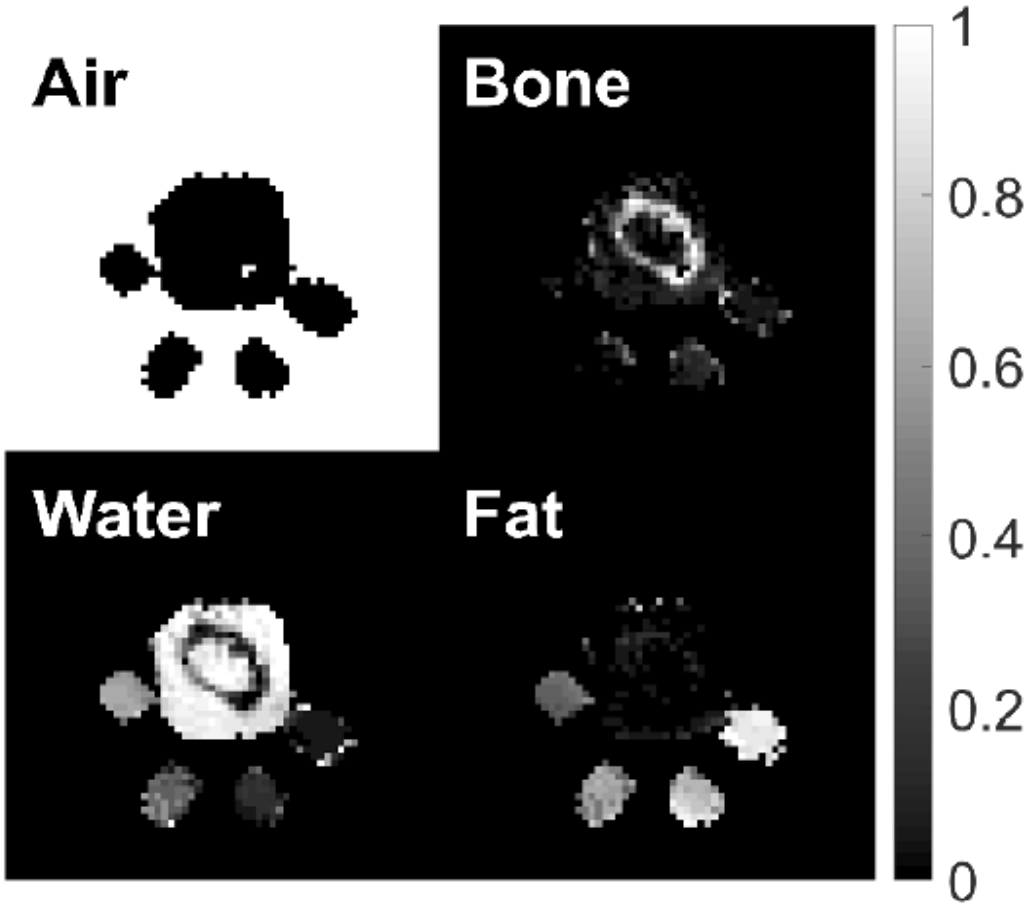
Nominal values



In-vitro experiment: tissue fraction maps



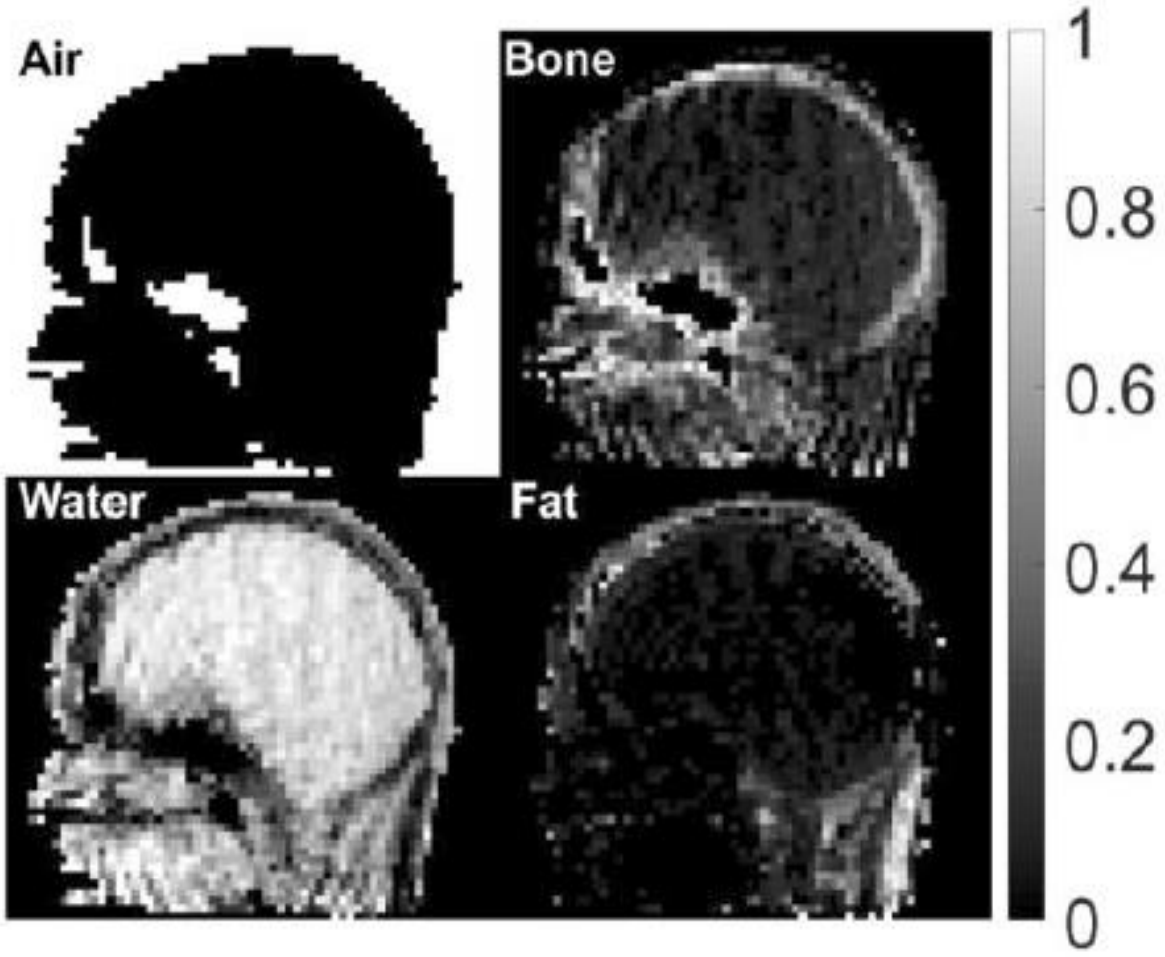
In-vitro experiment: tissue fraction maps



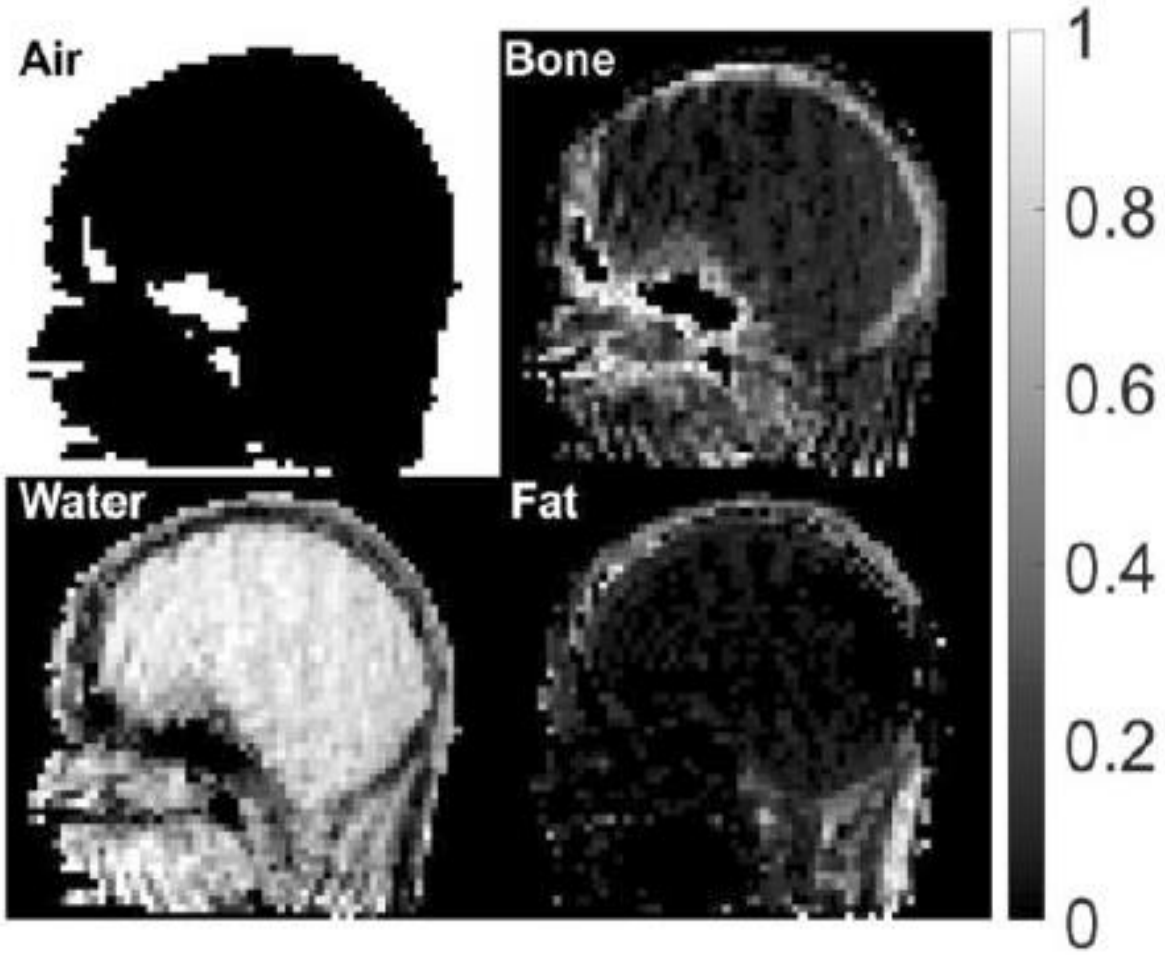
CCC with ground truth:

- **Water:** 0.94
- **Fat:** 0.96
- **Bone:** 0.90

In-vivo experiment: tissue fraction maps

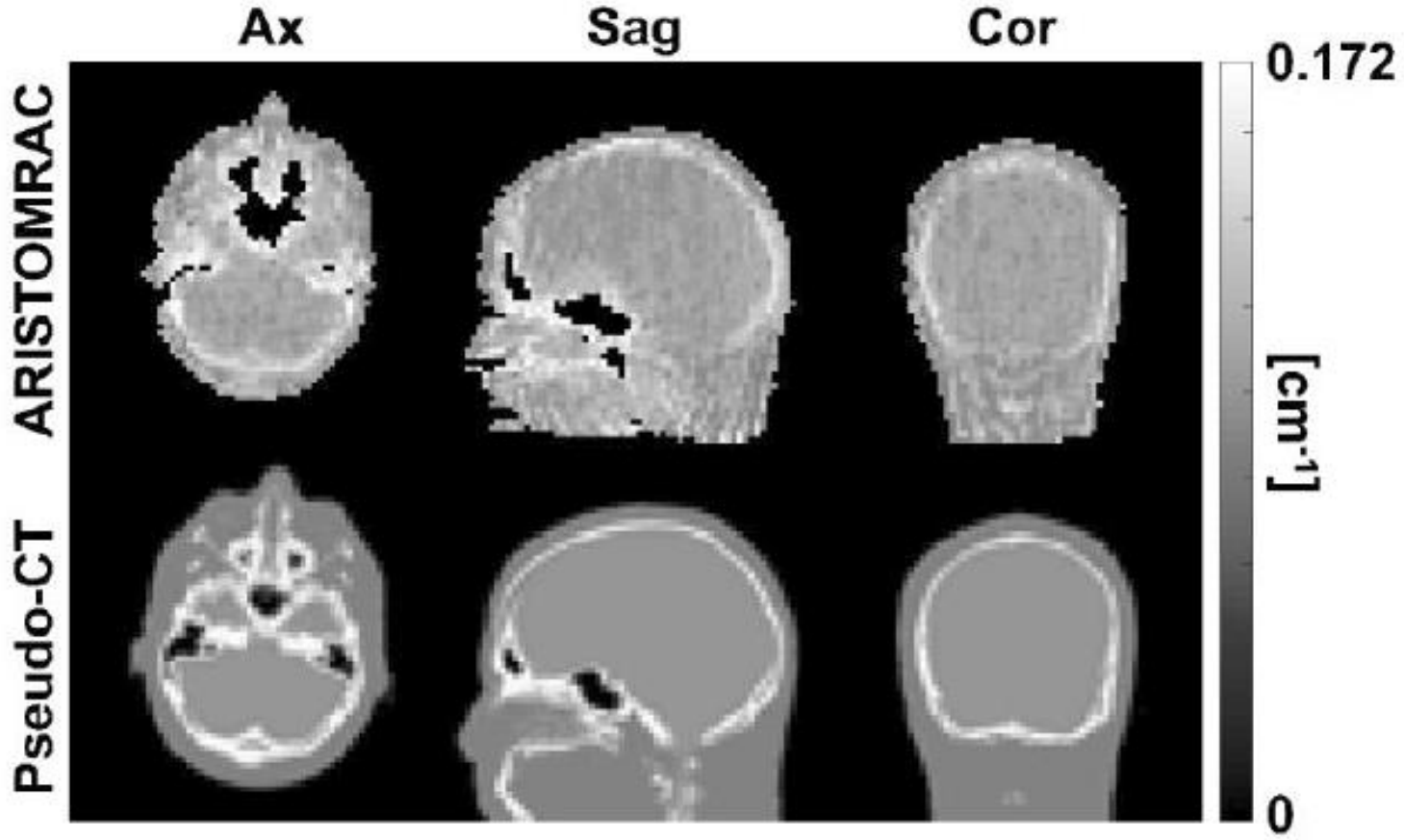


In-vivo experiment: tissue fraction maps



Correct classification of tissues!

In-vivo experiment: attenuation map



Conclusion

- Correct classification of tissues directly at PET resolution within a single acquisition (short scan time!)

- Must be validated by comparison with gold standard (CT)

Future perspectives

- Extend the multicomponent approach to other problems (e.g. CSF suppression)

- Try to circumvent the computational burden of increasing dimensionality to add more parameters (e.g. T2)

Thank you for your attention!

Backup

From signal to image

$$\boldsymbol{B} = \mathrm{B}_0\hat{\boldsymbol{z}} + \boldsymbol{Gr} \Rightarrow \omega = \omega(\boldsymbol{r})$$

Gradient fields

From signal to image

$$\boldsymbol{B} = \mathrm{B}_0\hat{\boldsymbol{z}} + \boldsymbol{Gr} \Rightarrow \omega = \omega(\boldsymbol{r})$$

Gradient fields

$$\mathrm{s(t)} \propto \int_V dV\rho(r)\exp(-i\gamma \int dt\boldsymbol{G}\,(t)\boldsymbol{r})$$

Spin spatial distribution

From signal to image

$$\boldsymbol{B} = \mathrm{B}_0\hat{\boldsymbol{z}} + \boldsymbol{Gr} \Rightarrow \omega = \omega(\boldsymbol{r})$$

Gradient fields

$$\mathrm{s(t)} \propto \int_V dV\rho(r)\exp(-i\gamma \underbrace{\int dt\boldsymbol{G}(t)\boldsymbol{r}}_{\stackrel{\mathrm{def}}{=} k})$$

Spin spatial distribution

From signal to image

$$\boldsymbol{B} = \mathrm{B}_0\hat{\boldsymbol{z}} + \boldsymbol{Gr} \Rightarrow \omega = \omega(\boldsymbol{r})$$

Gradient fields

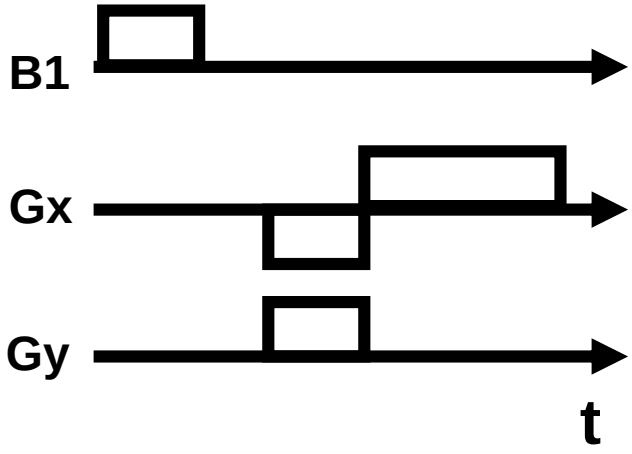
$$\mathrm{s(t)} \propto \int_V dV\rho(r)\exp(-i\gamma \underbrace{\int dt\boldsymbol{G}(t)\boldsymbol{r}}_{\stackrel{\mathrm{def}}{=} k})$$

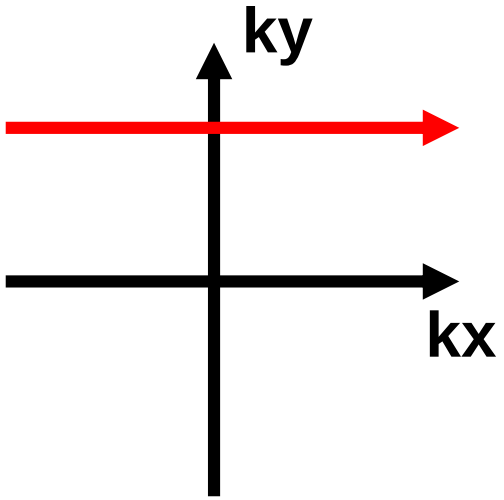
Spin spatial distribution

$$\mathrm{s(k)} \propto \int_V dV\rho(r)\exp(-i\boldsymbol{kr}) = \boldsymbol{FT}(\boldsymbol{\rho}(\boldsymbol{r}))$$

From signal to image

Cartesian





Radial