MRI more introduction…

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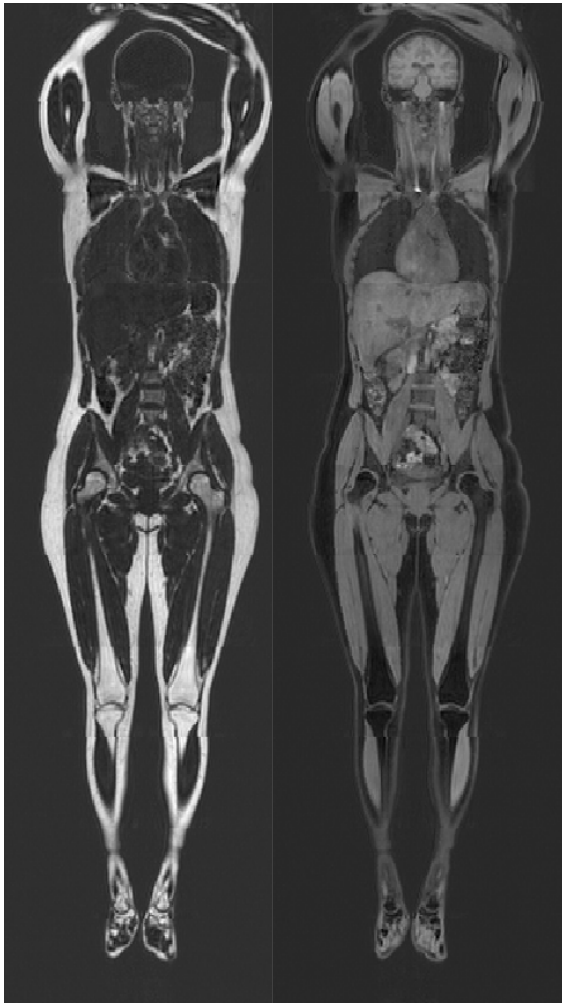
Purpose of lecture:

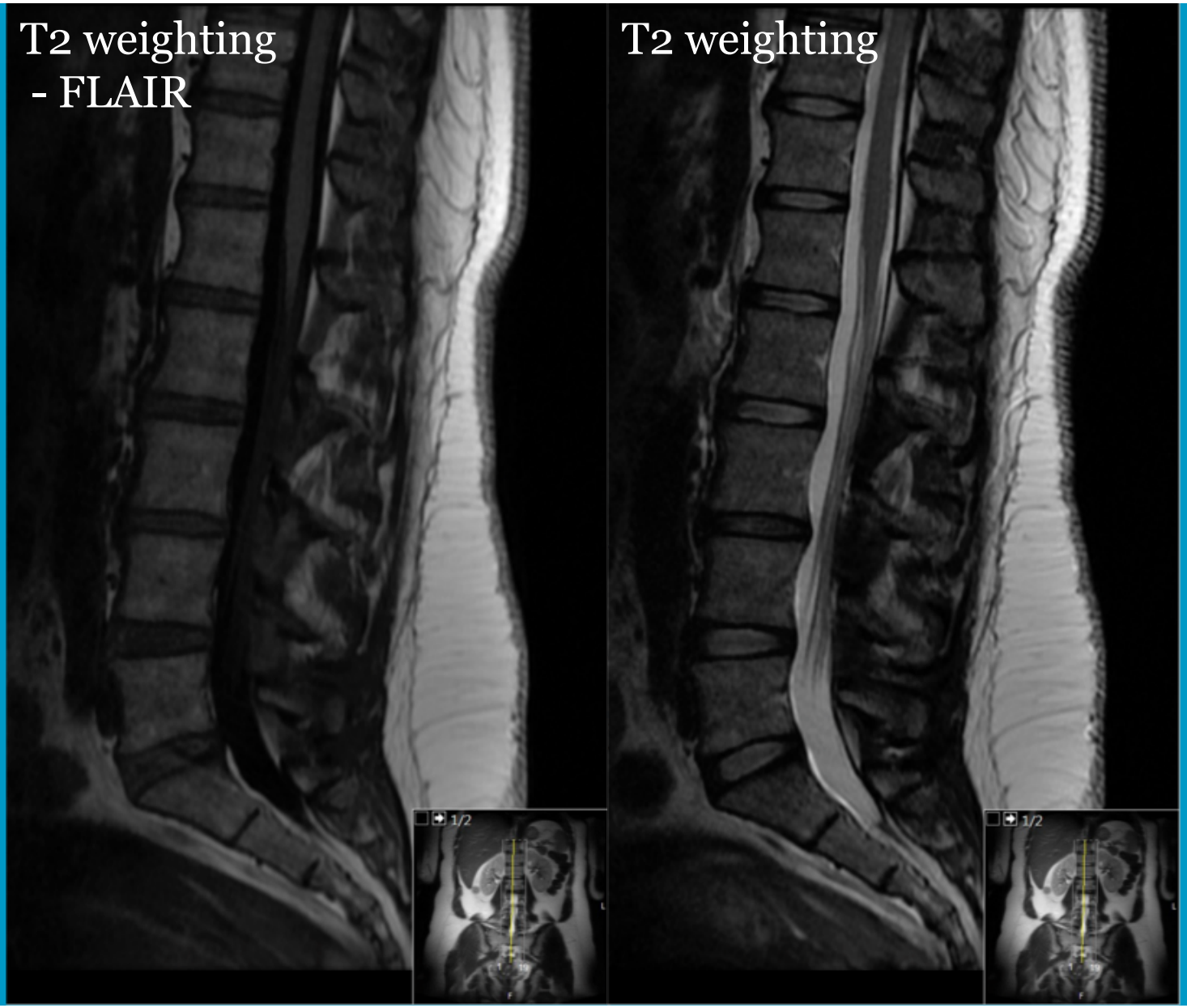
-More perspectives on MRI
-Introduction to quantitative MRI
-Some details on fat/water separated MRI

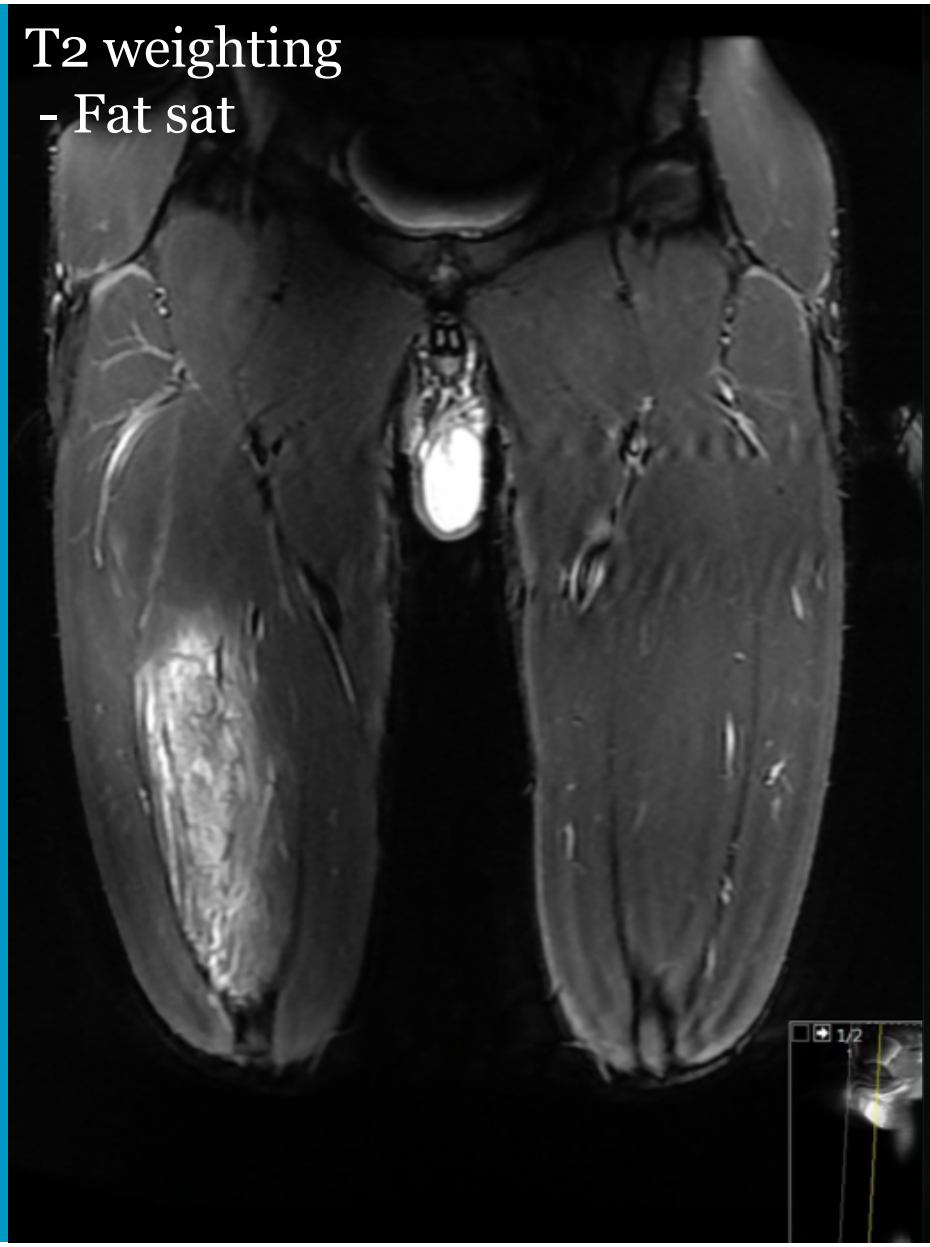
- Why do we image?
  - Understand what is injured or the cause of the patients pain/functional loss
  - Describe the local anatomy and function
  - Understand what tissue that is involved

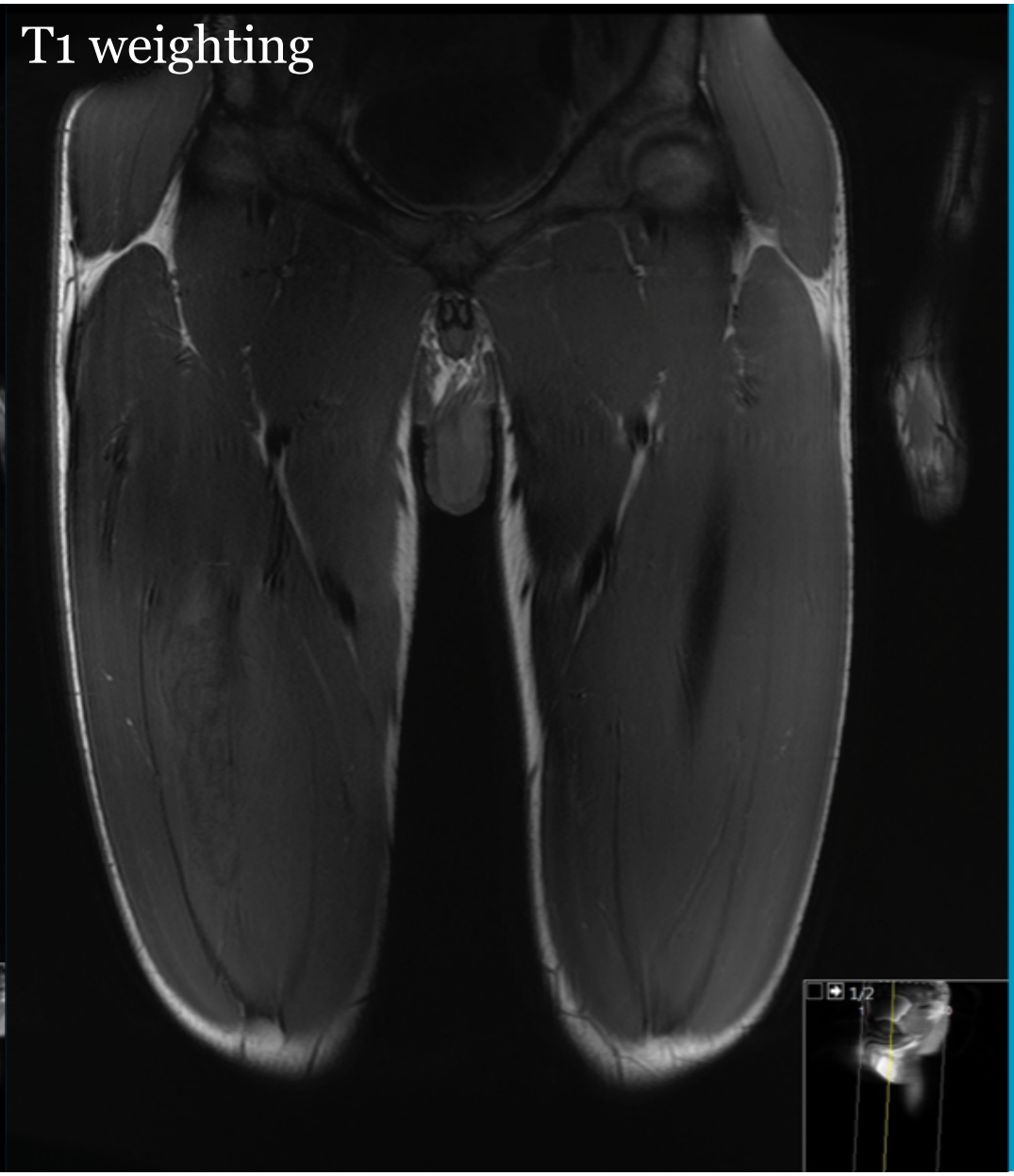
- What is imaged, focusing on MSK MRI?
  - Skeleton and joints
    - Bone
    - Bone Marrow
    - Cartilage
    - tendon
    - Fluid in joints/Free fluid
    - Structural damages
  - Soft tissue
    - Muscles
    - Adipose tissue
    - Fatty infiltration
    - Oedema and free fluid
    - Nerves
    - Vessels
    - Connective tissue
    - Atrofy, perfusion
    - Structural damages



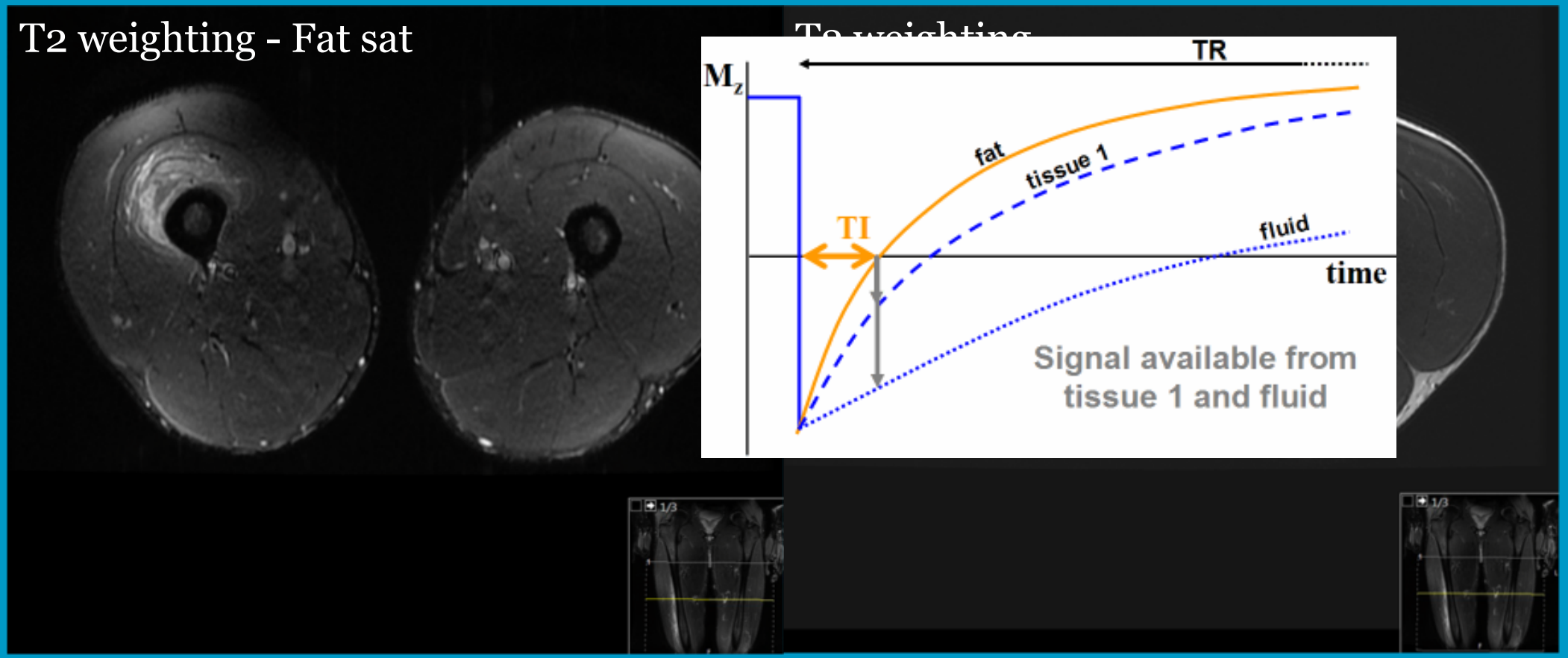
- What are the tools?
  - T1-weighting
  - T2-weighting
  - T2*-weighting
  - PD-weighting
  - FLAIR
  - UTE (Ultra short echo time MRI)
  - Fat suppression STIR/SPAIR
  - Fat/water-separation
  - Diffusion (Nerves/tumor)
  - Quantitative MRI


T2 weighting
- FLAIR
T2 weighting
1/2
1/2

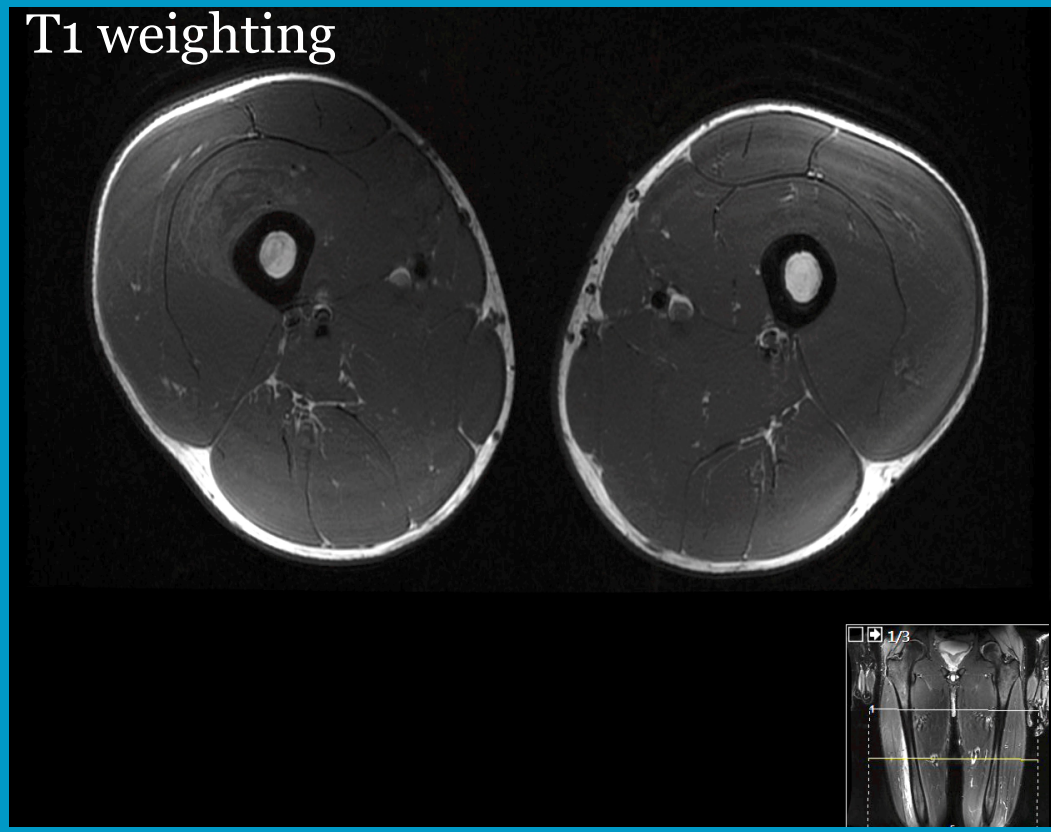

T2 weighting
- Fat sat


T1 weighting

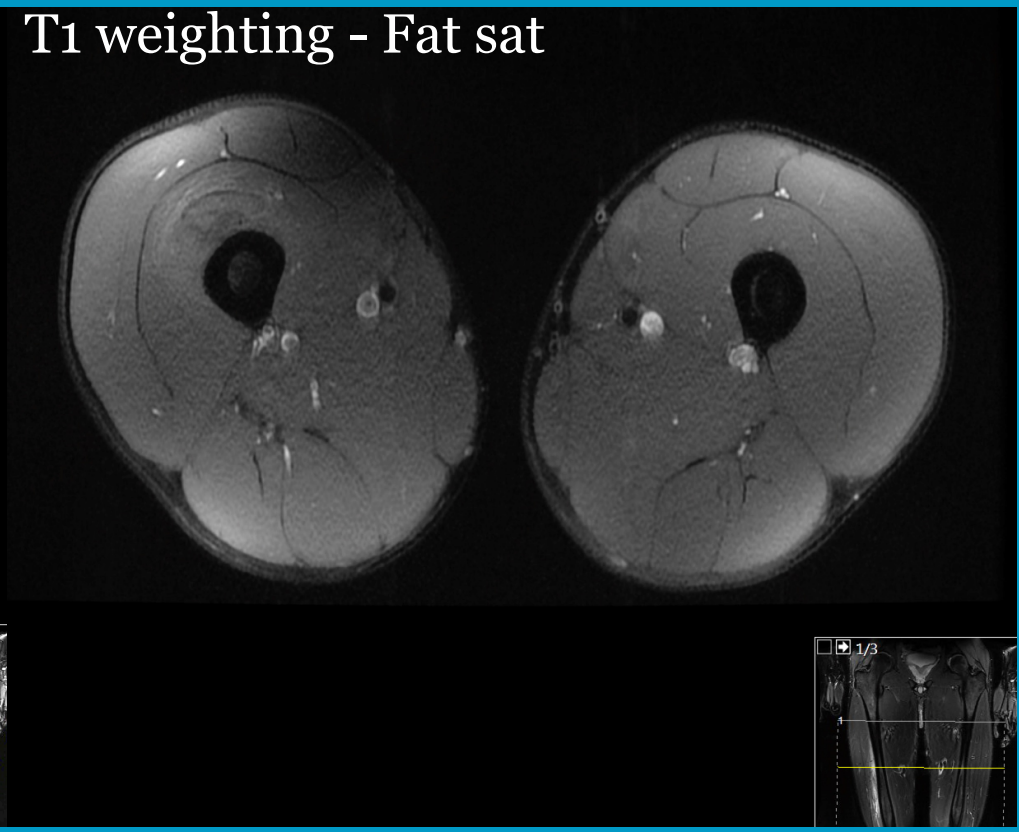
T2 weighting - Fat sat

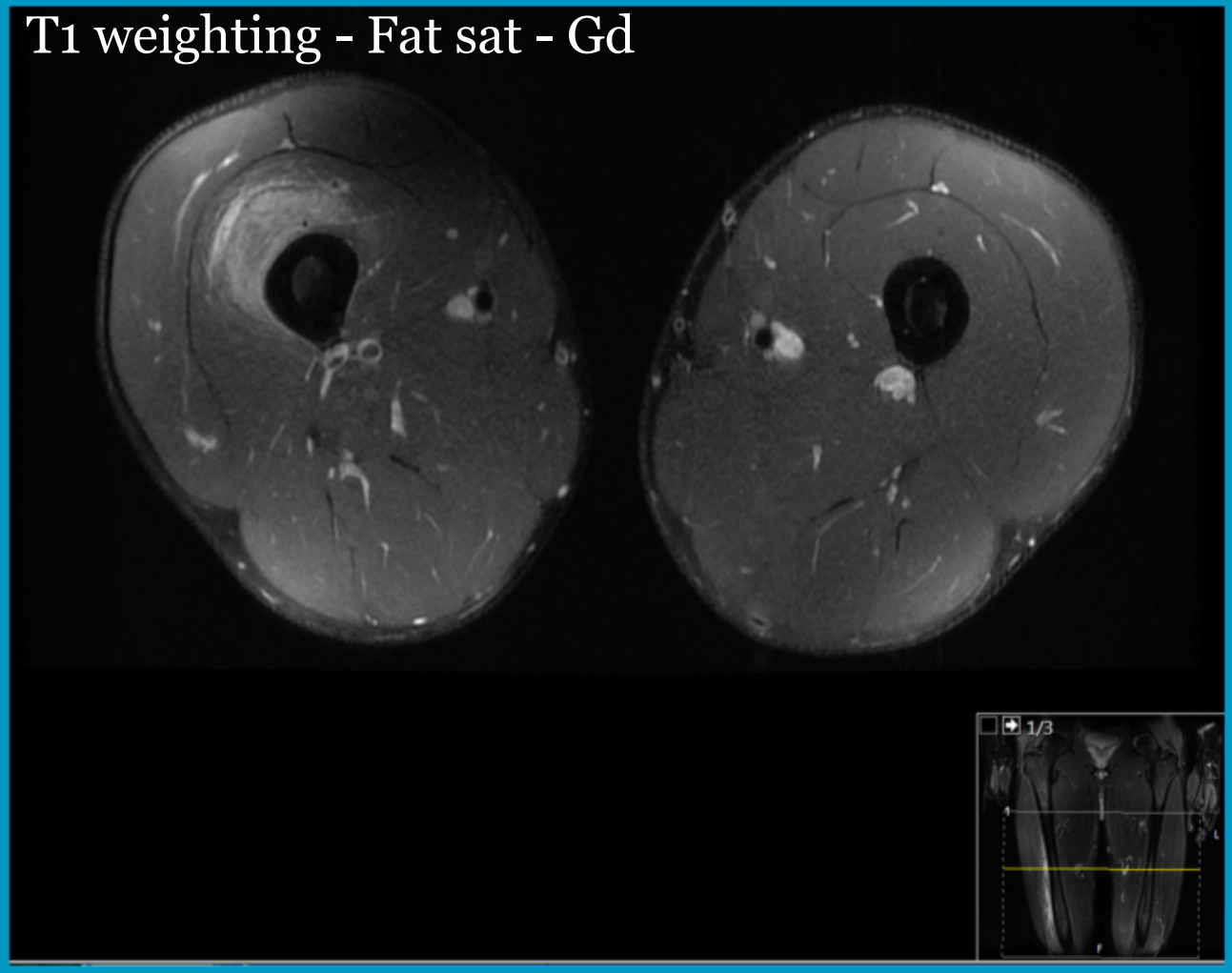


T1 weighting

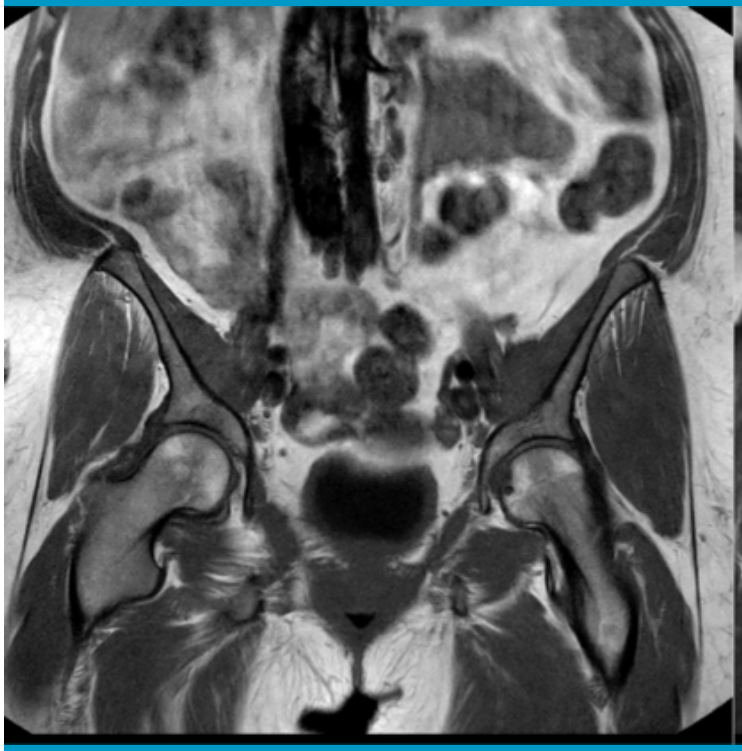


T1 weighting - Fat sat

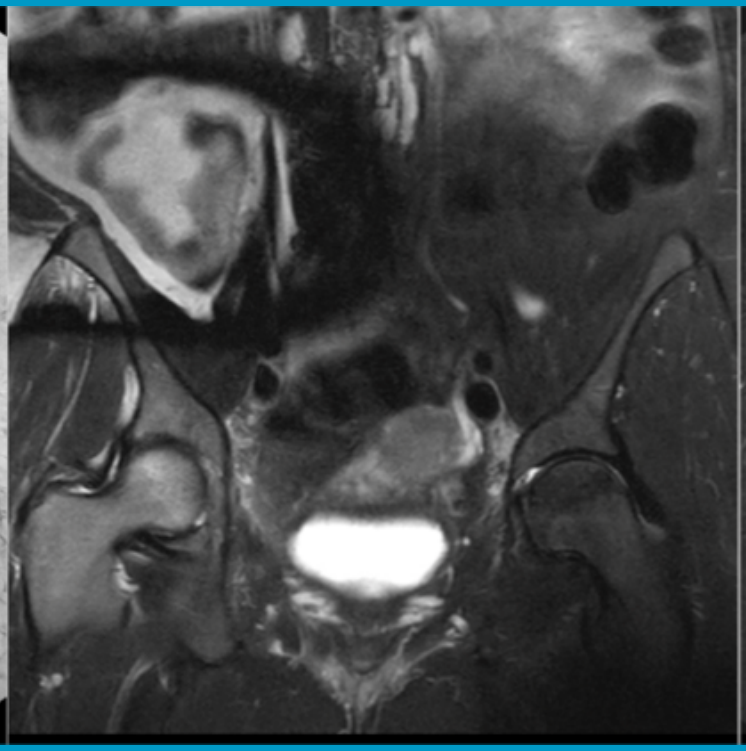



T1 weighting - Fat sat - Gd
1/3

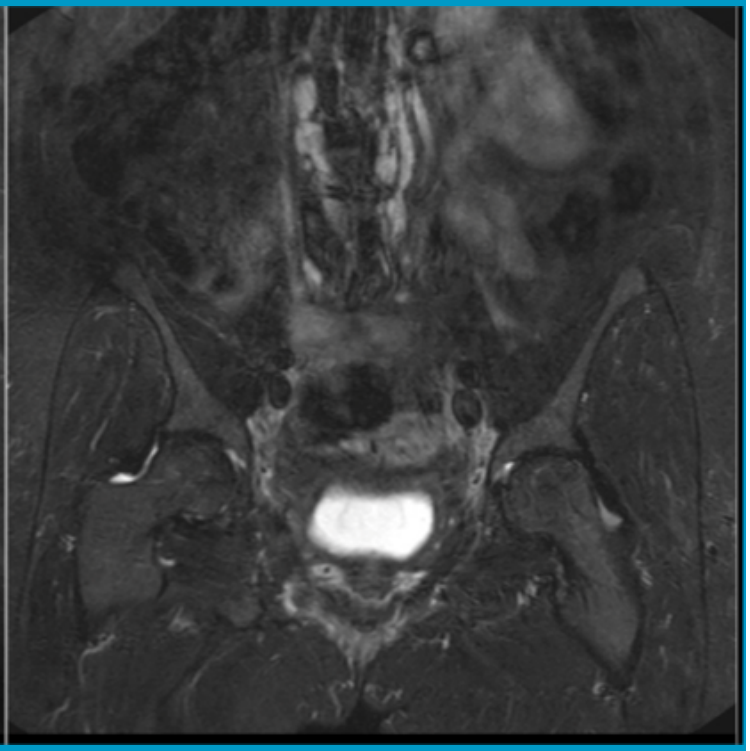
T1 weighting

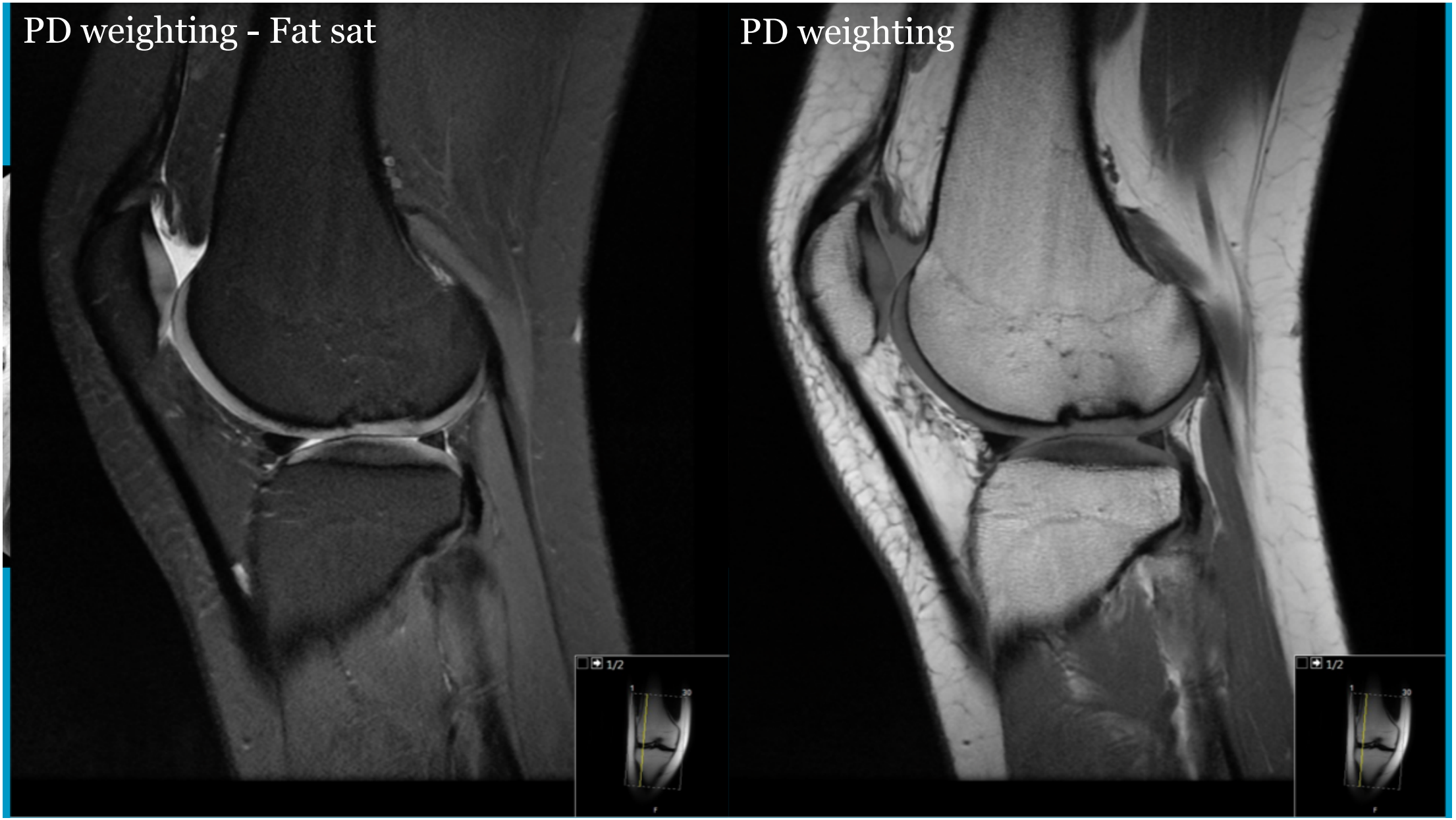


T2 SPAIR



T2 STIR




PD weighting - Fat sat
PD weighting
1/2
1/2

MR Quantification

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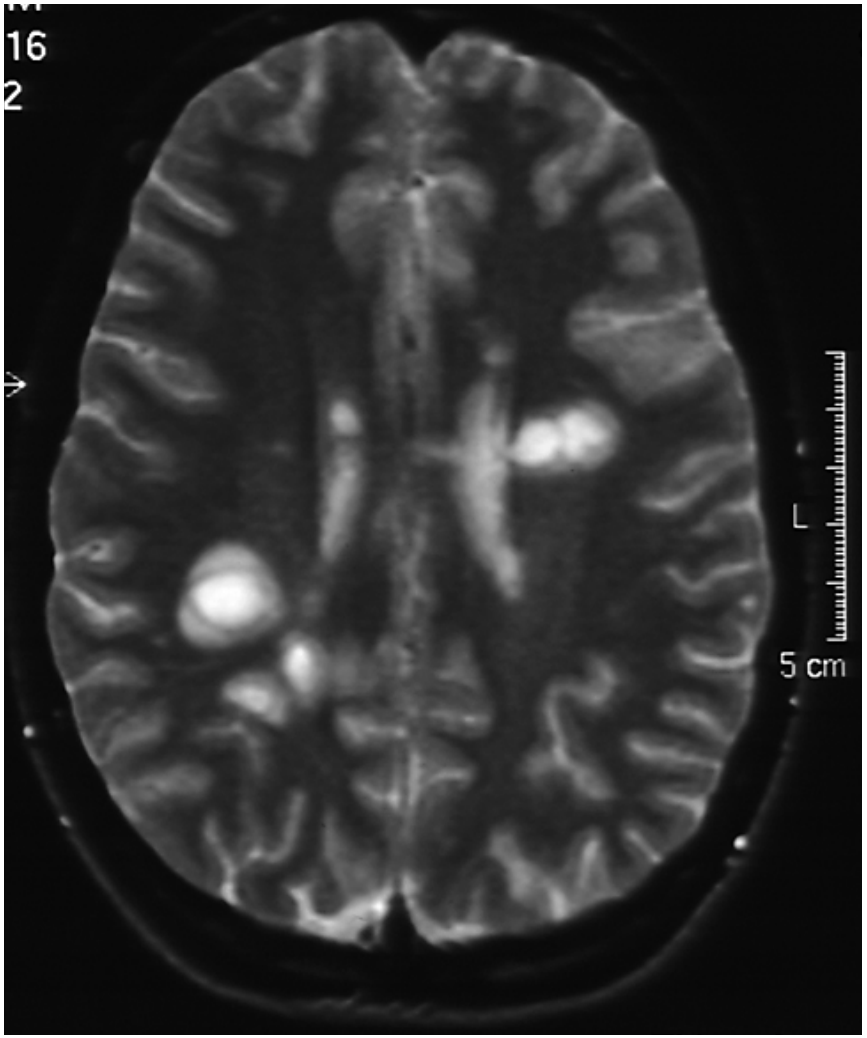

16
2
L
5 cm

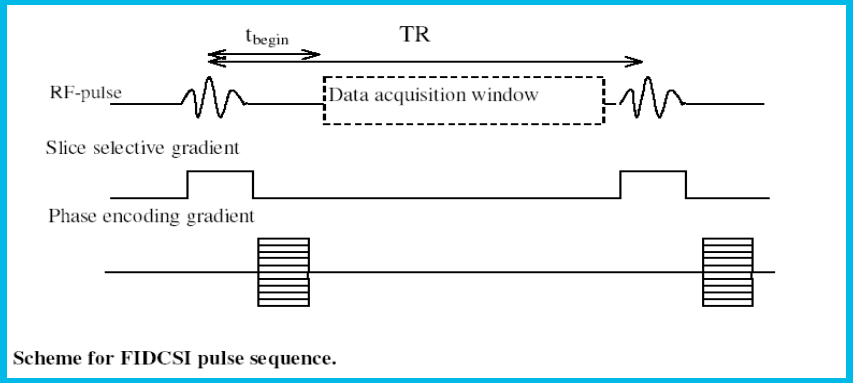
MR Quantification

- The procedure to obtain quantitative physically interpretable values from MR acquisition.
- MR is sensitive but is generally a qualitative technique
- The cause for this is different physical factors affecting the signal:
    - Spin density
    - T1 relaxation
    - T2 relaxation
    - Microscopic B0 inhomogeneities
    - Macroscopic B0 inhomogeneties
    - B1 inhomogeneities
    - Flip angle and repetition time
    - Flow
    - Diffusion
    - Chemical shift
    - Spin density
    - Excitation profiles
    - k-space sampling schemes
    - Temperature
    - …

Signal strength, the main factors

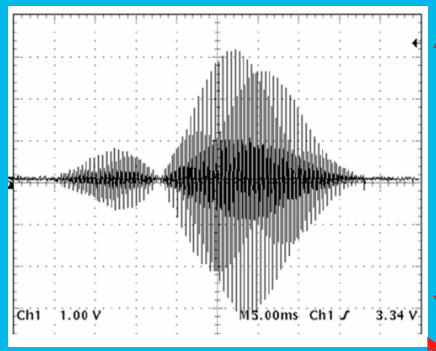
- PD
- T1
- T2 or T2*
- Flip angle
- Recieve coil sensitivity

Spin excitation



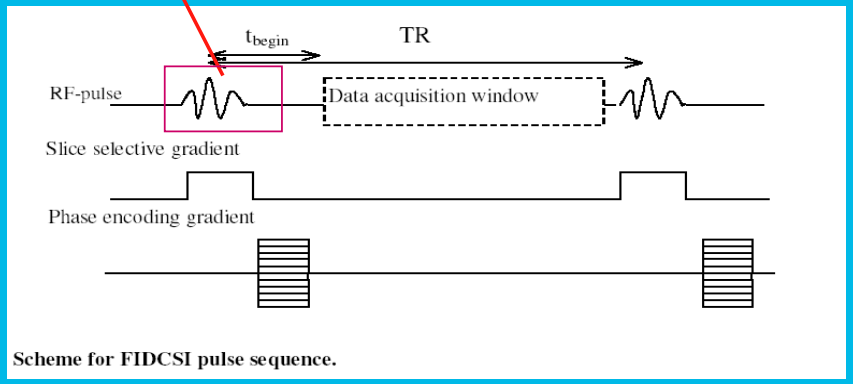
Scheme for FIDCSI pulse sequence.

Spin excitation



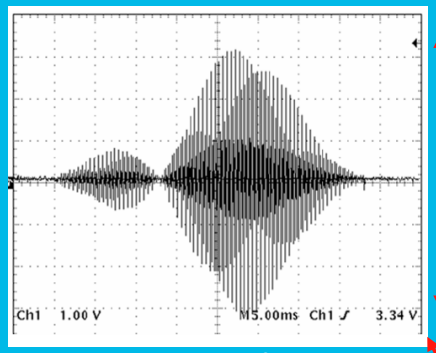
TA – Transmitter amplitude

Oscilloscope image of a RF - pulse



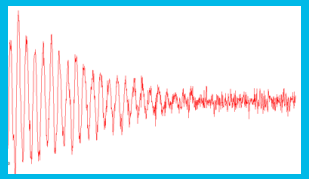
Scheme for FIDCSI pulse sequence.

Spin excitation

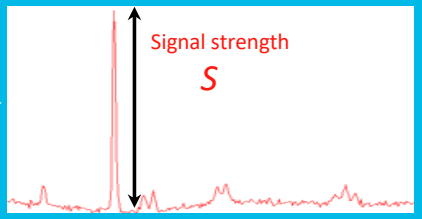


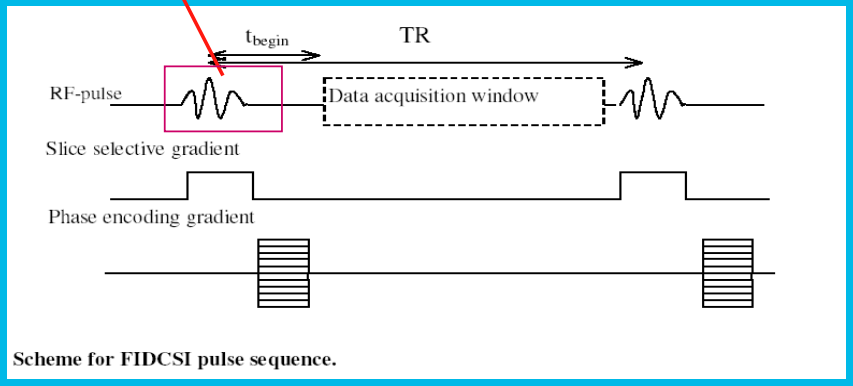
TA – Transmitter amplitude

Oscilloscope image of a RF - pulse



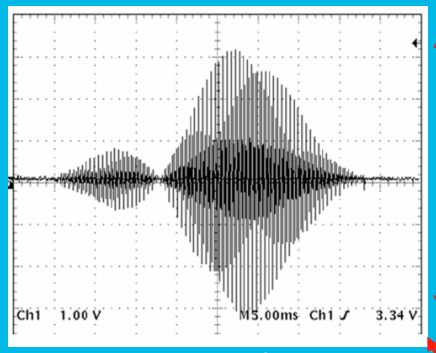
FFT



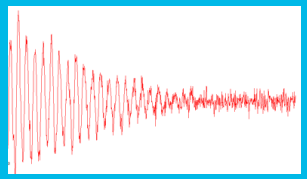


Scheme for FIDCSI pulse sequence.

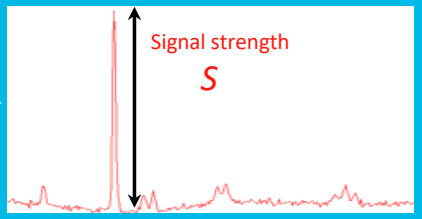
Spin excitation

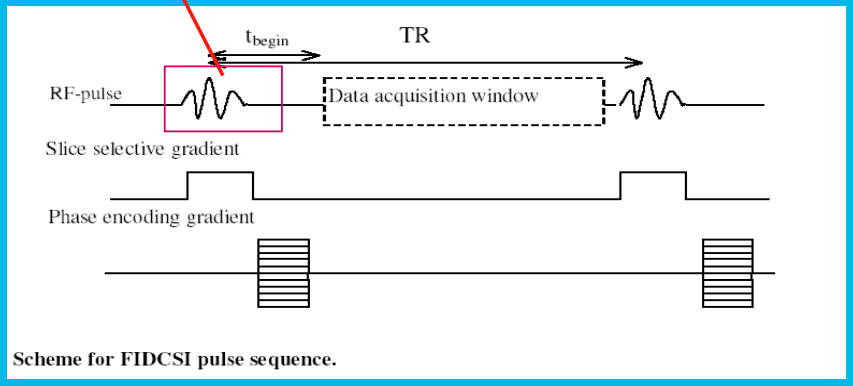


Oscilloscope image of a RF - pulse

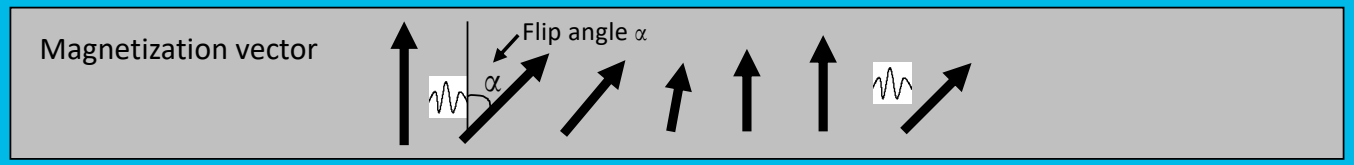


FFT





Scheme for FIDCSI pulse sequence.



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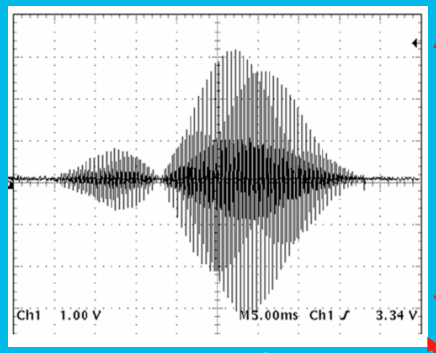
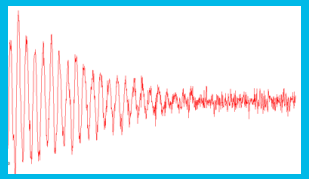
Quantitative MR

Spin excitation

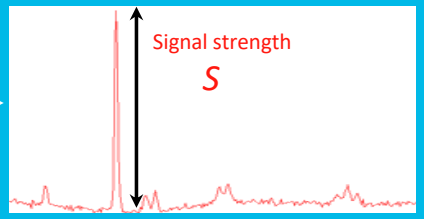


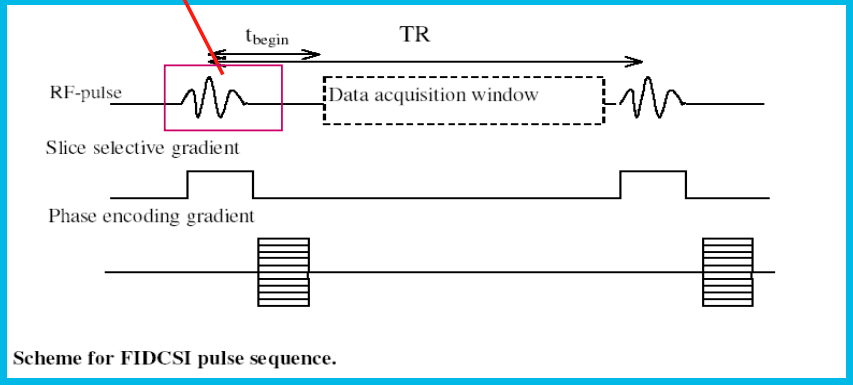
TA – Transmitter amplitude

Oscilloscope image of a RF - pulse



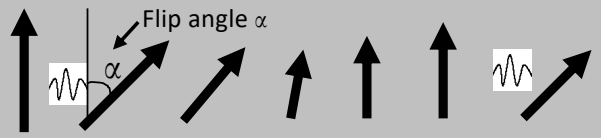
FFT



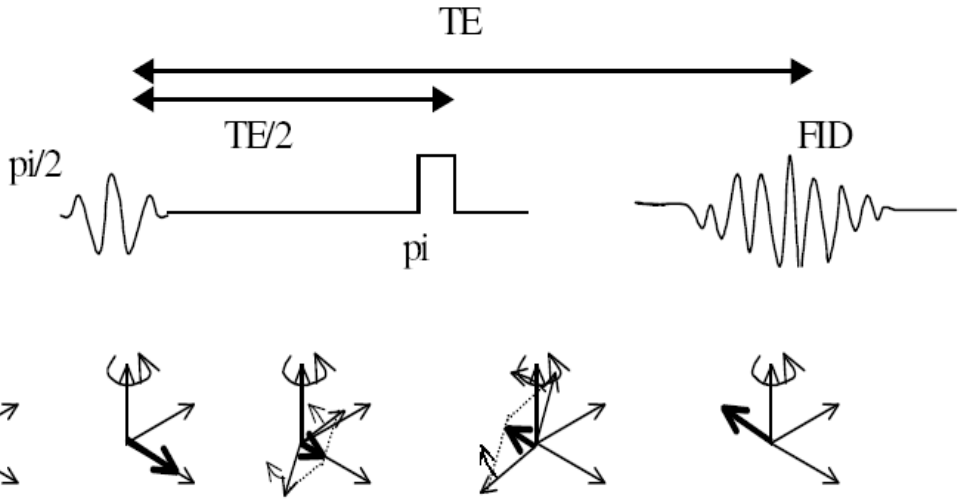


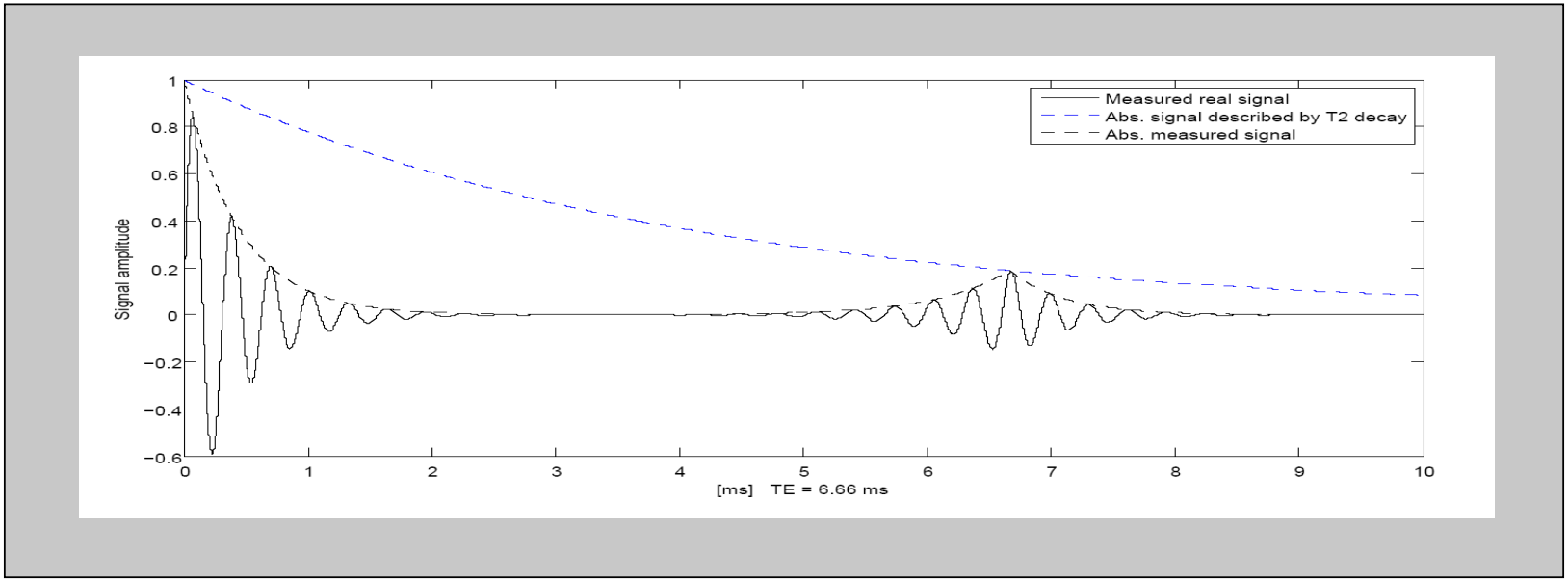
Scheme for FIDCSI pulse sequence.

Magnetization vector



Received signal


TE
TE/2
pi/2
pi
FID


Measured real signal
Abs. signal described by T2 decay
Abs. measured signal
Signal amplitude
[ms] TE = 6.66 ms

(Clever) brute force by QRAPMASTER

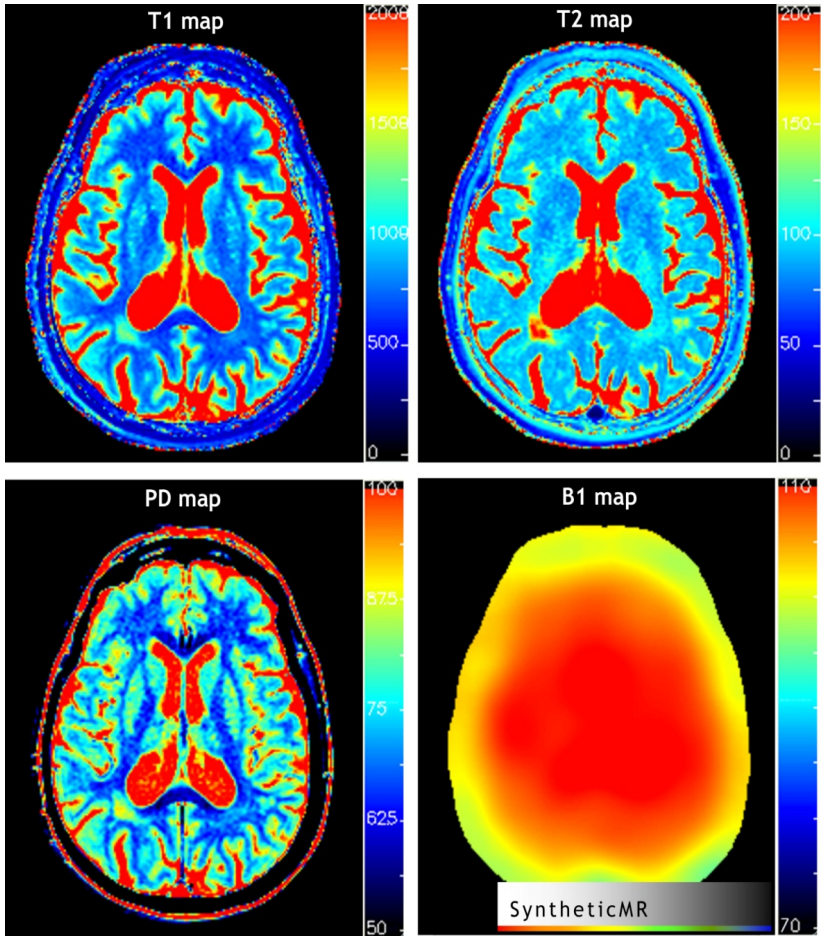
Try to correct for ”everything” based on data from one single scan

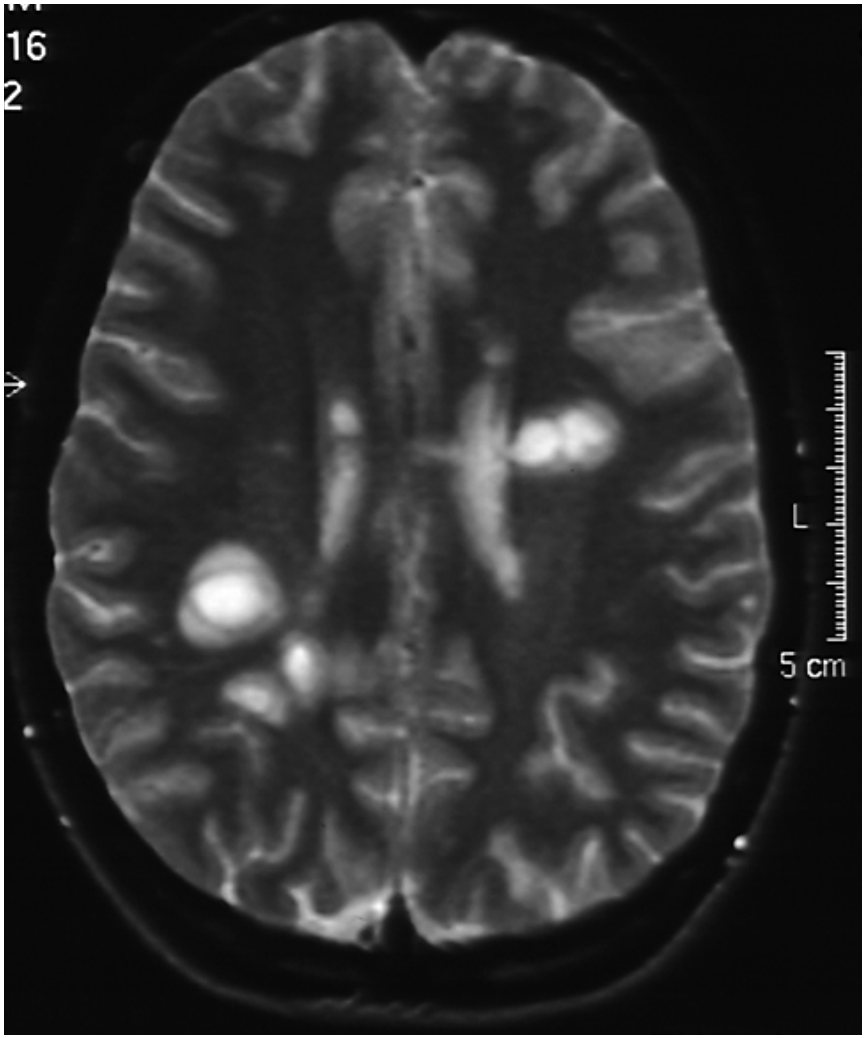
- T1 mapping by saturation recovery
- T2 mapping by multi echo (GRASE) spin echo imaging
- B1 by measuring the effectiveness of the saturation pulse
- Sensitivity correction via reciprocity priniciple and internal referencing
- Proton density (PD) after correction of everything
- Data is acquired in interleaved 2D slices, whole brain coverage in 1x1x4 mm3 res within 6 minutes.

Quantitative Magnetic Resonance Imaging

A fundamentally different approach is the absolute quantification of MRI parameters such as T1 and T2 relaxation and proton density. A special scan enables the absolute measurement of these MR parameters simultaneously, including even the B1 field homogeneity.

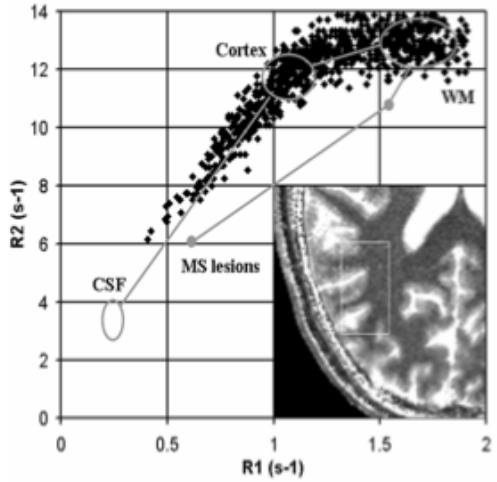
The example has a resolution of 1 x 1 x 5 mm
25 slices were acquired in 5:34 minutes on a patched 1.5T Philips Achieva R261.



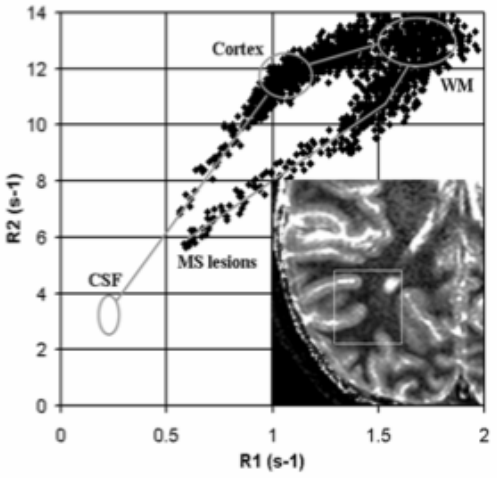

16
2
L
5 cm

Using the absolute values of T1, T2 and PD

Using Quantitative MRI similar tissue (Cerebro-spinal Fluid, Cortex, White matter) will always appear on the same place in a quantitative MR parameter space. Tissue can therefore be geometrically characterized into various types.
Differences from normal, healthy types is clearly seen in this parameter space and is quantitative, both in deviation as in volume.



Healthy volunteer

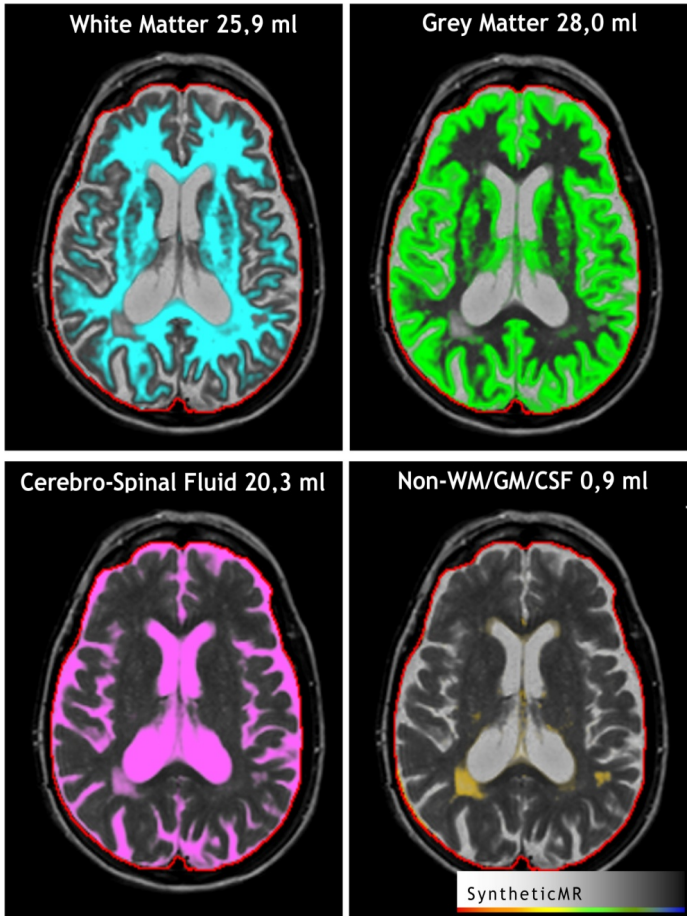


Multiple Sclerosis

Synthetic tissue images

Characterization of tissue types provides a rapid and robust workflow for diagnose. Instantly images are synthesized showing tissue parameters, tissue volume and tissue type.

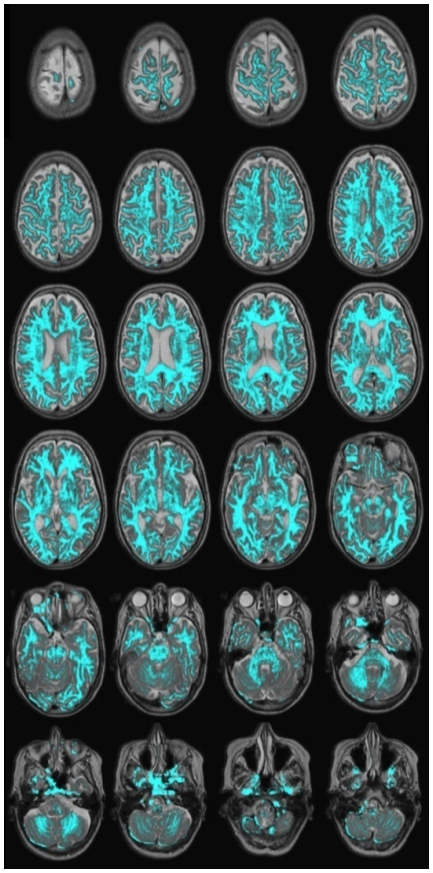
Very importantly, the user has access to an image containing the remaining tissue, Non-WM/GM/CSF, that indicates a high risk of pathology.



Automatic brain segmentation for atrophy follow-up

The Synthetic tissue images can be used for patient follow-up, for example to check for atrophy.

As an example this female from 1919 has an estimated 362 ml white matter, 592 ml grey matter and 312 ml CSF. The total brain tissue volume is 954 ml with a filling fraction of 75%.



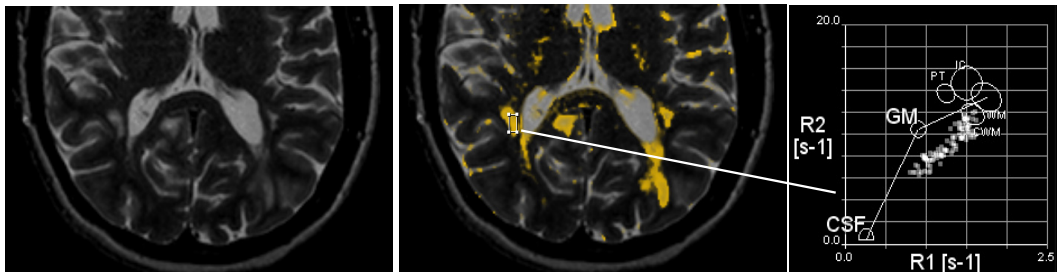
Only white matter is shown

Slice	WM	GM	CSF	Non
1	0,3	0,8	13,0	0,4
2	3,3	9,2	14,9	0,3
3	5,2	13,9	18,3	1,0
4	8,2	19,2	18,3	1,0
5	11,7	24,7	17,1	1,1
6	17,6	26,6	15,9	1,2
7	20,6	29,3	14,1	2,1
8	27,4	28,0	12,7	3,3
9	27,6	26,9	16,3	3,9
10	27,9	27,6	18,5	2,8
11	28,4	30,3	17,3	2,7
12	27,6	31,9	17,0	2,2
13	28,1	34,0	16,0	1,9
14	25,0	36,4	15,0	1,9
15	24,8	35,4	12,2	2,4
16	19,9	34,9	12,2	2,6
17	14,9	36,0	12,0	1,7
18	10,4	32,5	11,6	2,0
19	8,2	30,1	10,7	1,9
20	8,4	22,1	10,9	1,5
21	6,3	20,0	8,3	1,2
22	4,9	18,9	4,3	1,3
23	3,3	14,5	3,0	1,7
24	2,0	9,1	2,7	1,3
	362	592	312	43

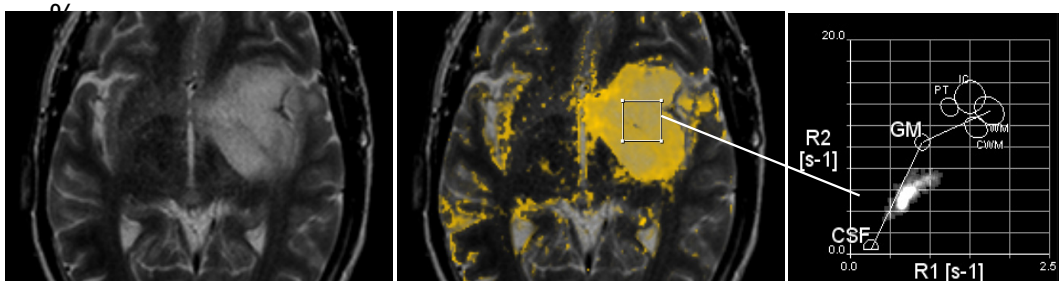
Pathology characterization

The Non-WM/GM/CSF map can be used for pathology characterization and volume estimation. Many neuro-degeneative diseases behave differently in the quantitative MR parameter space.

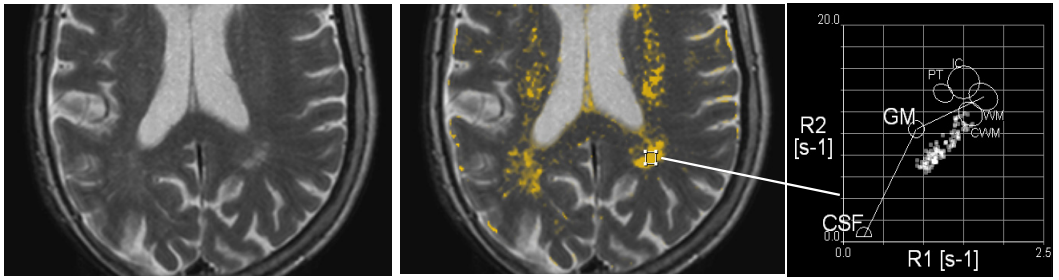
A relaxation rate R1-R2 plot is show with data from the ROI's. There are clear differences between Multiple Sclerosis, Tumors and Ischemic lesions. As a reference the CSF, GM and WM clusters are displayed in the plot.



Multiple Sclerosis R1 = 1.1 s^{-1}, R2 = 8.2 s^{-1}, PD = 96 %



Tumor R1 = 0.7 s^{-1}, R2 = 5.3 s^{-1}, PD = 98 %

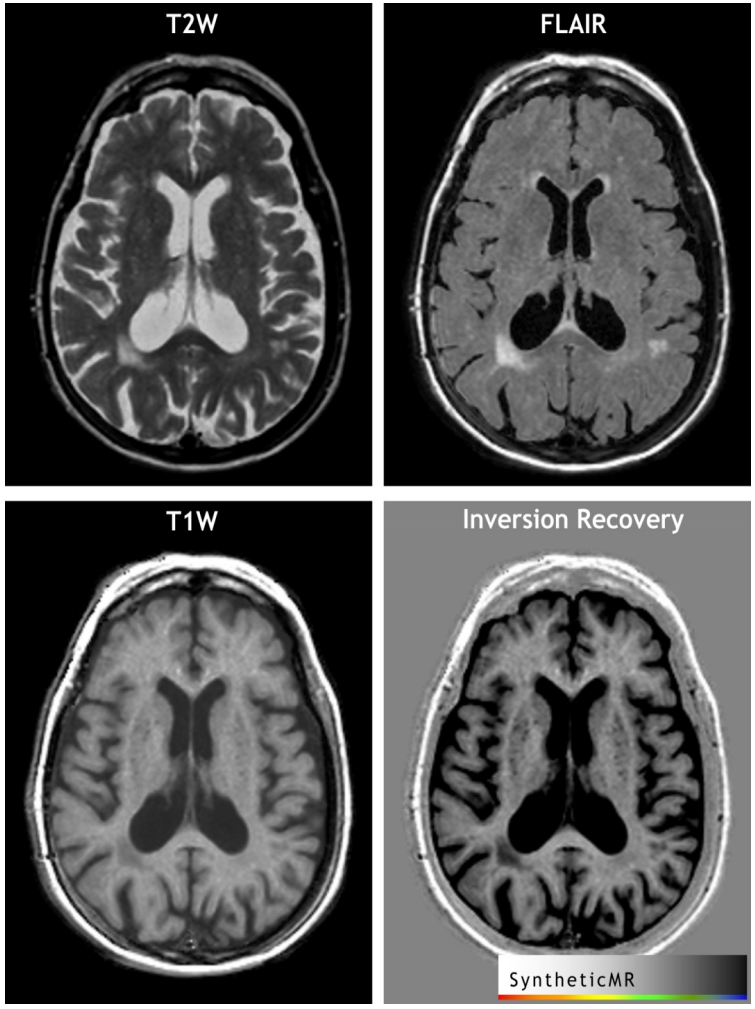


Ischemia R1 = 1.2 s^{-1}, R2 = 8.5 s^{-1}, PD = 74 %

Synthetic MRI images

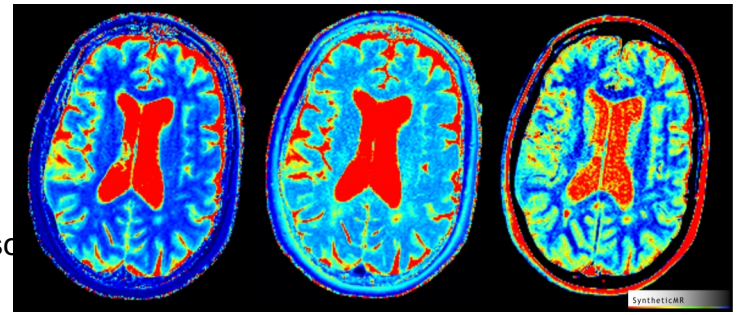
To confirm the results, or to check for certainty, Synthetic MRI images can be shown, using the same input scan. These images may even replace some of the conventional scans of the examination.

Based on T1, T2 and PD any T1-weighted, T2-weighted, FLAIR or Inversion Recovery image can be synthesized, with a free choice of echo time T_E, repetition time T_R and inversion delay $T_{inversion}$, without rescanning the patient.

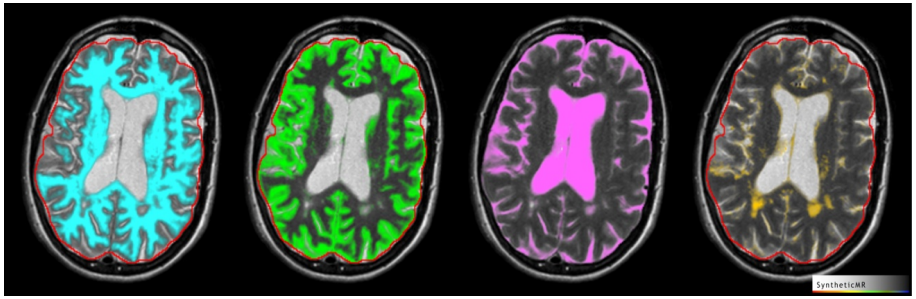


Summary of the Synthetic MRI approach

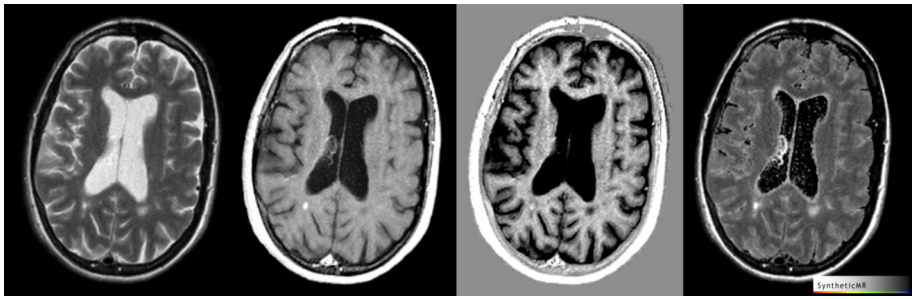
Quantitative parameter maps
-> Tissue characteristics from one single sc
-> Reduced scan time



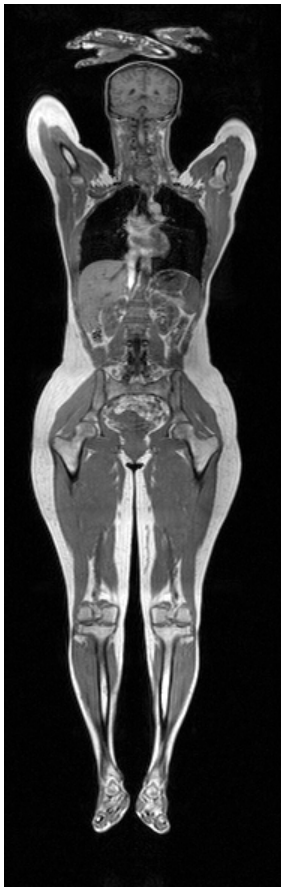
Synthetic tissue images
-> Quantitative status and follow-up
-> Faster image interpretation time

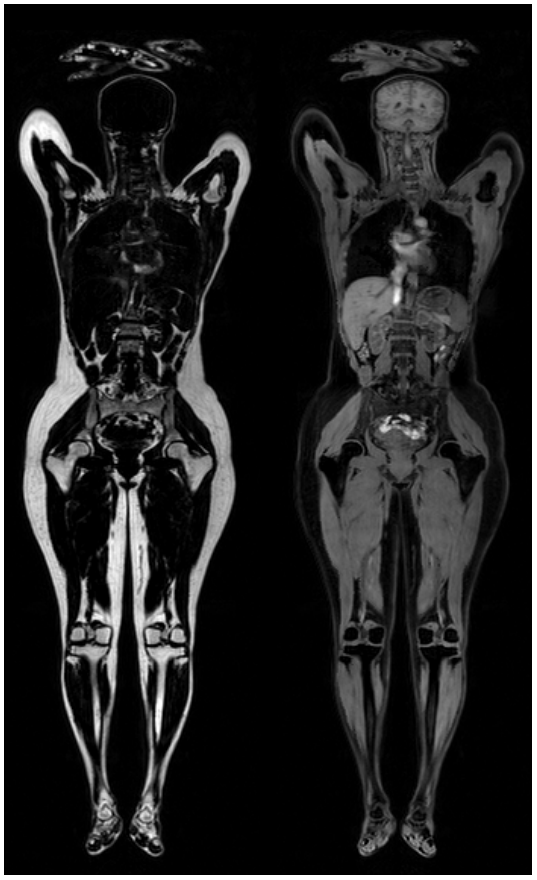


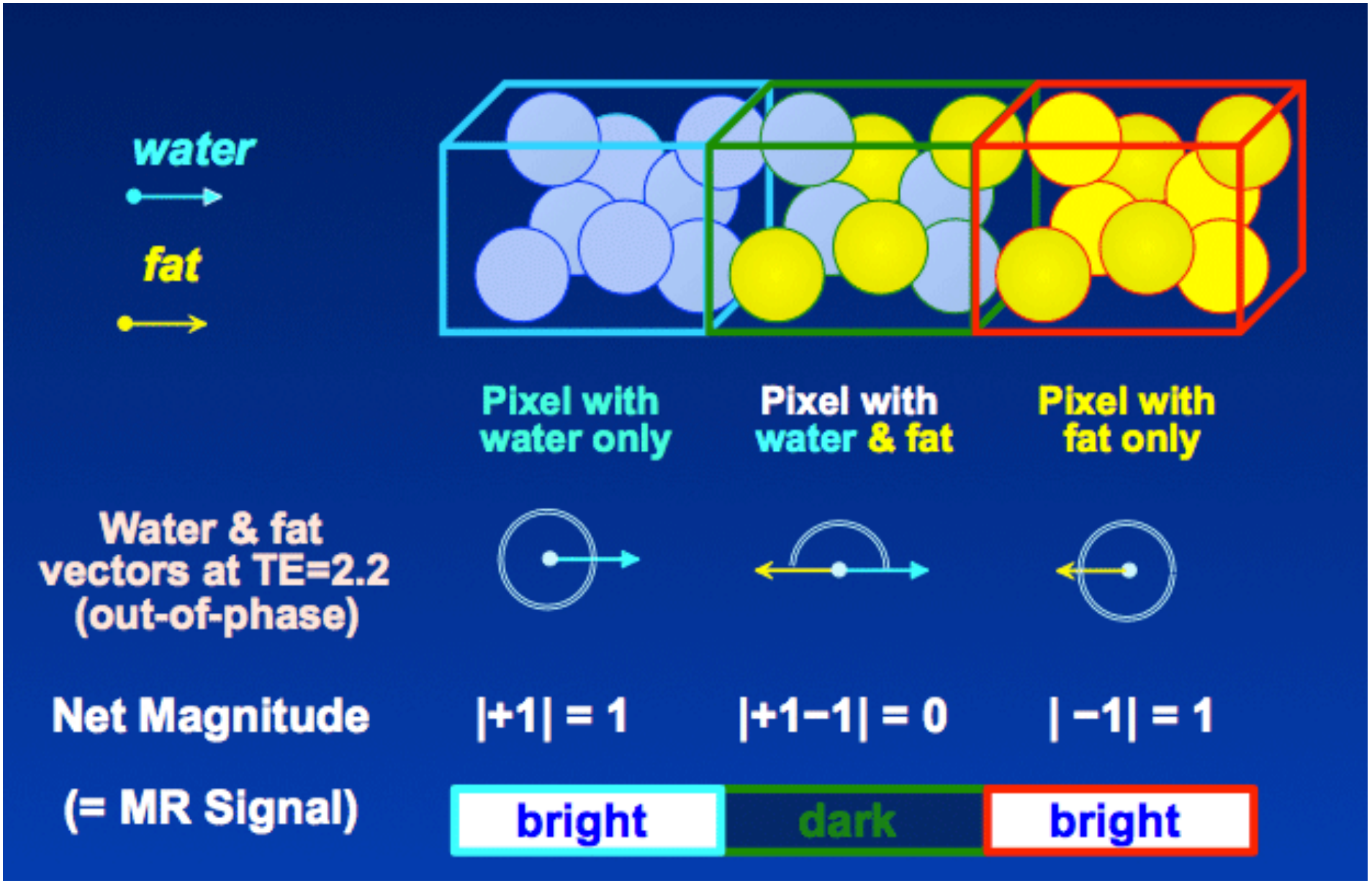
Synthetic MRI images
-> Visual diagnosis support
-> Scanner protocol optimization

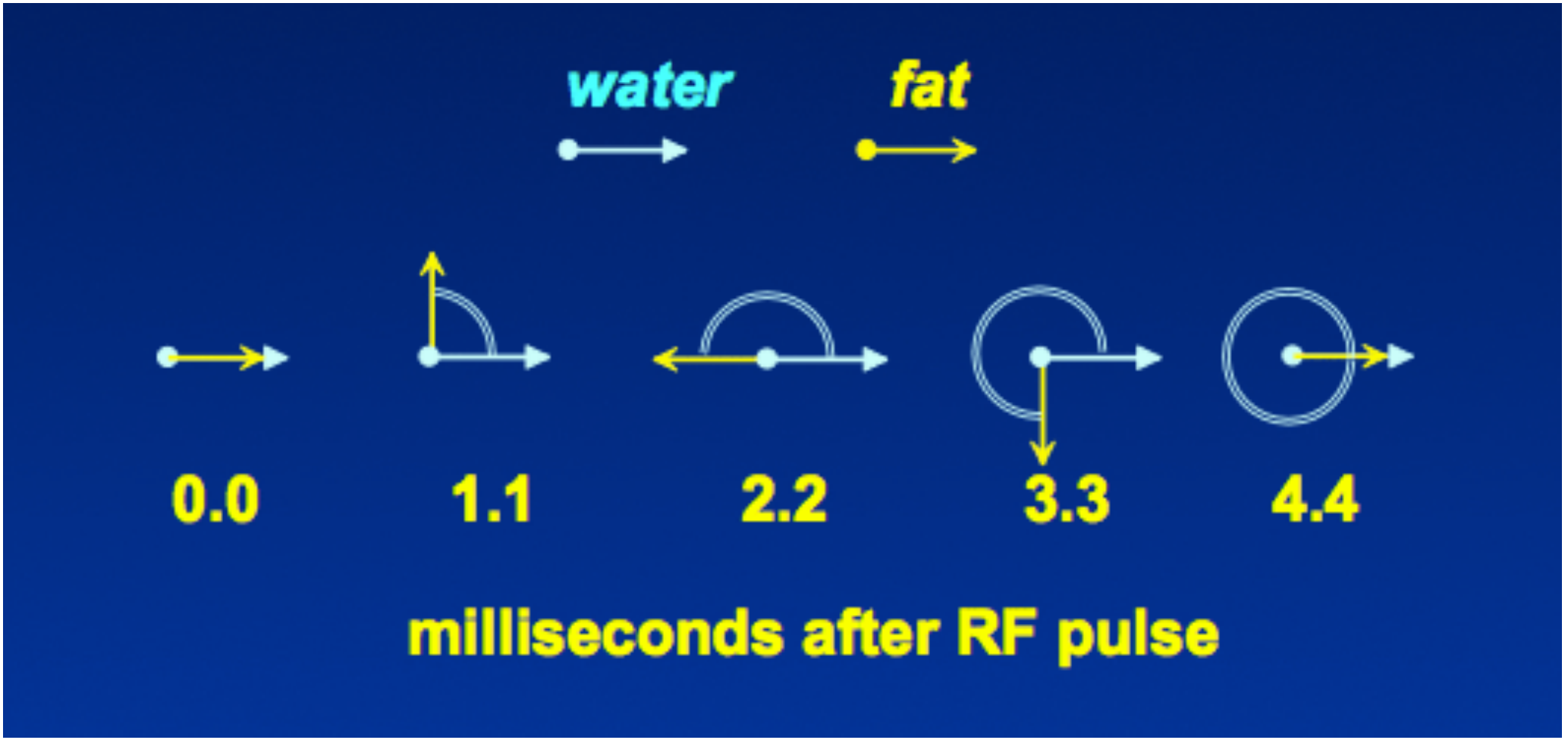


Fat-water separated imaging - Dixon






water
fat
Pixel with water only
Pixel with water & fat
Pixel with fat only
Water & fat vectors at TE=2.2 (out-of-phase)
Net Magnitude
|+1| = 1
|+1−1| = 0
| −1| = 1
(= MR Signal)
bright
dark
bright


water
fat
0.0
1.1
2.2
3.3
4.4
milliseconds after RF pulse

Fat/Water Imaging

- 2-point Dixon – a simplified view
  - Acquire two echoes
    - Fat and water in opposed phase: OP = F - W
    - Fat and water in phase: IP = F + W
  - Calculate fat and water images
    - F = ½ (IP + OP)
    - W = ½ (IP - OP)

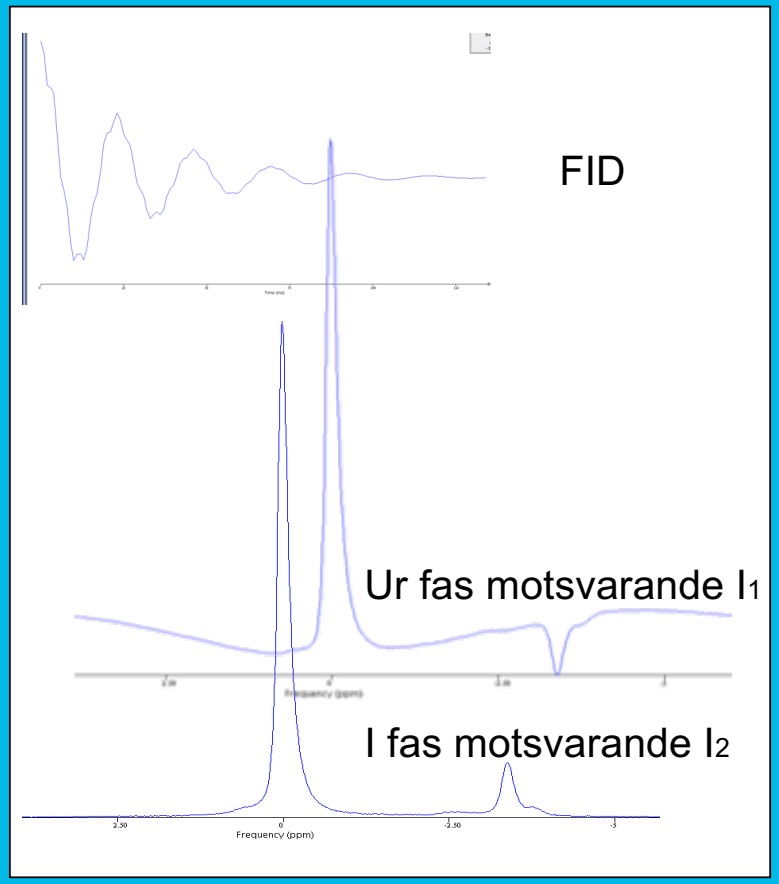
2 point Dixon

$$I_1 = (w - f)e^{i\phi_1}$$
$$I_2 = (w + f)e^{i\phi_2}$$

$$\tilde{I}_1 = I_1 e^{-i\tilde{\phi}_1} \approx w - f$$

$$\tilde{I}_2 = I_2 e^{-i\tilde{\phi}_2} \approx w + f$$

$$\tilde{I}_1 + \tilde{I}_2 = w - f + (w + f) = 2 \cdot w$$
$$\tilde{I}_2 - \tilde{I}_1 = w + f - (w - f) = 2 \cdot f$$



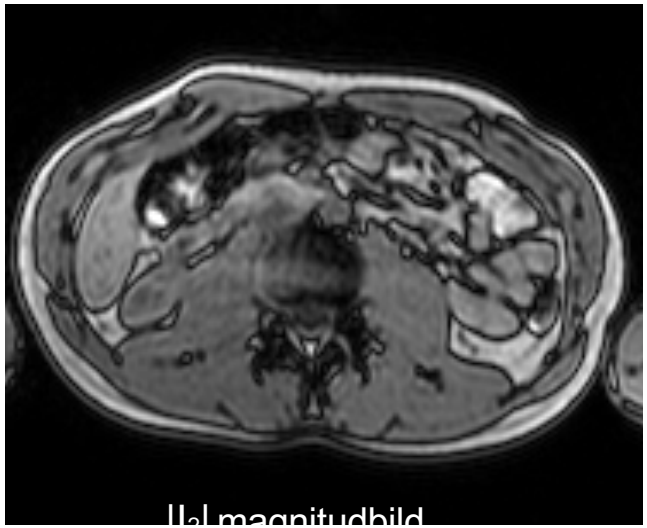
Protonspektrum av vatten och fett

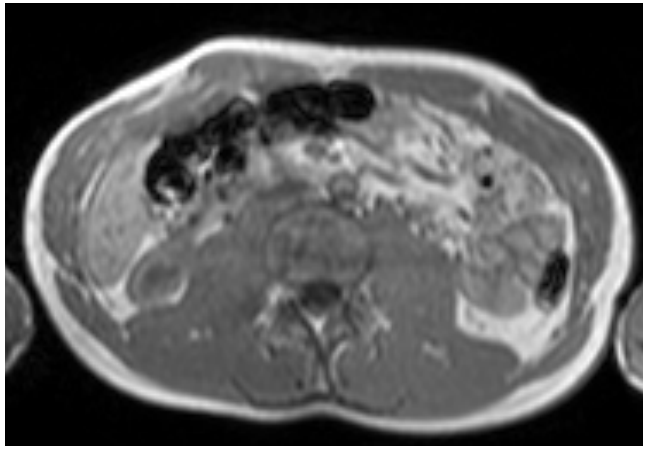
$$I_1 = (w - f)e^{i\phi_1}$$
$$I_2 = (w + f)e^{i\phi_2}$$

$$\tilde{I}_1 = I_1 e^{-i\tilde{\phi}_1} \approx w - f$$

$$\tilde{I}_2 = I_2 e^{-i\tilde{\phi}_2} \approx w + f$$

$$\tilde{I}_1 + \tilde{I}_2 = w - f + (w + f) = 2 \cdot w$$
$$\tilde{I}_2 - \tilde{I}_1 = w + f - (w - f) = 2 \cdot f$$

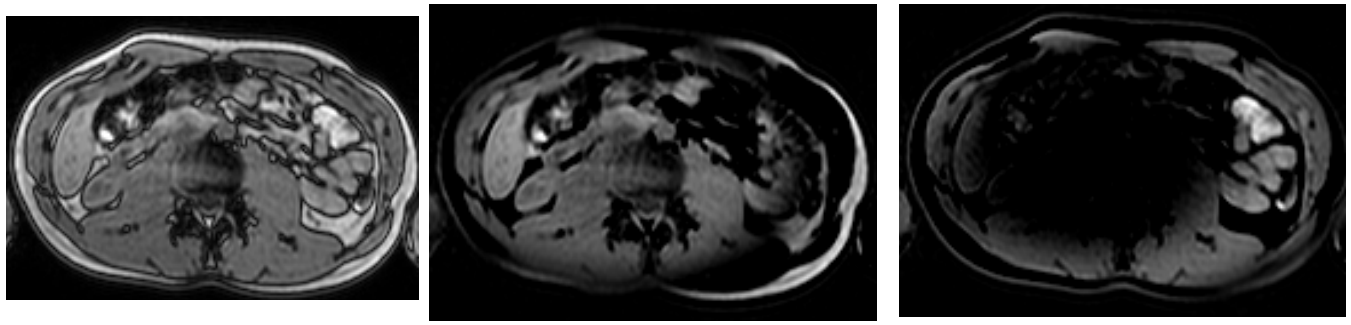


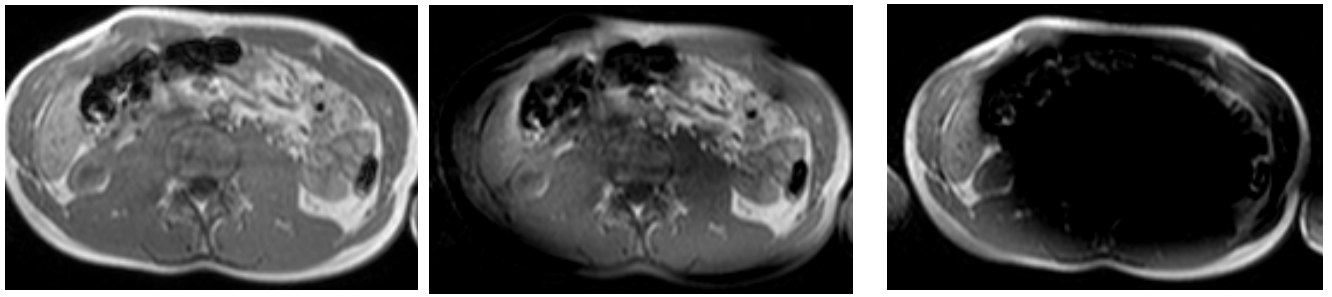


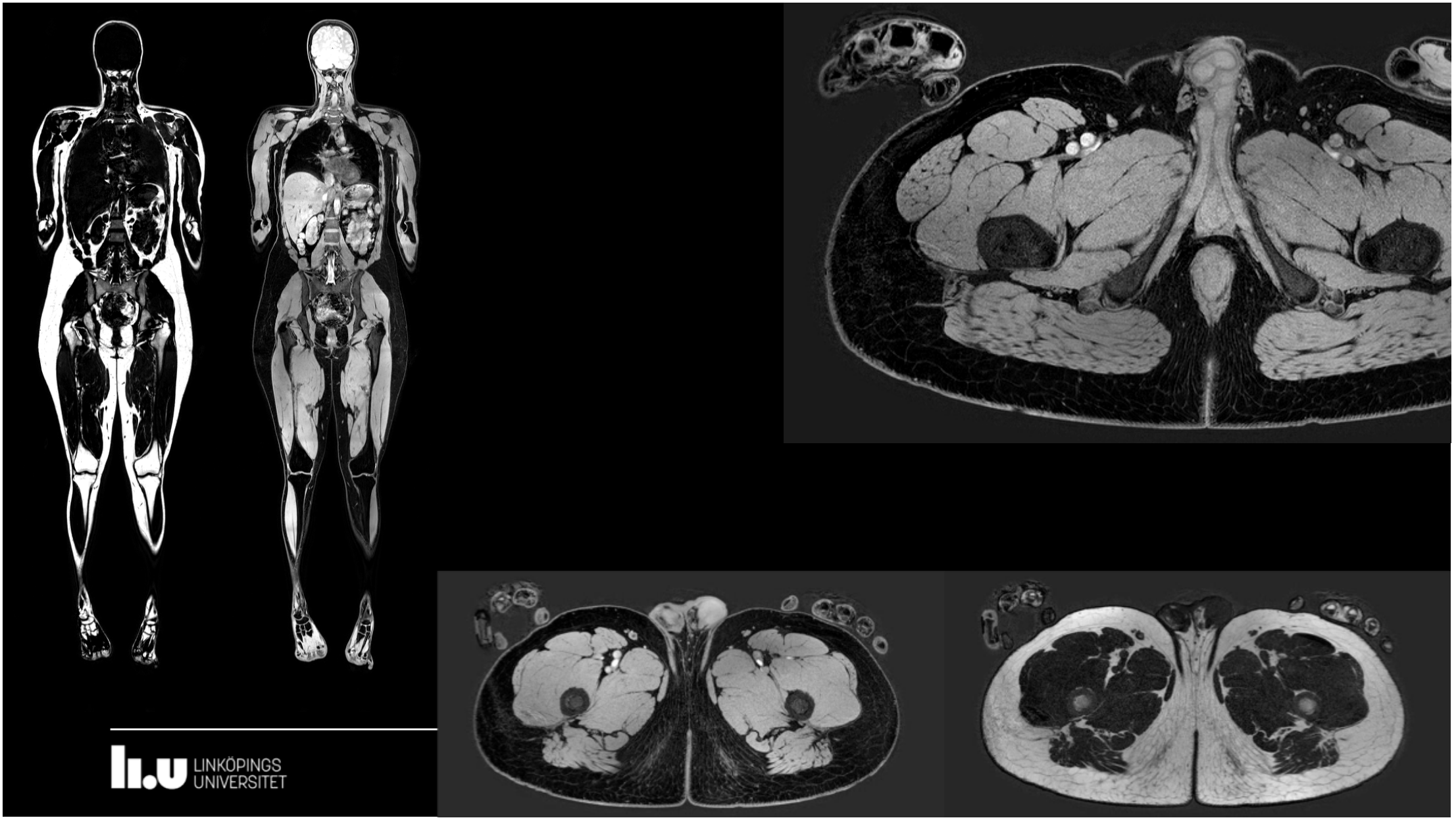
$$I_1 = (w - f)e^{i\phi_1}$$
$$I_2 = (w + f)e^{i\phi_2}$$

$$\tilde{I}_1 = I_1 e^{-i\tilde{\phi}_1} \approx w - f$$

$$\boxed{\tilde{I}_2 = I_2 e^{-i\tilde{\phi}_2} \approx w + f}$$



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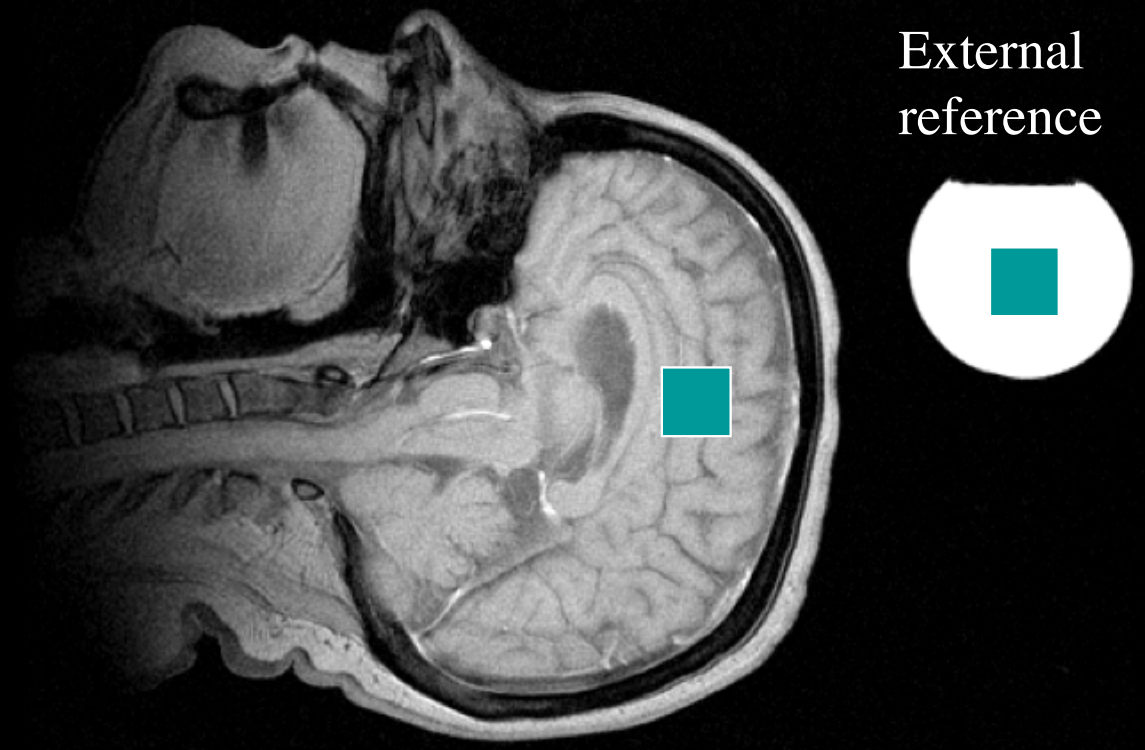
Machine constant calibration

- By including an external reference in the experiment. C may be estimated if the B_1 field is measured in the different positions.

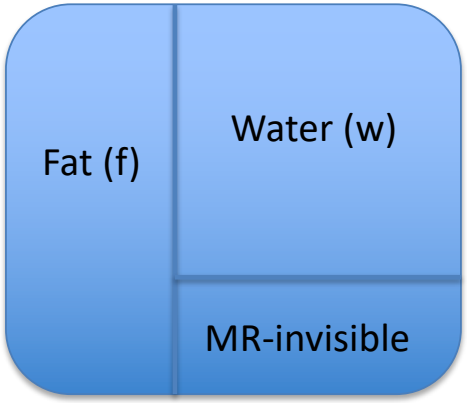


Internal reference calibration

- Find tissue or tissue properties that can be used to find the local sensitivity
  - Fat in subcutaneous tissue
  - Total proton content in tissue
  - Metabolite in brain or pure water …
- Advantages
  - Both B1- and B1+ can be measured
  - Often more robust to signal saturation
  - Often only solution – modern scanners is difficult to calibrate with external references
- Disadvantages
  - You rely on an internal reference that can be affected by measurement or disease.

The Proton Density Fat Fraction (PDFF)!!?

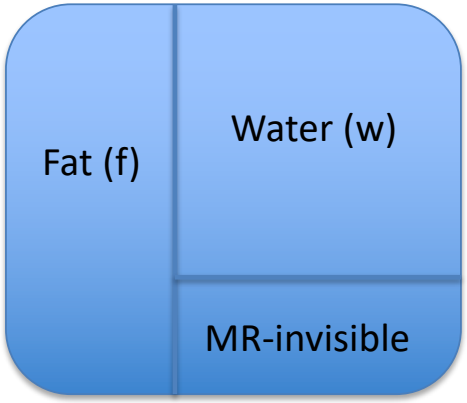
- Most MR-quantification of concentrations uses water signal referencing.
- PDFF is usually used for fat quantification.
- PDFF is defined as f/(f+w), f and w are relaxation corrected fat and water signal.
- PDFF
  - removes dependency on variable MR scanner sensitivity.
  - is well validated in liver fat quantification. (using MRS and liver biopsies)
  - Assumes that $\text{fraction}_{\text{water}}$ is proportional to $\text{fraction}_{\text{MR-invisible}}$
  - Not always true – MR-invisible varies with air, signal voids, fibrosis etc.



The Proton Density Fat Fraction (PDFF)!!?

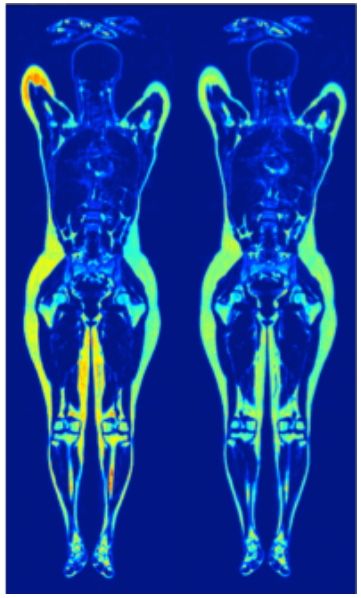
- The fat and water signals are dependent on several factors:
  - Sensitivity of coils,
  - flip angle, TE and TR
  - T1,
  - T2(*),
  - fat/water separation technique, signal cross talk etc.
- PDFF dependent on strong assumption of high certainty of T2* and T1 estimation,
  T2* and T1 mapping is time consuming,
- Accuracy depends on low flip angle, implies low SNR and time consuming multi echo acquisition.

I.e. Not compatible with rapid high resolution whole body coverage

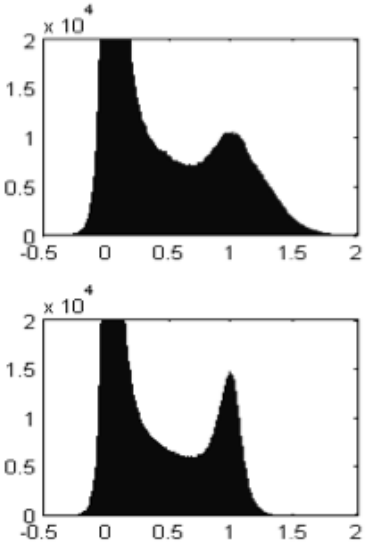


Consistent Intensity Inhomogeneity Correction - CIIC

- Creates quantitative fat image*
- Pure adipose tissue is used as an internal reference
- A bias field is interpolated using Multi scale Adaptive Normalized Averaging (MANA)** and is compensated for.



Before After



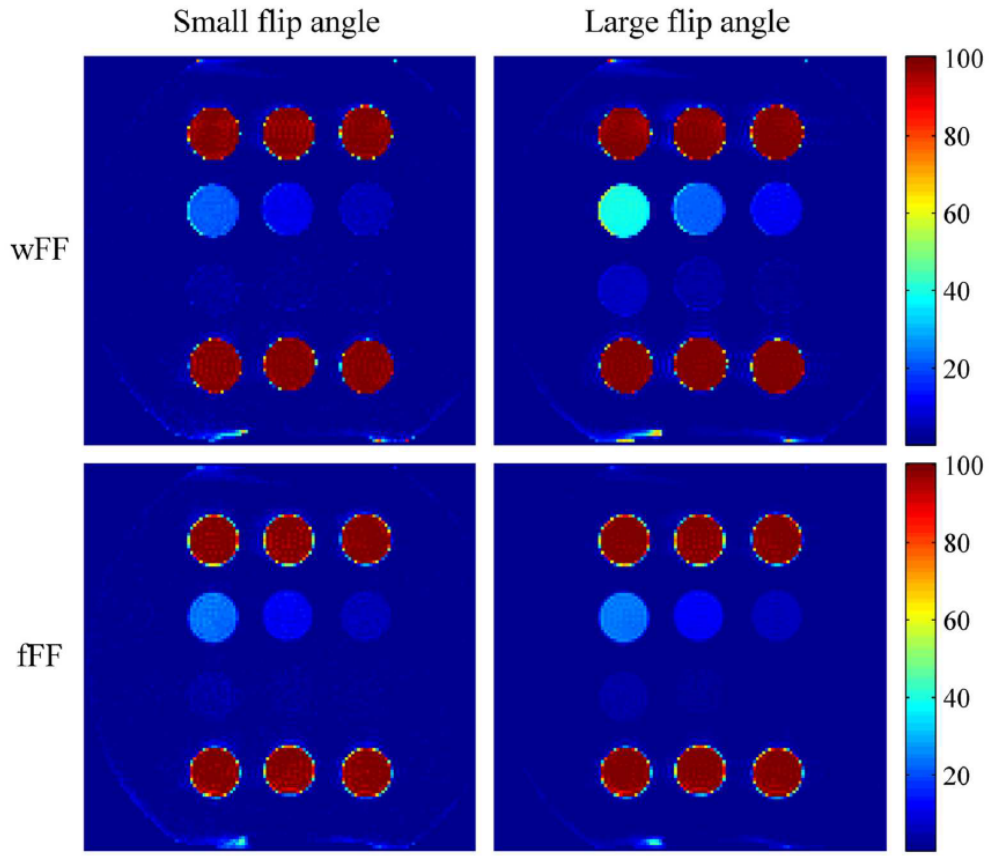
Before

Fat signal histogram

After

*Dahlqvist Leinhard et al, ICPR 2008. **Romu et al, ISBI 2011, Andersson et al jMRI, 2015.

Fat referencing allows robust fat quantification with high SNR scanning



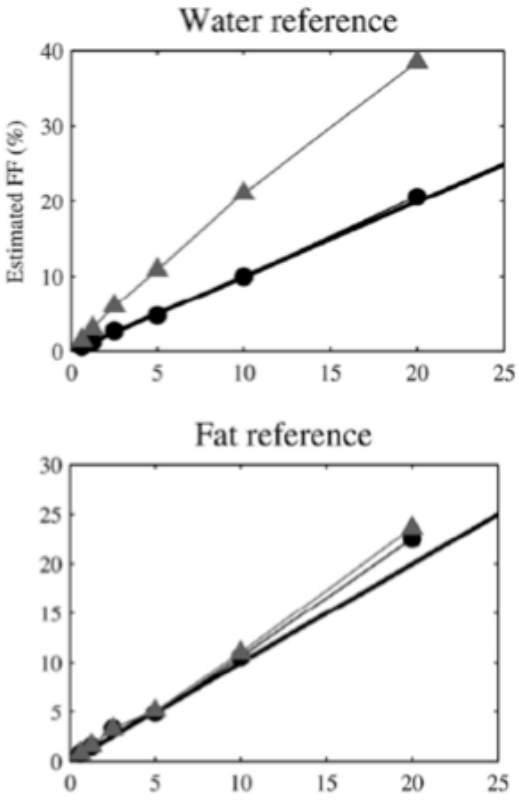
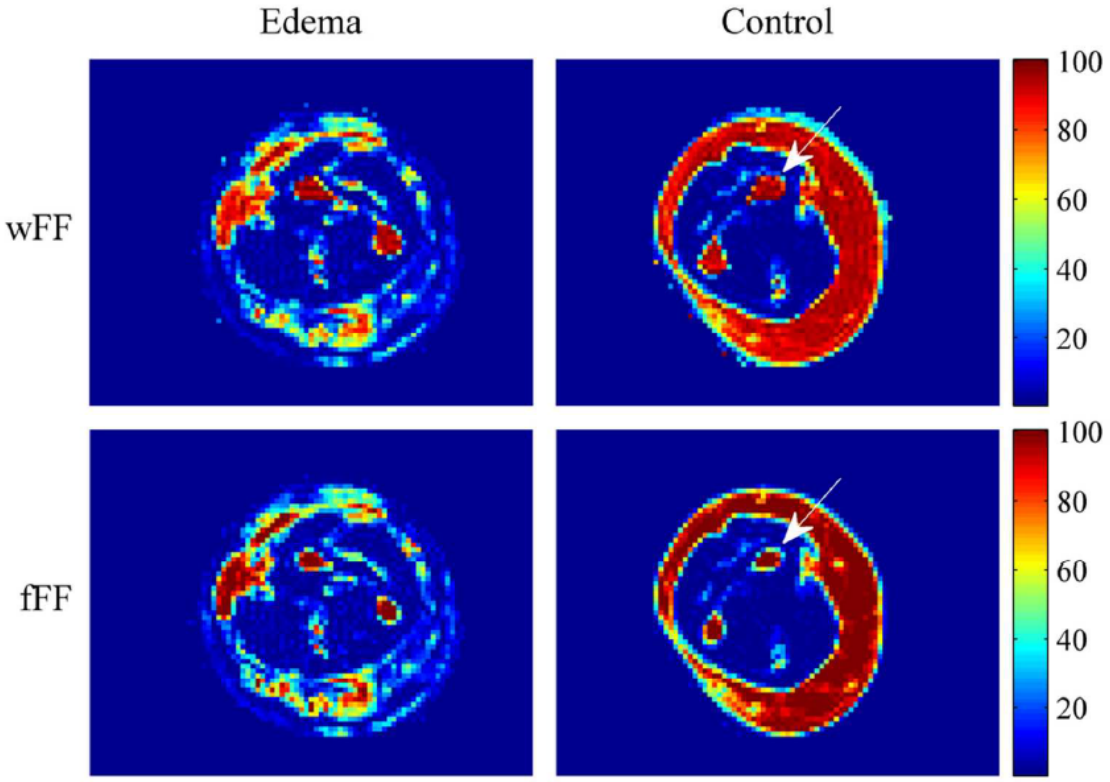


Figure 1. Phantom small (left) and large (right) flip angle wFF (top) and fFF (bottom) maps. The color scale represents a FF range from 0 % (blue) to 100 % (red). Six soybean oil vials (three in top and three on bottom) were included to provide a fat reference for fFF reconstruction. The two center rows of vials contain Intralipid/water mixtures with FFs ranging from 20 % (top left) to 0.63 % (bottom right). The large flip angle wFFs are higher compared to the large flip angle fFFs.

Peterson et al. jMRI 2015

Fat referencing allows robust fat quantification of intra muscular adipose tissue (IMAT) in vivo



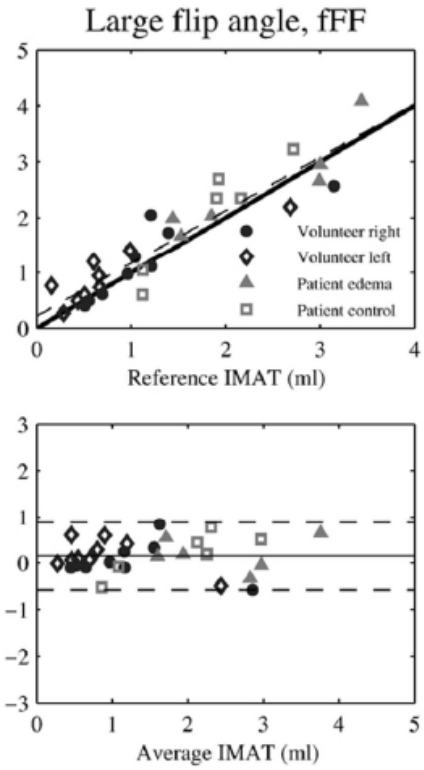


Figure 4. Examples of small flip angle wFF (top row) and fFF (bottom row) maps of the edematous, liposuctioned arm (left column) and healthy arm (right column) of a lymphedema patient. The color scale represents a FF range from 0 % (blue) to 100 % (red). Only small areas of adipose tissue remain in the subcutaneous layer of the liposuctioned arm. The white arrow point to an example in which the FF estimation in bone differ between the fat and water reference approaches.

Peterson et al. jMRI 2015

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