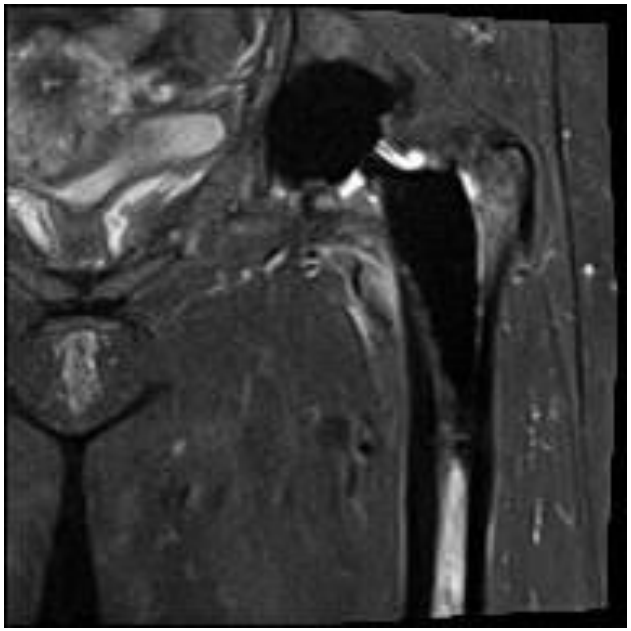
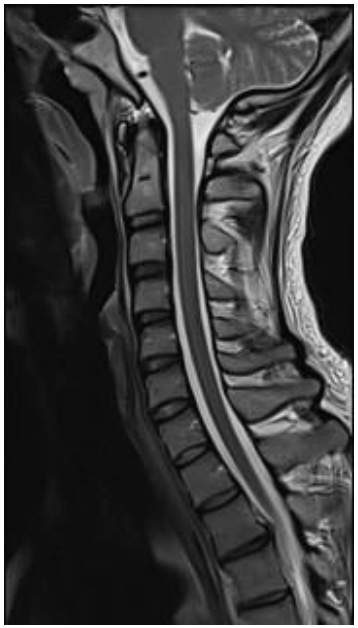
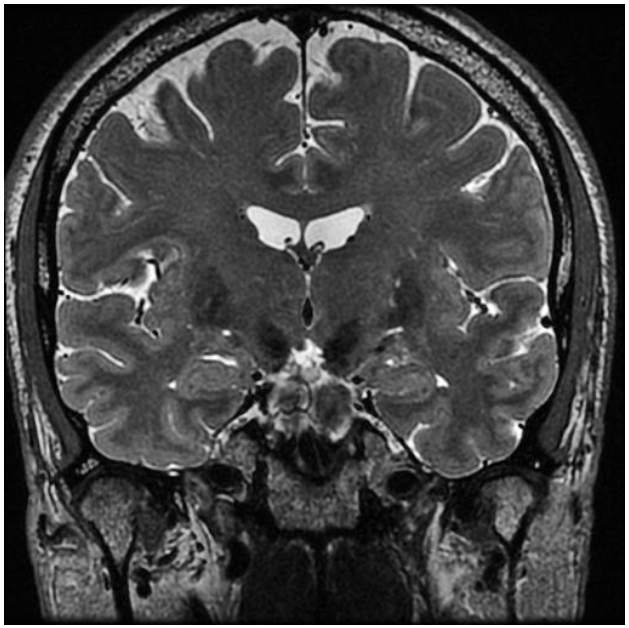
Magnetic Resonance Imaging

F.R.C.R. Physics Lectures

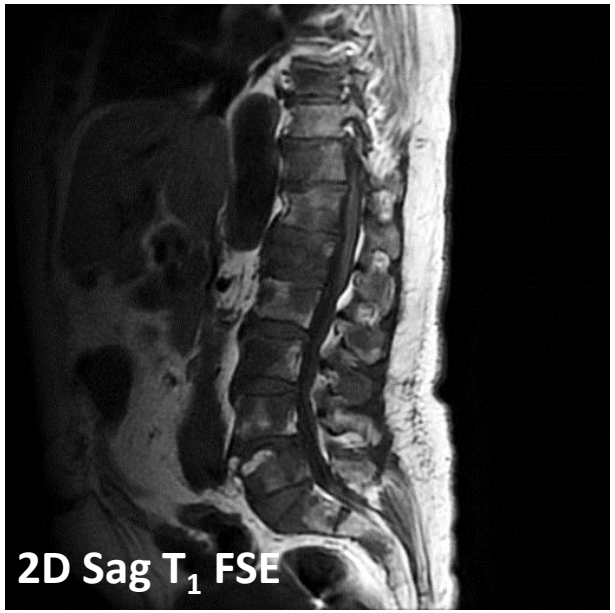
Lawrence Kenning PhD

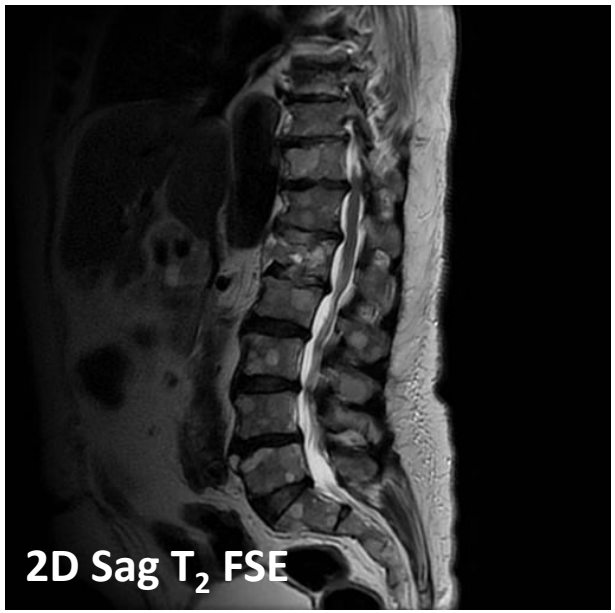
7.4 Frequency-dependant techniques

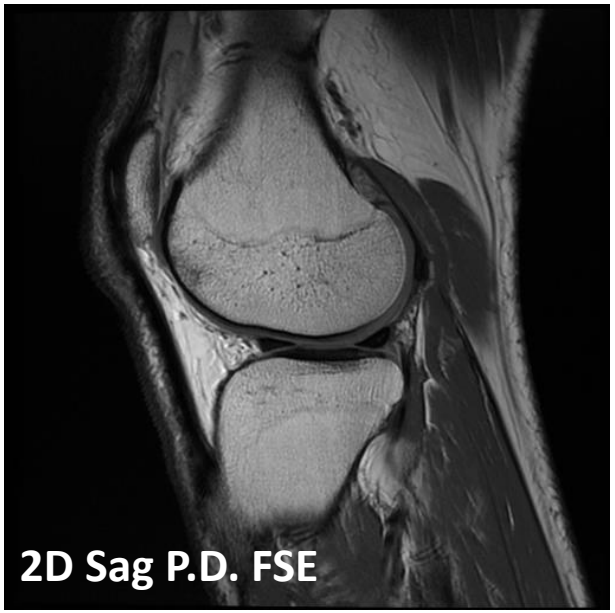
- Understanding of chemical shift: fat & water
- Fat saturation
- In-phase & out-of-phase TEs, Dixon
- Awareness of MR spectroscopy (MRS) and appropriate TEs for particular clinical questions

Fat issue

- Fat is hyperintense (bright) signal on T_1, T_2 and P.D. weighted imaging
- On T_2 and P.D. weighting imaging fluid is hyperintense
- On T_1 weighed post-contrast imaging, the effect of gadolinium is hyperintense

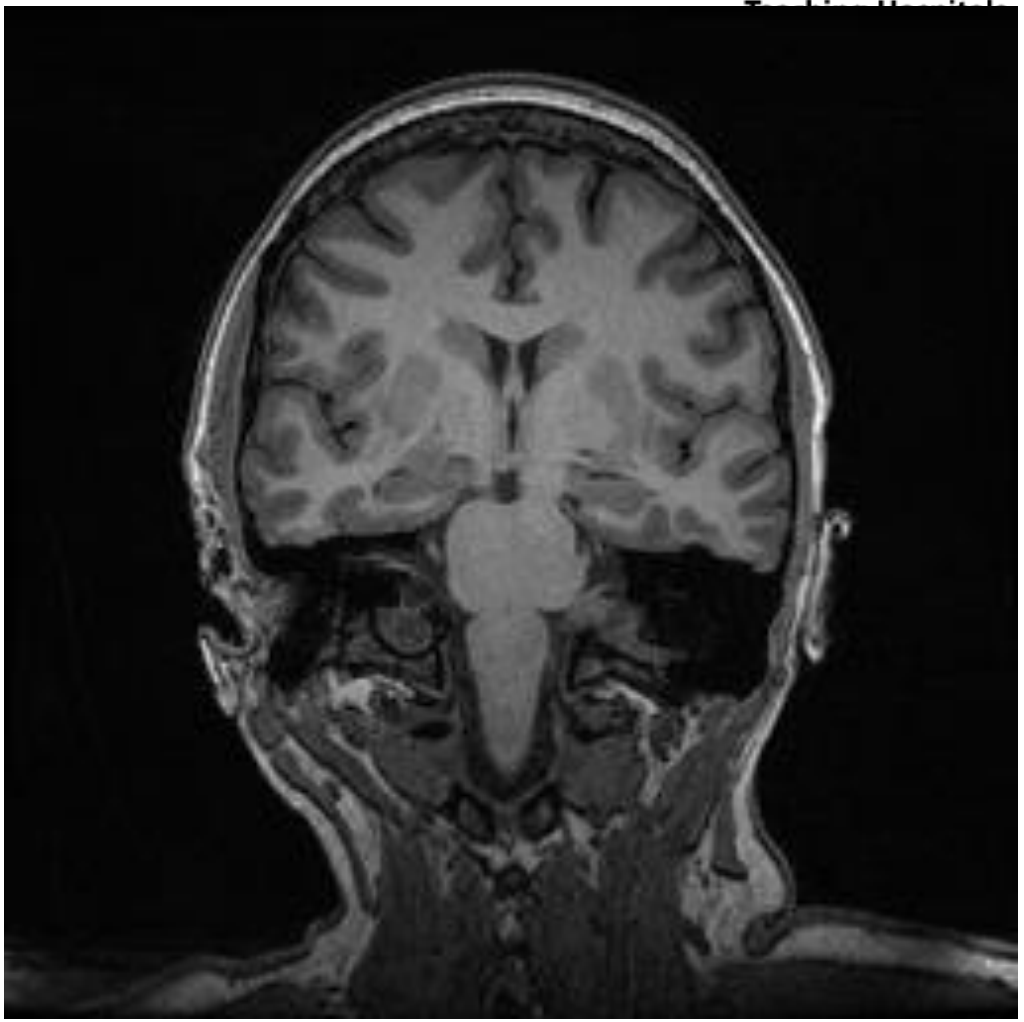




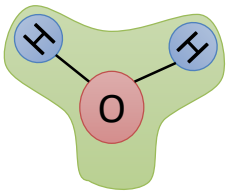


Water and Fat Molecules

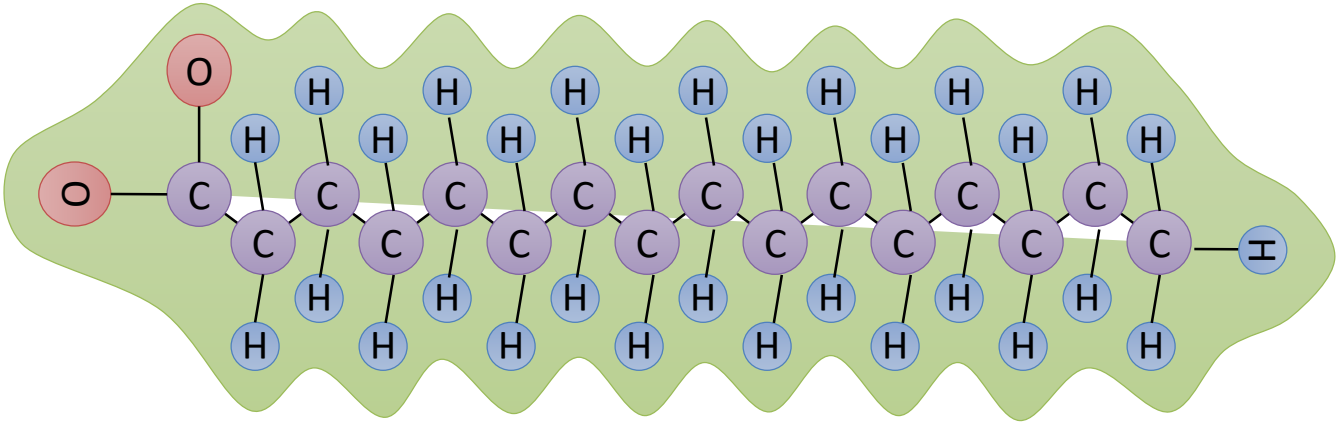
- Signal from water and fat both originate from **protons** but there are two key differences:
- **Relaxation Times**
- **Chemical Shift**



Water molecule H_2O



Fat molecule $-CH_2-$



- Fat has a shorter T_1 relaxation rate than water
- The two dominate fat peaks (1.3ppm and 0.9ppm) experience a lower local magnetic field (B_0) due to the electron shielding compared to water (4.7ppm)
- Fat precesses at a lower frequency than water

Tissue	T_1 1.5T (ms)
Fat	260
Liver	500
Grey Matter	900
CSF	2400

Chemical Shift

- electron cloud around an atom shields the nucleus from the magnetic field (σ):

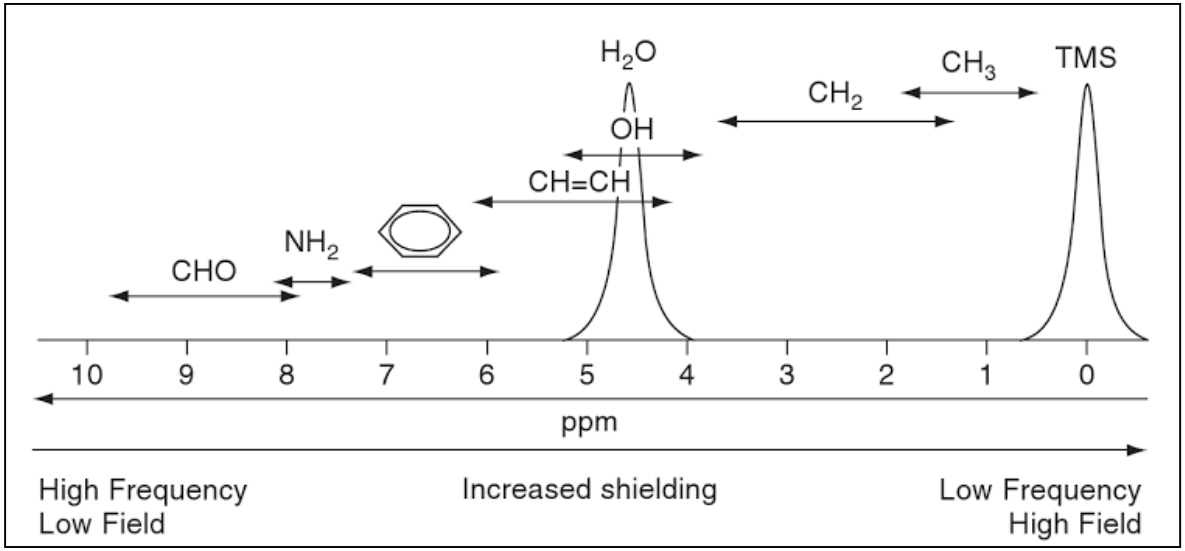
- different resonant frequencies for different molecules

$$\omega_0 = \gamma(1-\sigma)B_0$$

γ = gyromagnetic ratio

B_0 = magnetic field strength

ω_0 = resonant frequency



Water and Fat Molecules

- The two dominate fat peaks (1.3ppm and 0.9ppm) experience a lower local magnetic field (B_0) due to the electron shielding compared to water

- Fat precesses at a lower frequency than water

- Chemical shift is 3.5ppm

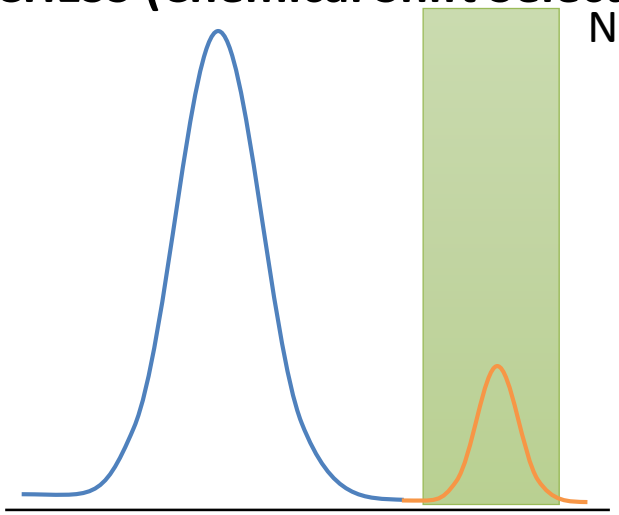
1.5T scanner the fat-water frequency difference (Δf)

$\Delta f = (64\ MHz)(3.5\ ppm) = (64 \times 10^6\ Hz)(3.5 \times 10^{-6}) \approx$ **<u>220 Hz</u>**

3.0T scanner the fat-water frequency difference (Δf)

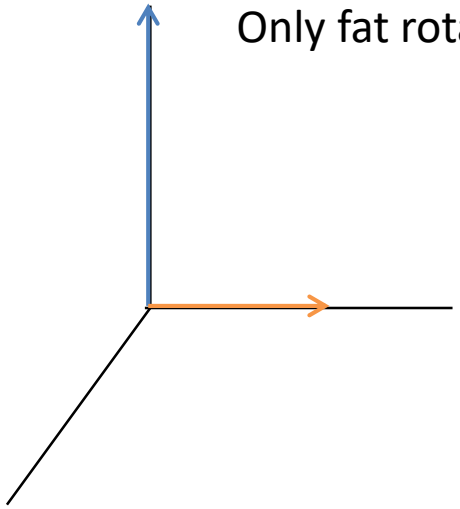
$\Delta f = (128\ MHz)(3.5\ ppm) = (128 \times 10^6\ Hz)(3.5 \times 10^{-6}) \approx$ **<u>440 Hz</u>**

CHESS (Chemical Shift Selective) aka 'fat sat'

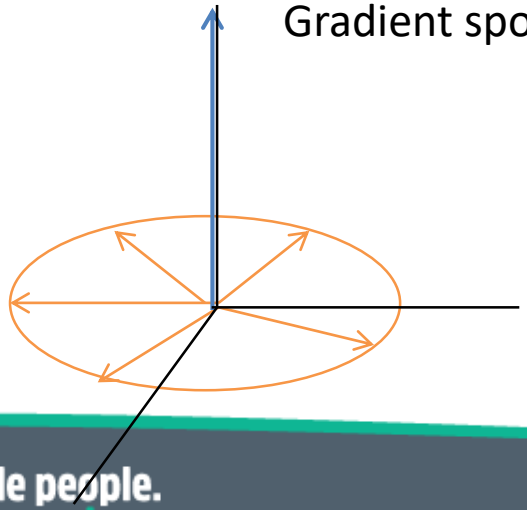


Narrow excitation RF pulse

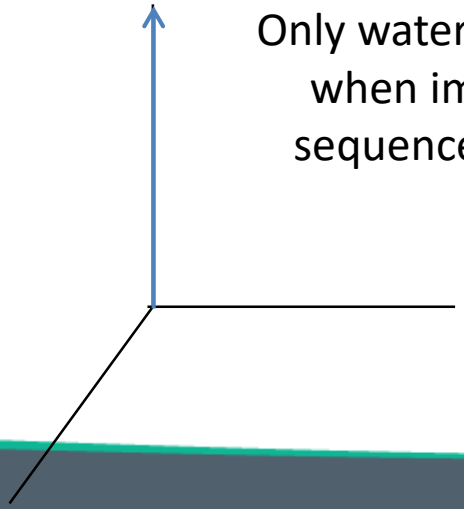
3.5ppm



Only fat rotated

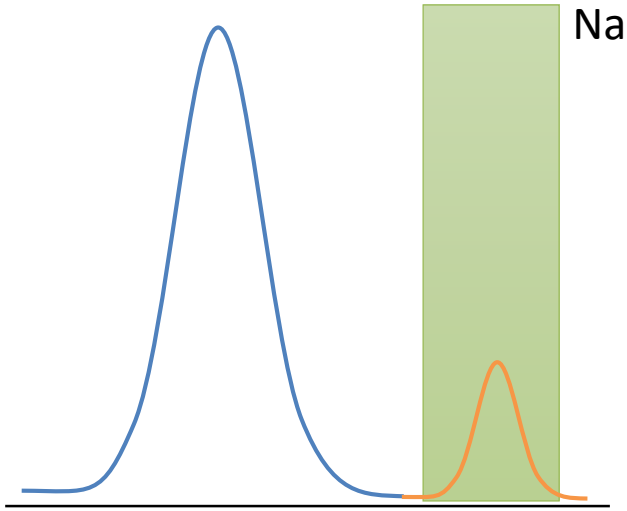


Gradient spoiling

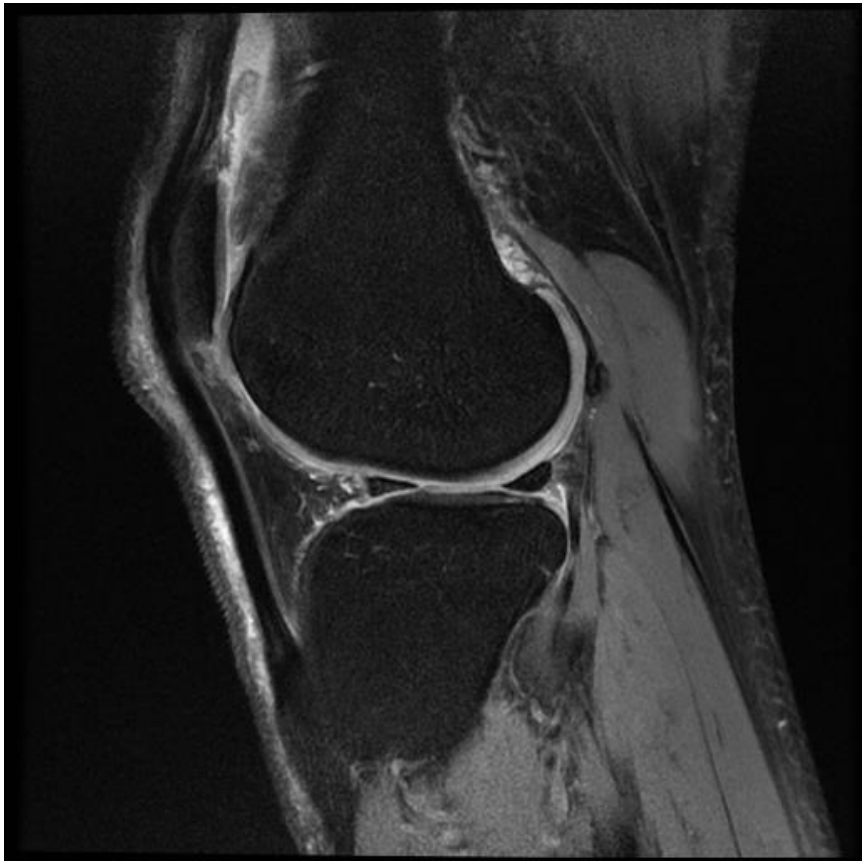


Only water remains when imaging sequence starts

CHESS (Chemical Shift Selective) aka ‘fat sat’



Narrow excitation RF pulse



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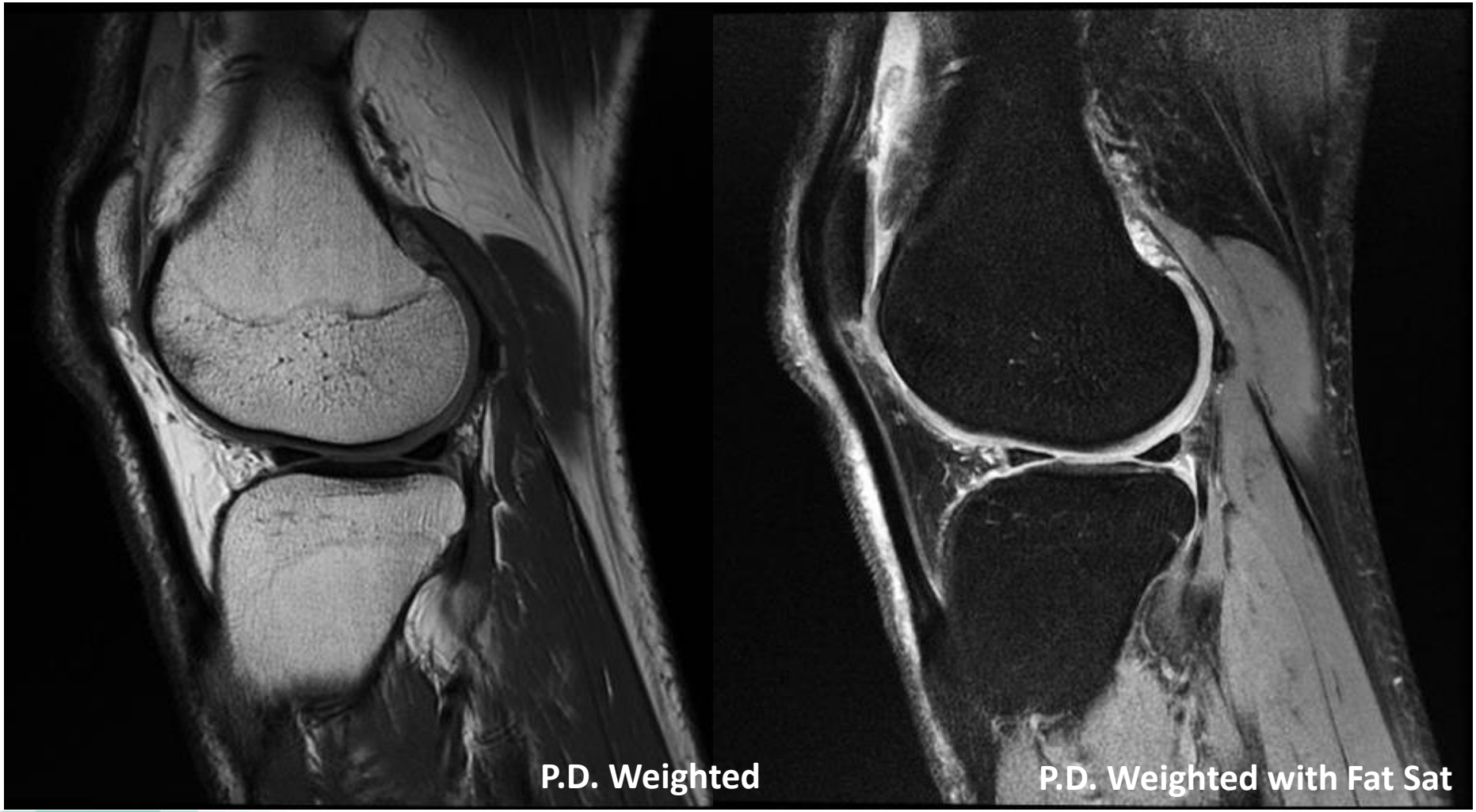

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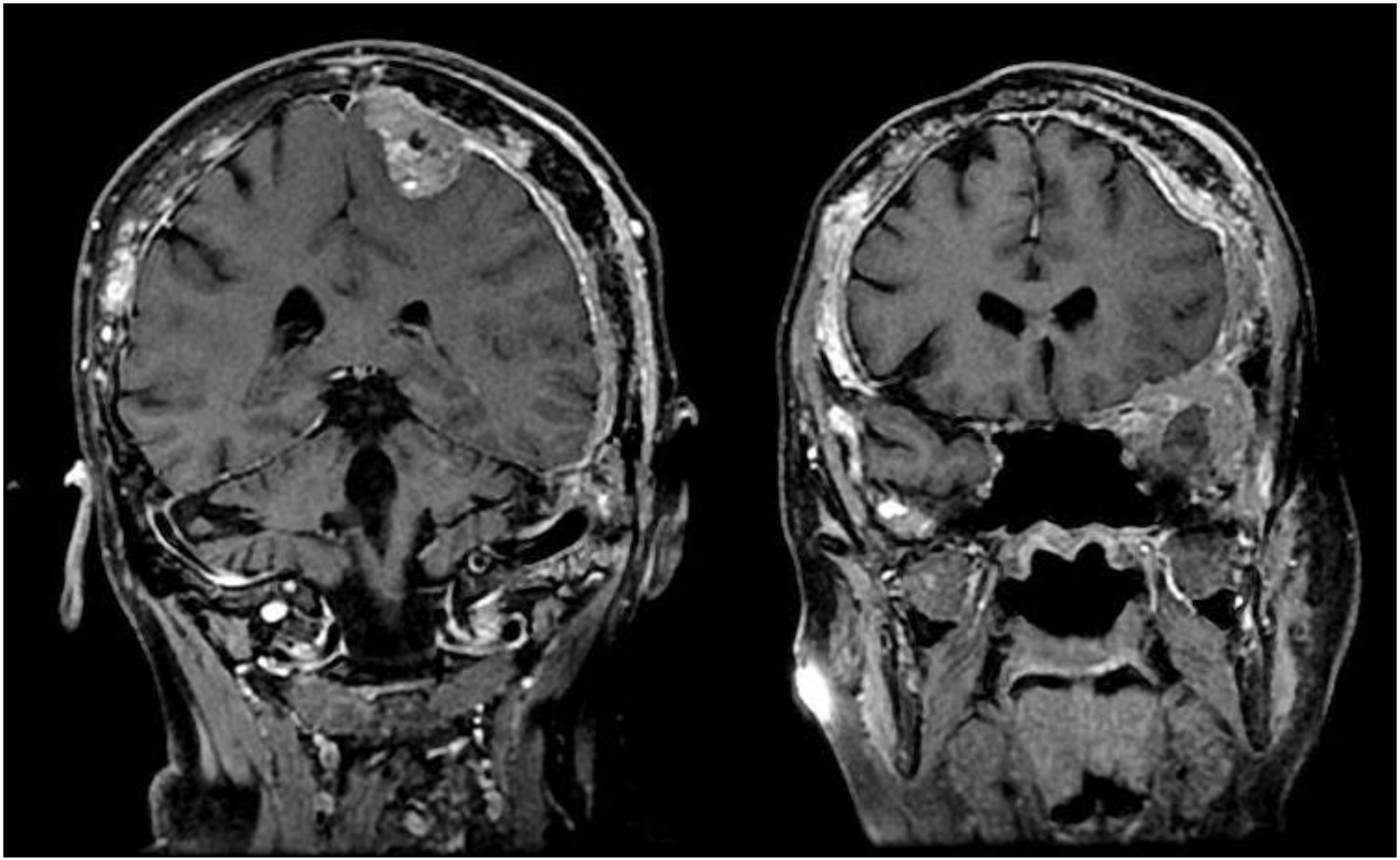


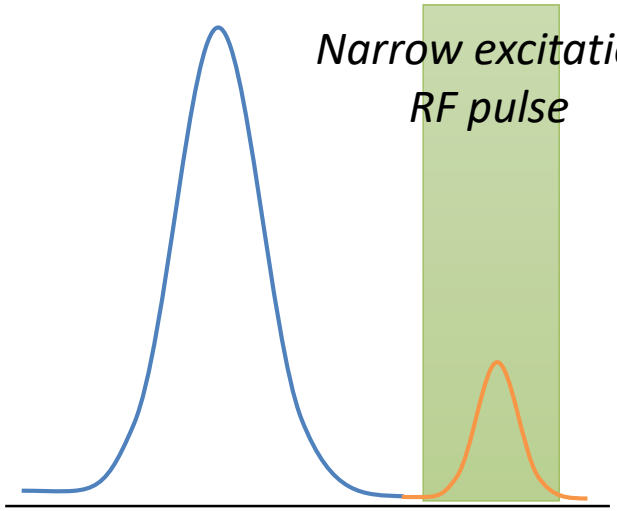
CHESS (Chemical Shift Selective) aka 'fat sat'

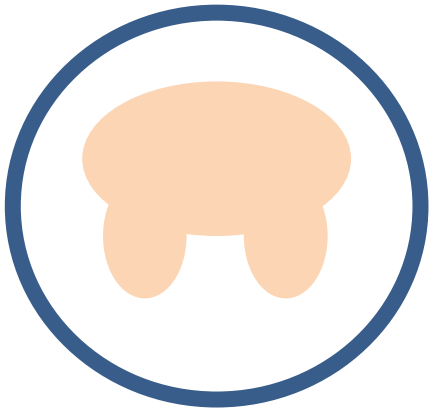
B_0 inhomogeneity – a lack of a homogeneous main magnetic field

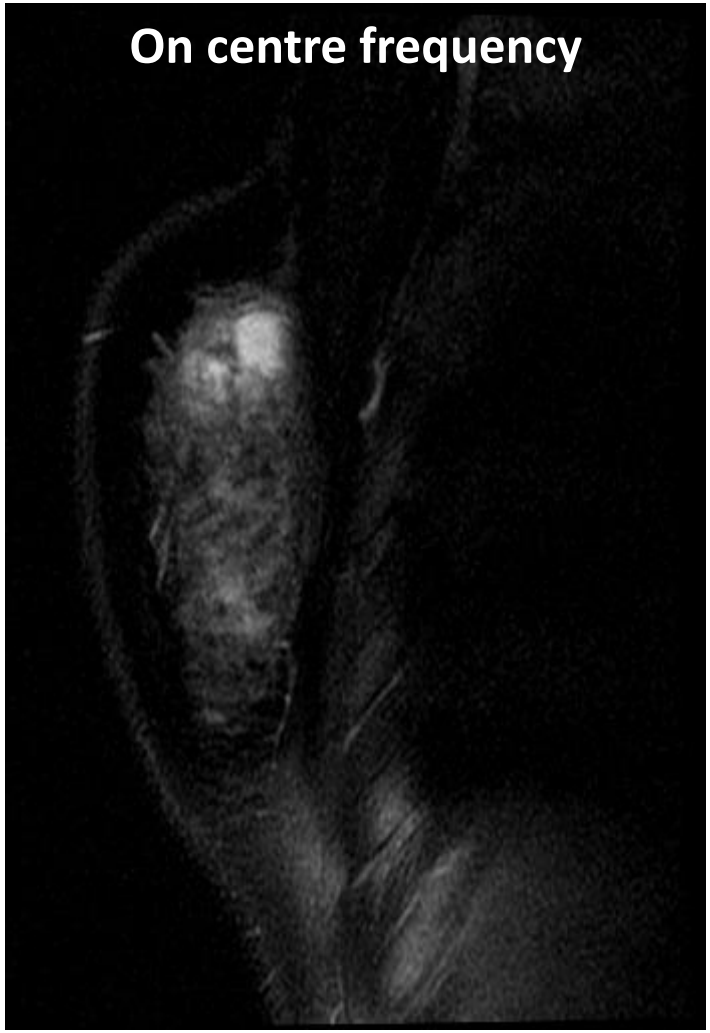
- Different locations within the imaging volume experience a different B_0 and consequently precessional frequency

- The bandwidth of the initial narrow RF pulse may not excite all fat within the field

CHESS (Chemical Shift Selective) aka ‘fat sat’







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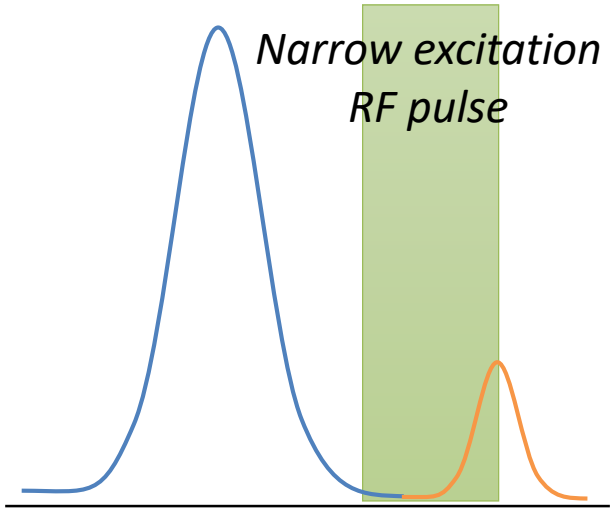

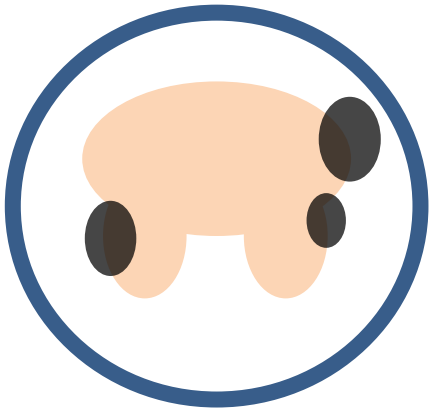

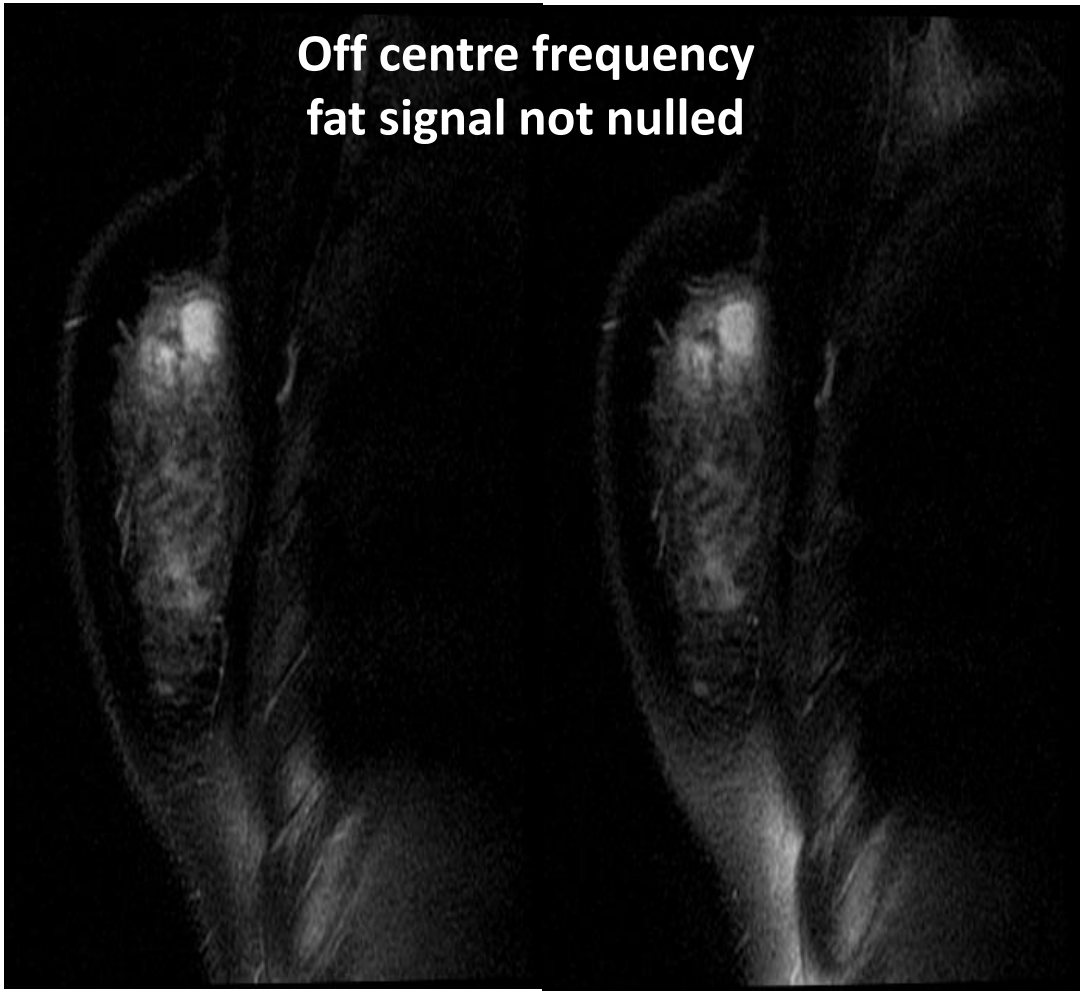

Fat saturation

NHS
Hull University Teaching Hospitals
NHS Trust

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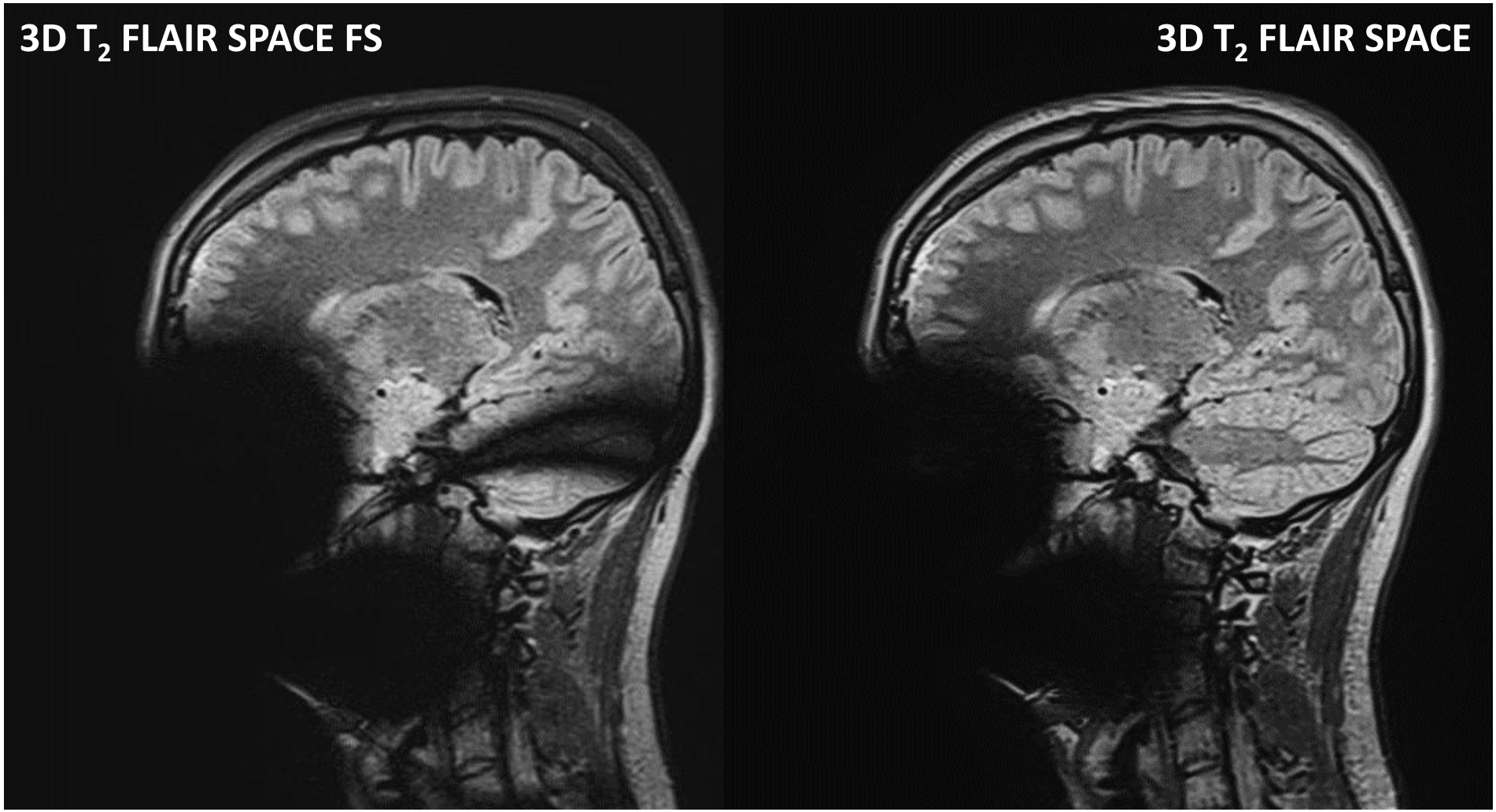

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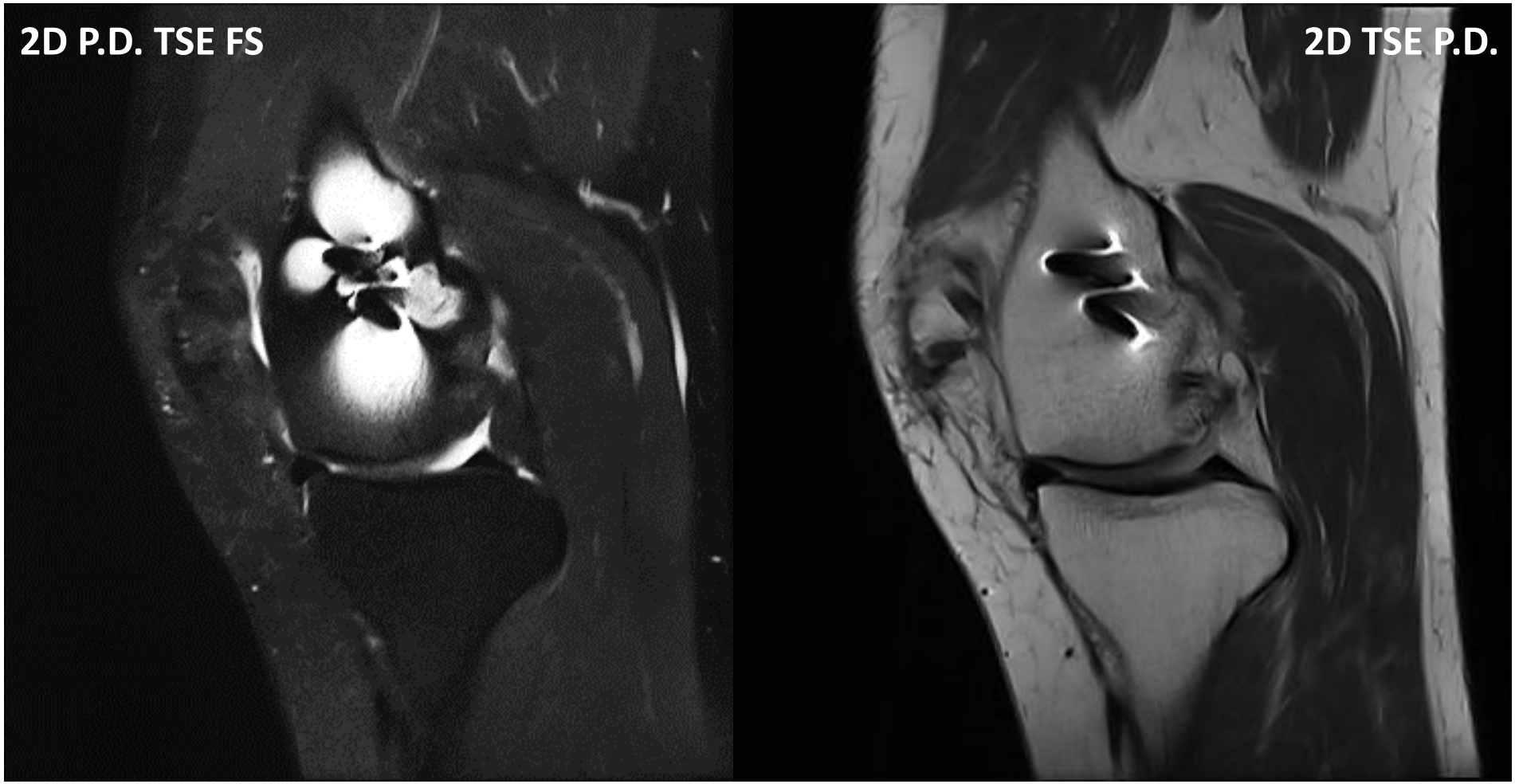

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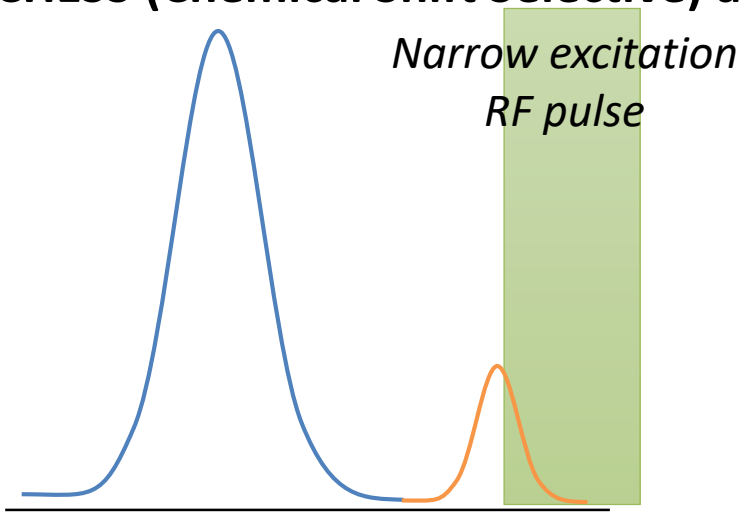
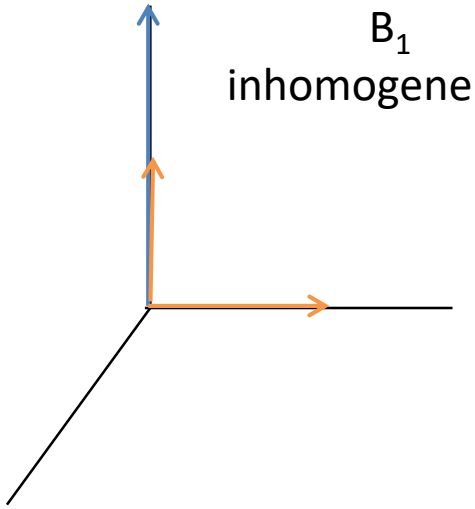
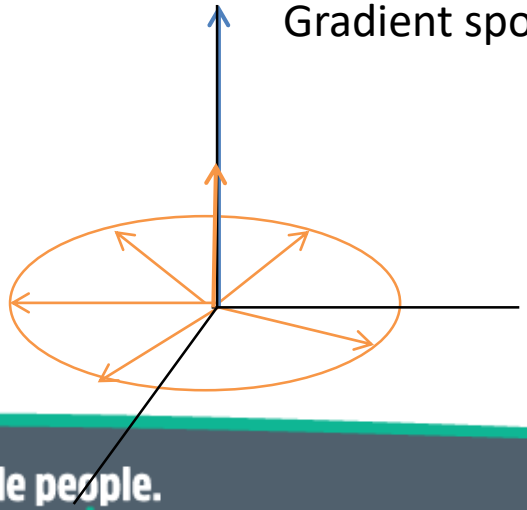
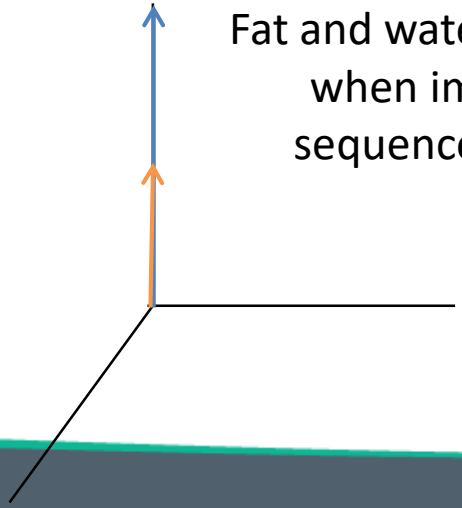


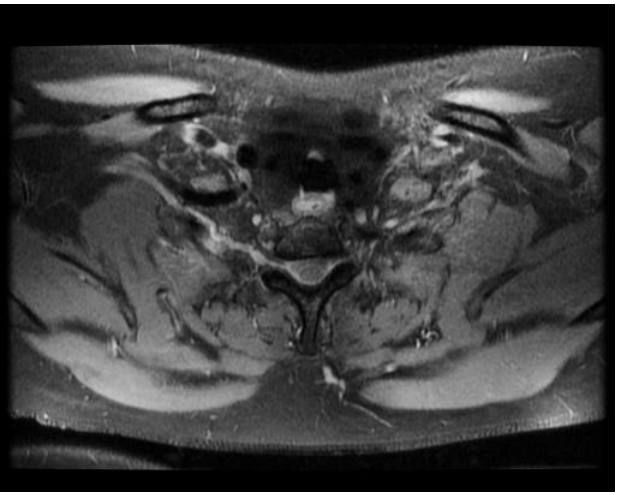


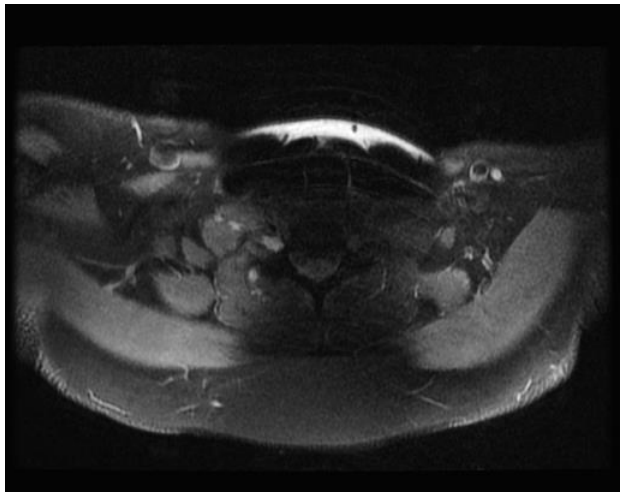


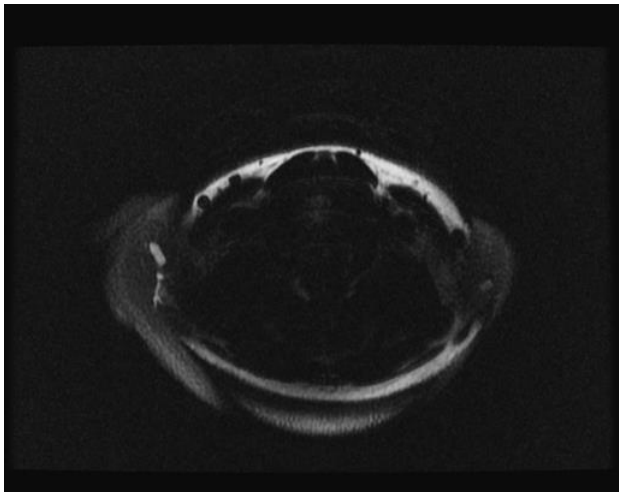


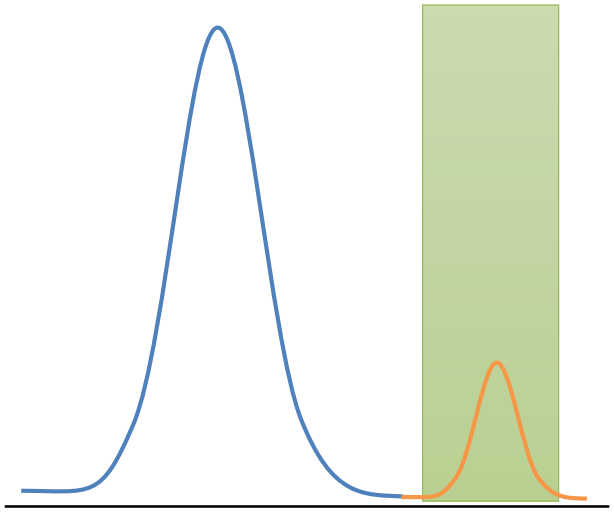
Fat saturation

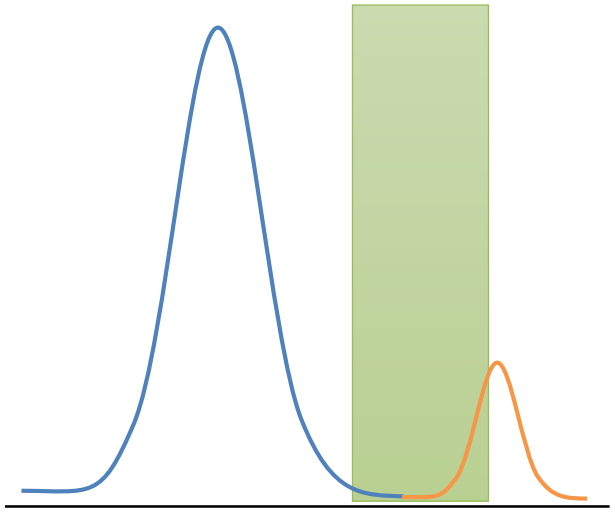
CHESS (Chemical Shift Selective) aka ‘fat sat’

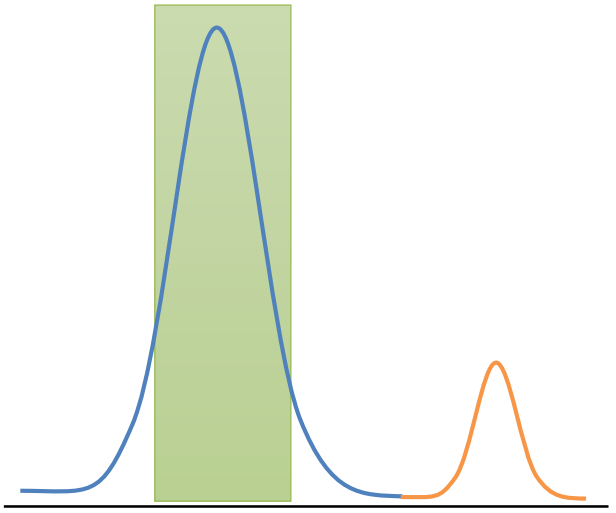












CHESS (Chemical Shift Selective) aka 'fat sat'

B_1 inhomogeneity – a variable flip angle across the imaging field.

- Different locations within the imaging volume experience a different flip angle
- A significant longitudinal component remains for fat resulting in non saturation of all fat signal

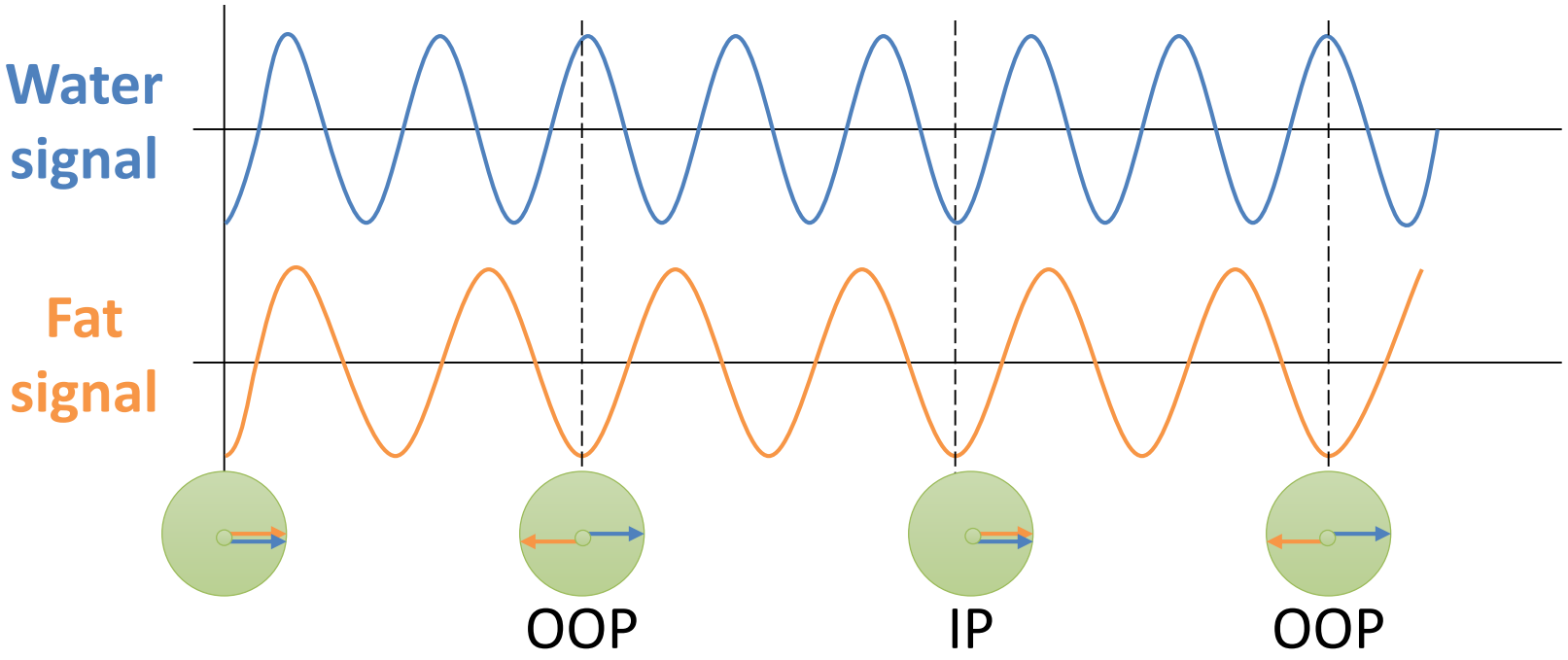
CHESS (Chemical Shift Selective) aka 'fat sat'

Advantages	Disadvantages	Suggested applications
Versatile	Sensitive to B_0 and B_1 inhomogeneities	Most applications except areas with poor homogeneity*
Applicable to most pulse sequences	Low sequence efficiency	
Relatively fast		

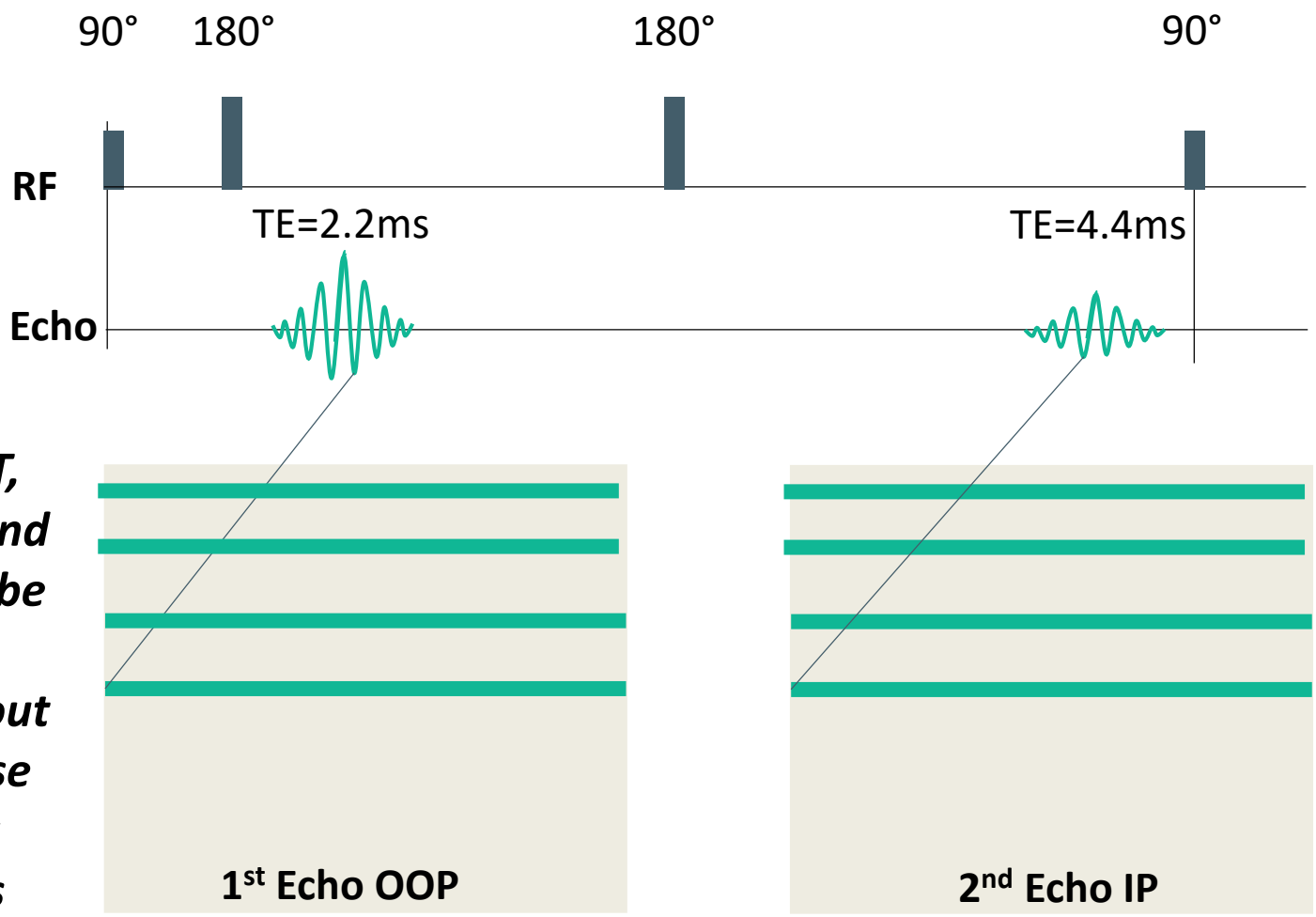
*off isocentre imaging, metal implants, anatomy with large shape differences e.g. breast, head and neck

Phase Cycling

- Differences in precessional frequencies of water and fat cause signals to move in phase (IP) and out of phase (OOP) with one another.



- **Dixon Technique (DIXON/FLEX/IDEAL)**

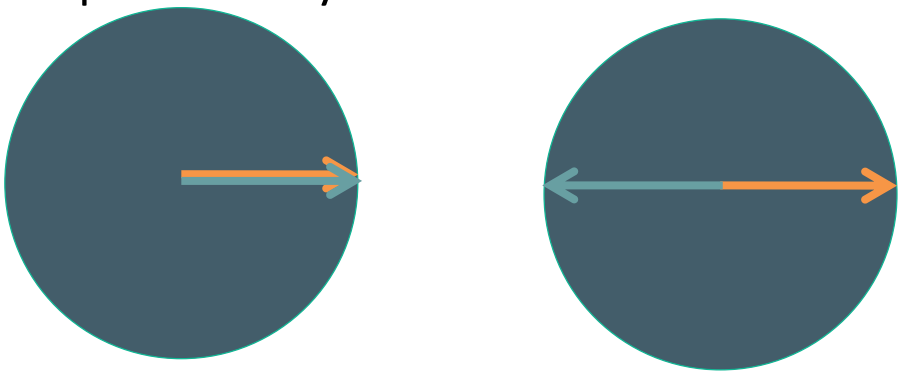


At 1.5T, water and fat will be in-phase/out of phase every 2.2ms

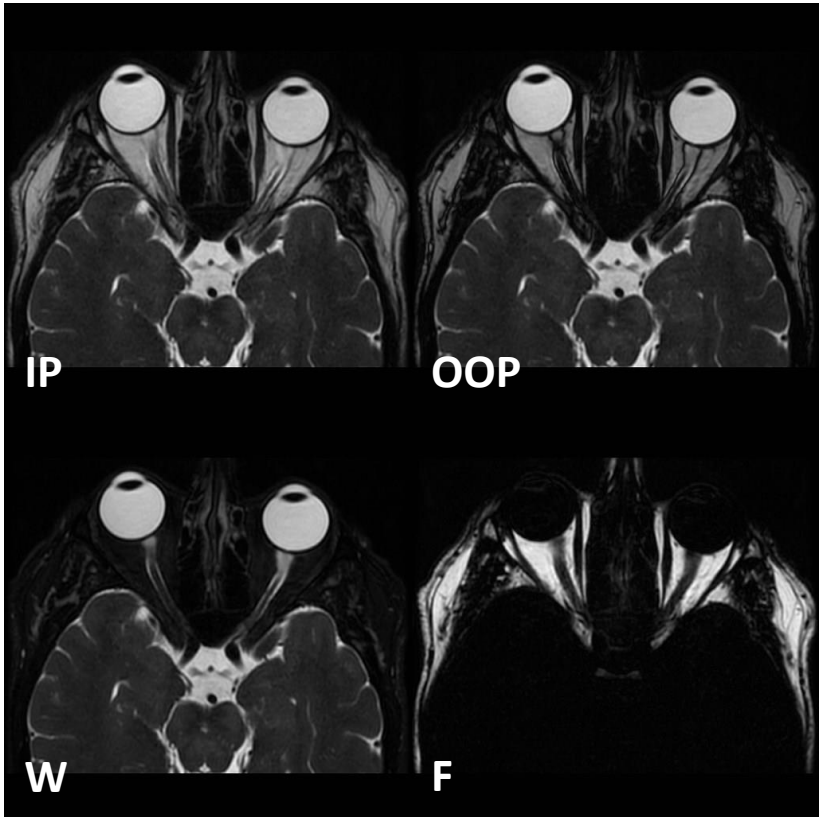
Dixon Technique (DIXON/FLEX/IDEAL)

- IDEAL - Iterative Decomposition of Water and Fat With Echo Asymmetry and Least-Squares Estimation

- Due to different precessional frequencies, water and fat become IN and OUT of phase every 2.2ms at 1.5T



In Phase = Water + Fat **Out of Phase = Water – Fat**

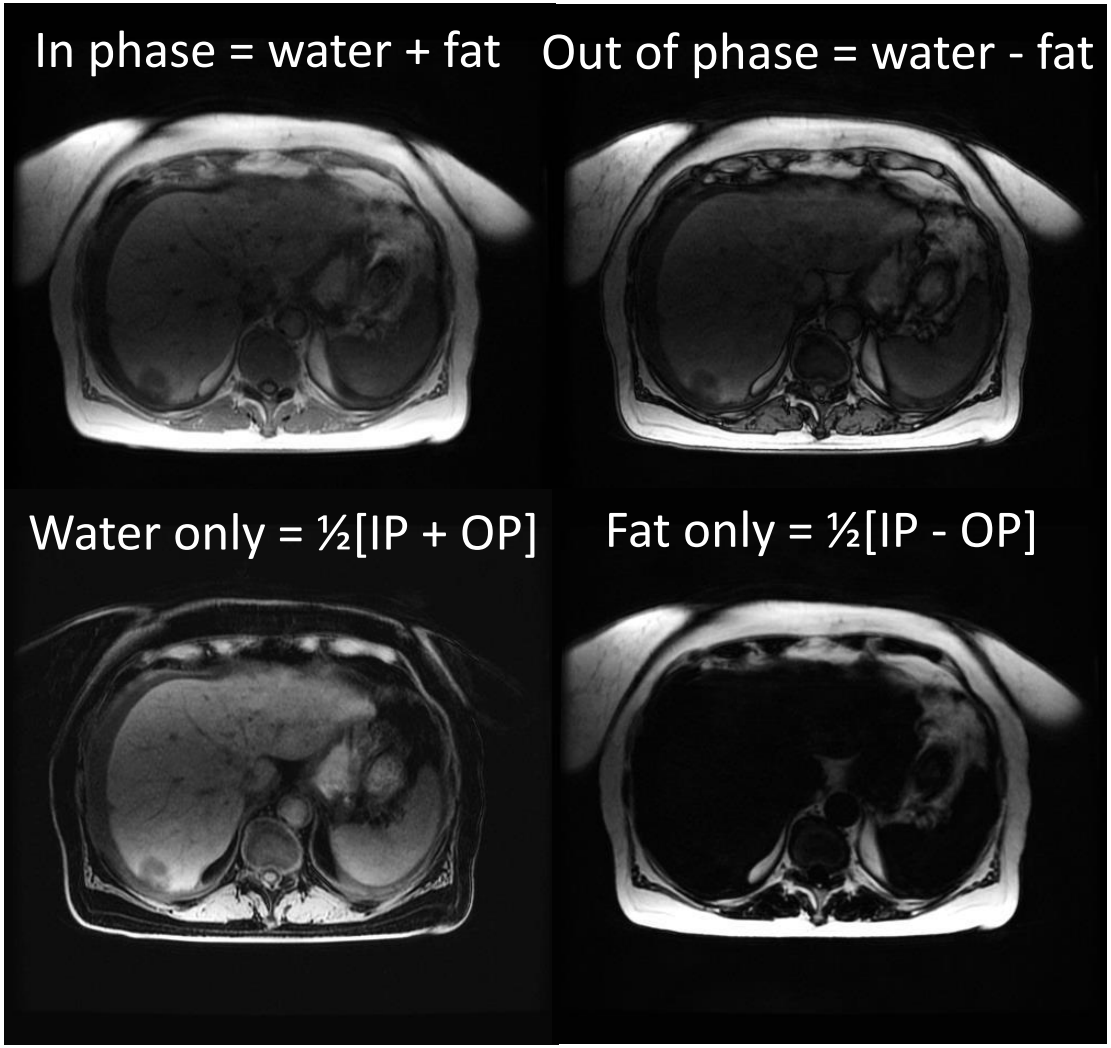


½ [IP + OP] = ½ [(W+F) + (W–F)] = Water

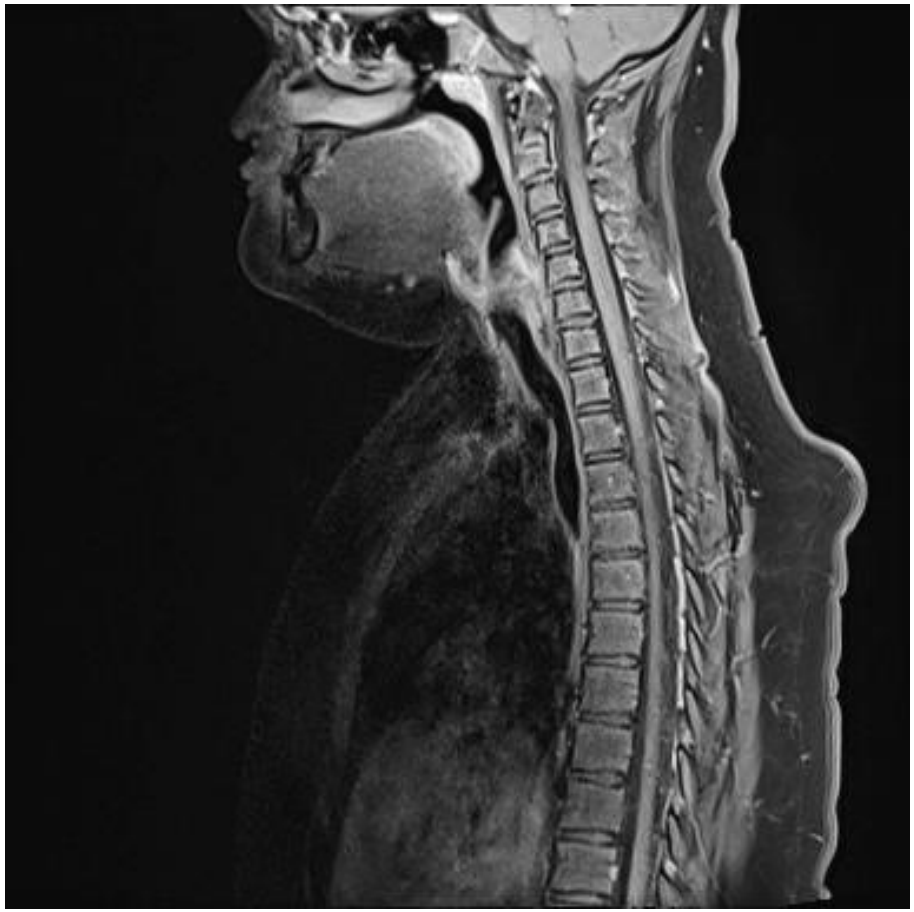
½ [IP – OP] = ½ [(W+F) – (W–F)] = Fat

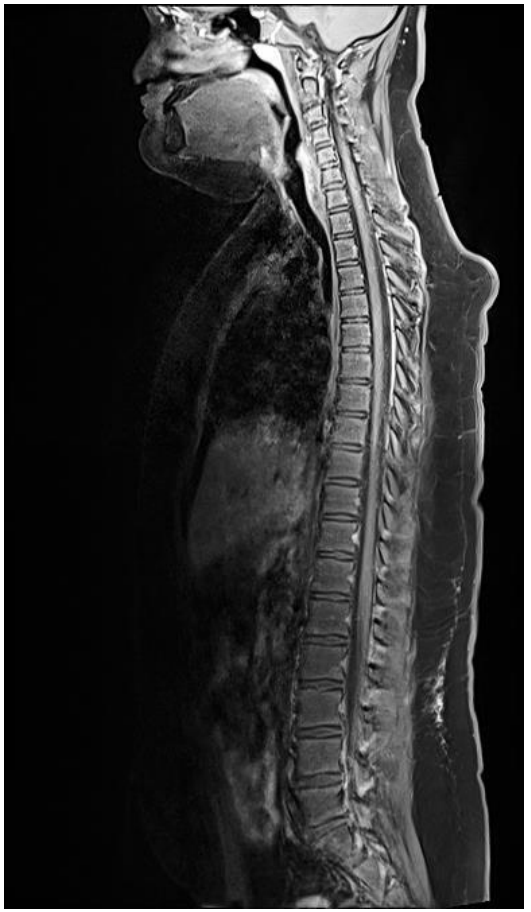
Dixon W. Simple proton spectroscopic imaging. Radiology 1984;153: 189 –194

Dixon Technique

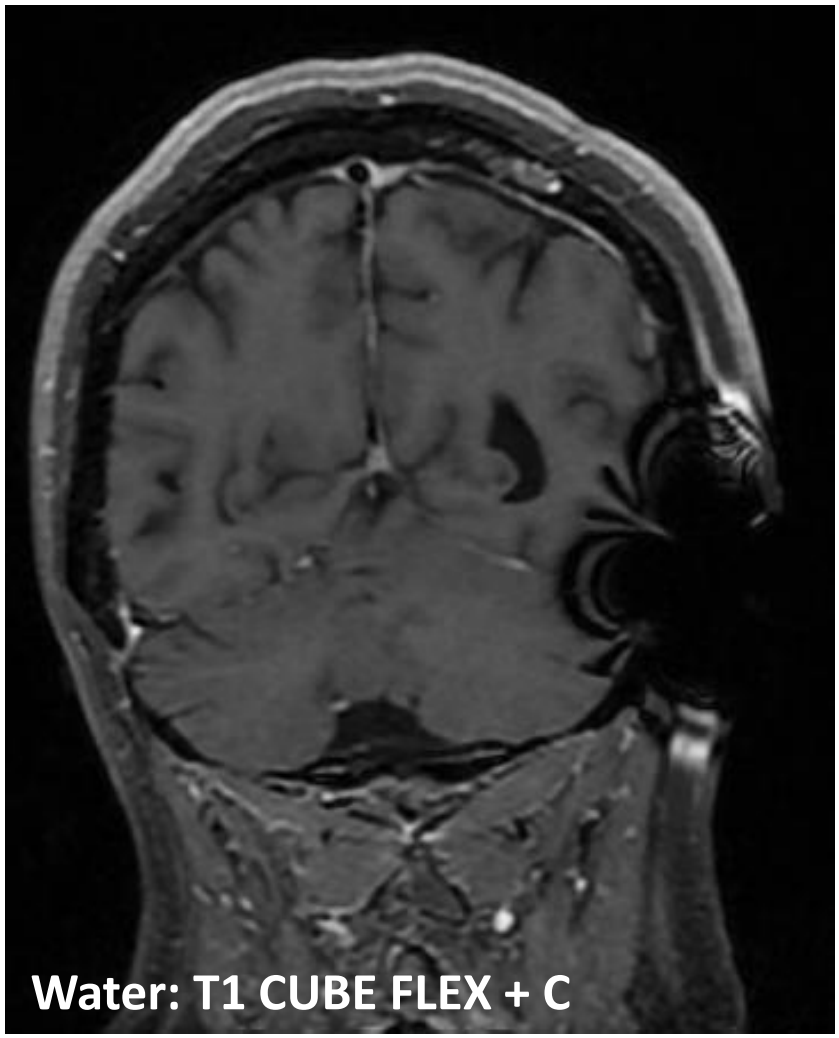


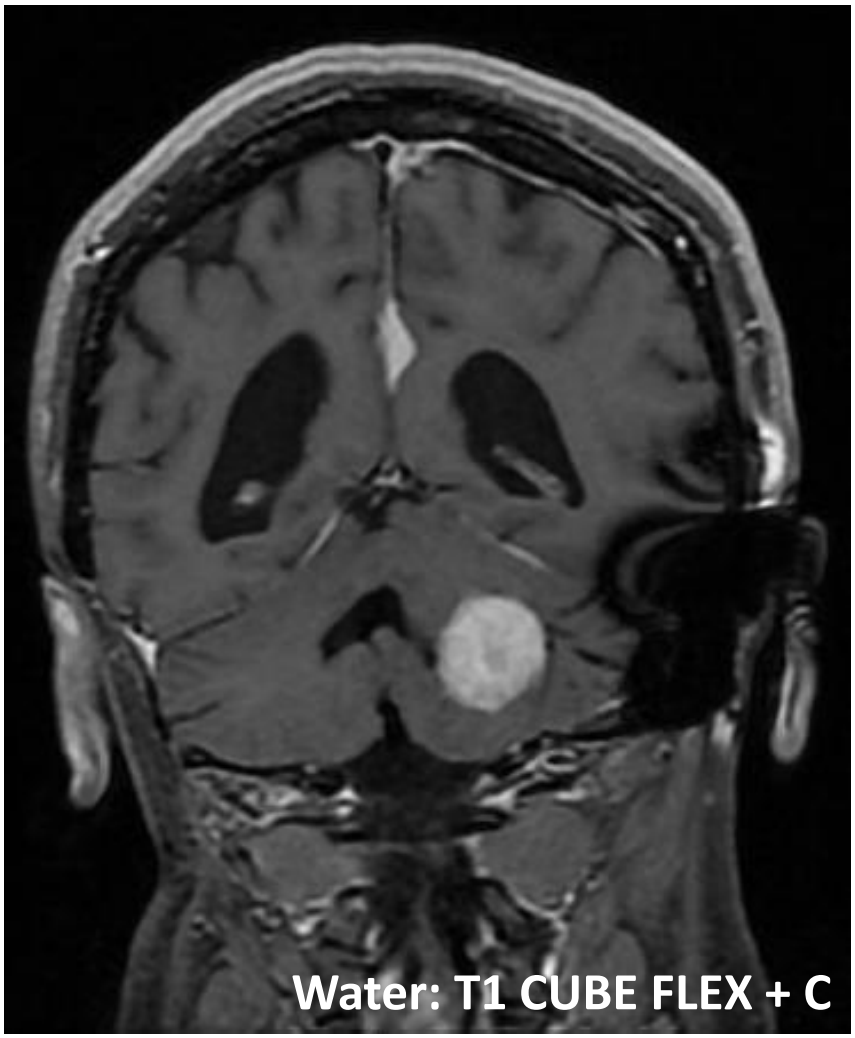
DIXON fat-nulling technique





DIXON fat-nulling technique – Robust in the presence of metal



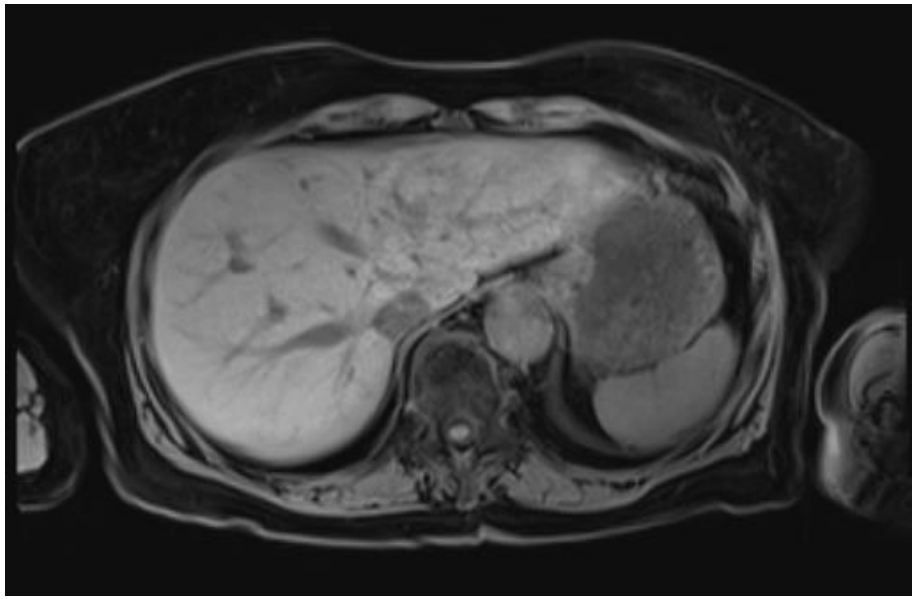


Dixon Technique

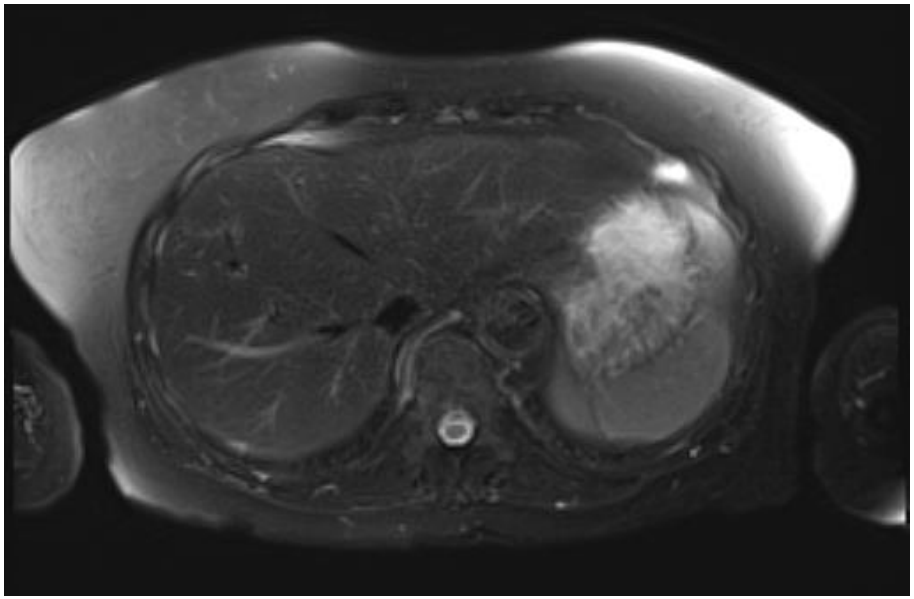
Advantages	Disadvantages	Suggested applications
Insensitive to B_0* and B_1 inhomogeneities	Long scan times	Anywhere CHESS or water excitation fail
Robust fat nulling even over large FOV's	Complex reconstruction	Especially good for large FOV, unfavourable anatomy or in the presence of metal
High SNR (√echoes)	Swapping artefact	
Multiple image types		

*three or four point Dixon techniques only

Dixon Technique

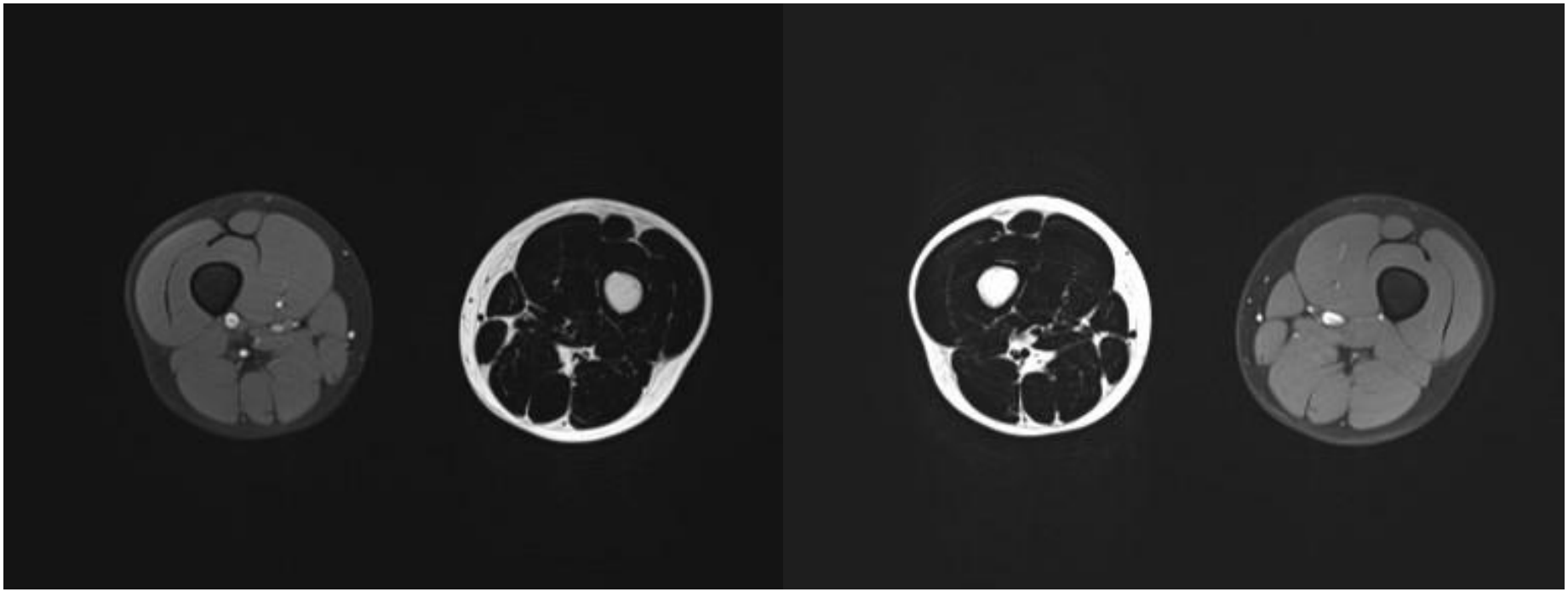


DIXON



CHESS

DIXON swap artefact

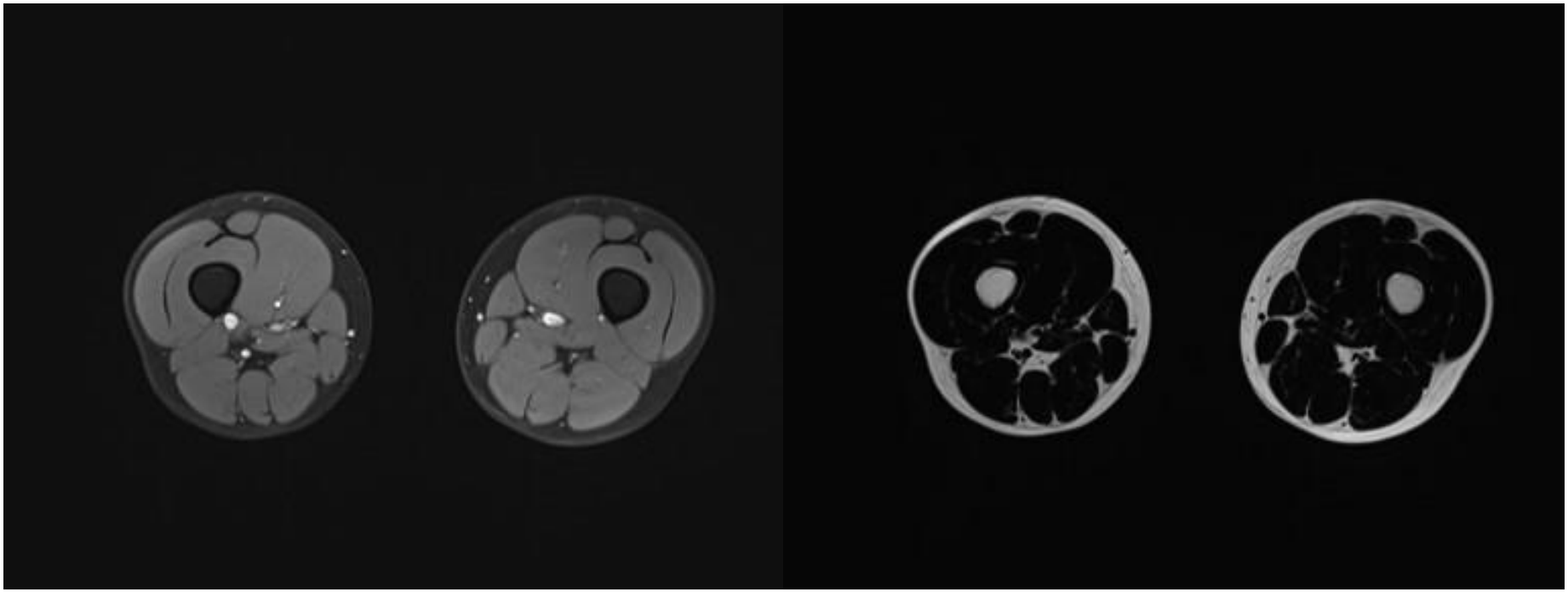


WATER **FAT**

DIXON swap artefact

Local or global swap depending on vendor algorithm

Correct DIXON swap artefact

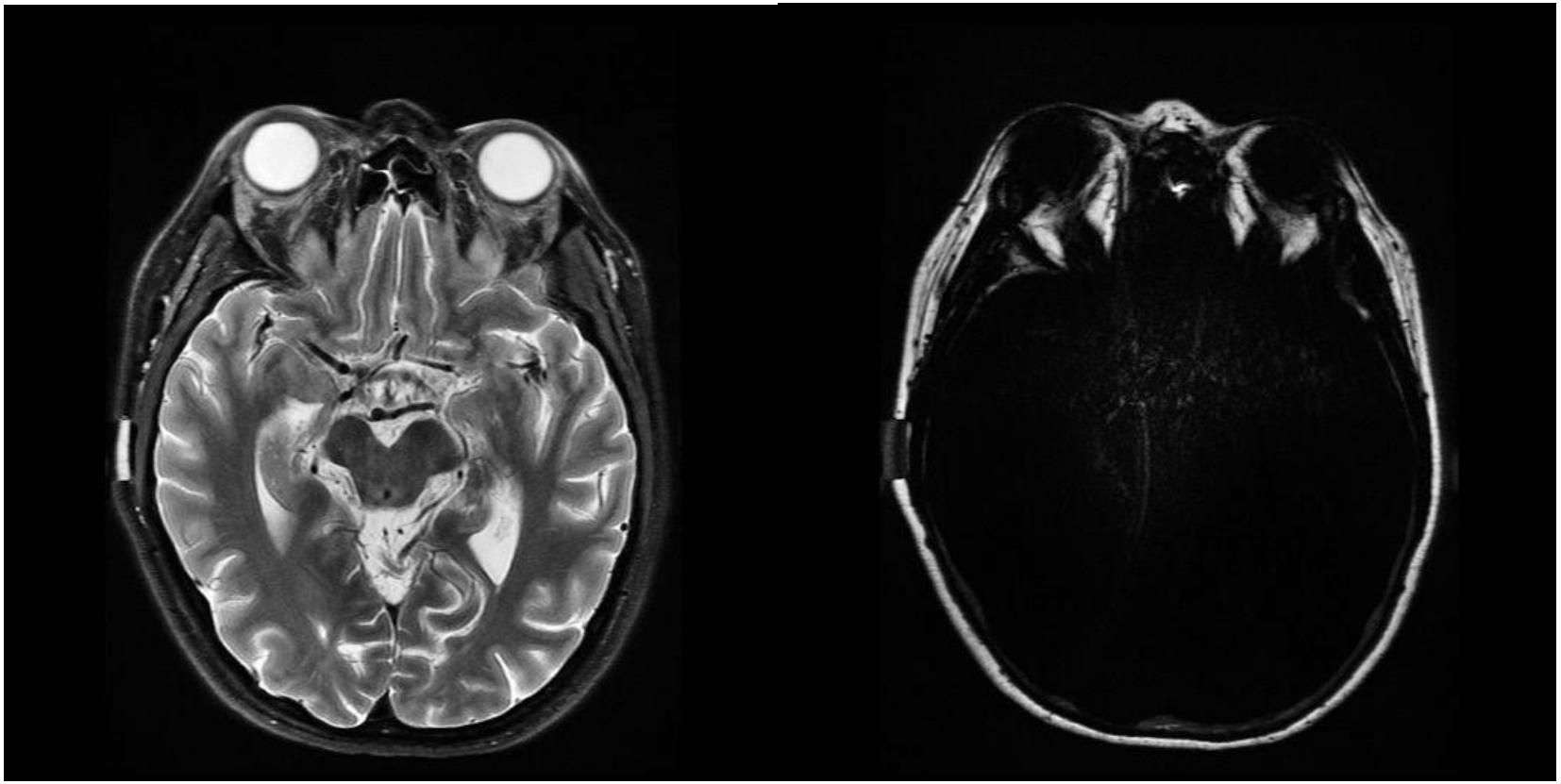


WATER **FAT**

DIXON swap artefact

Local or global swap depending on vendor algorithm

DIXON swap artefact



DIXON swap artefact

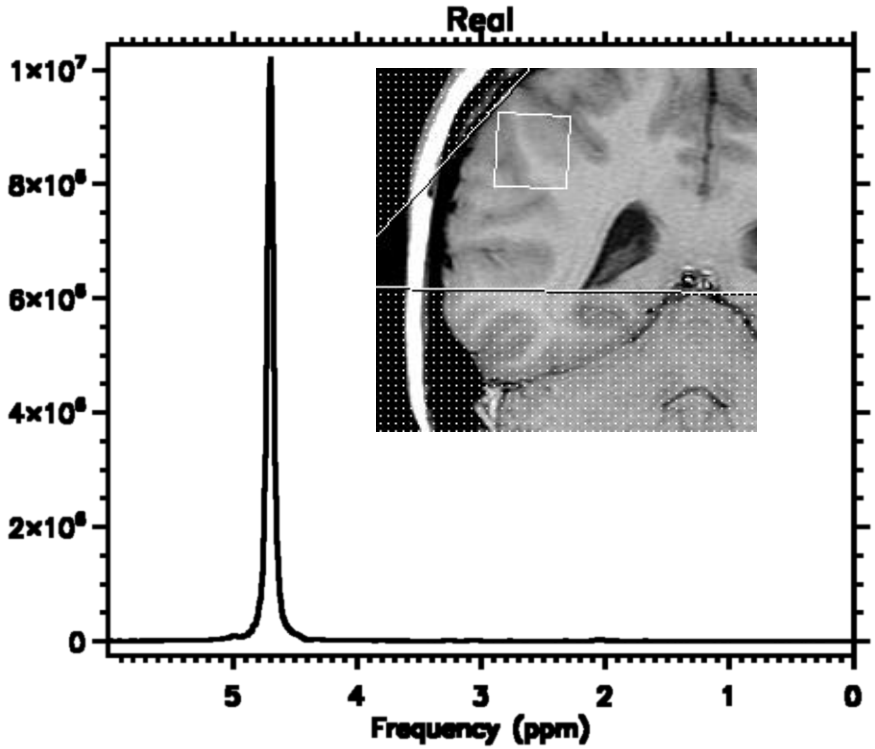
Local or global swap depending on vendor algorithm

In-phase & out-of-phase TEs, Dixon

Technique	GE	Siemens	Philips
Fat saturation – chemical	Fat Sat	Fat Sat	SPIR
Dixon Fat-Water separation for FSE	IDEAL/FLEX for FSE	Dixon TSE	mDixon TSE
Dixon Fat-Water separation for 3D GRE	LAVA-Flex	Dixon VIBE	mDixon

Magnetic Resonance Spectroscopy (MRS):

- MRS is a non-invasive tool for measuring metabolism in tissue
- Examines metabolite signals thousands of times smaller than the water signal in MRI
- 'Virtual Biopsy'



Chemical Shift

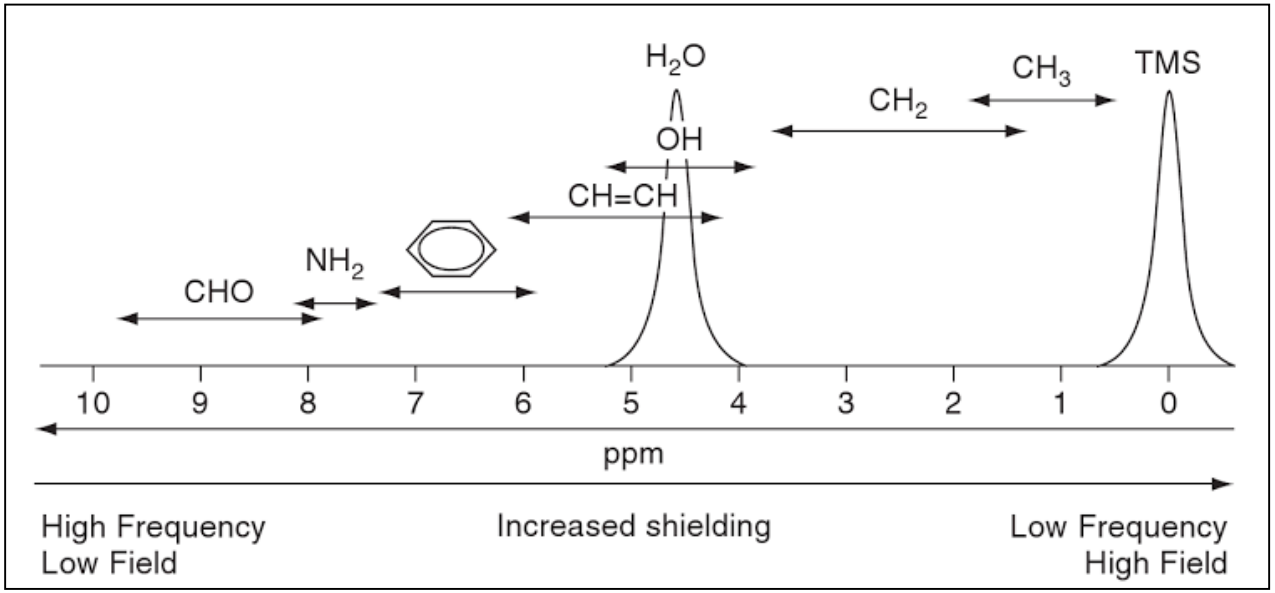
- MR spectroscopy utilises chemical shift properties of different nuclei

- electron cloud around an atom shields the nucleus from the magnetic field (σ):

$$\omega_0 = \gamma(1 - \sigma)B_0$$

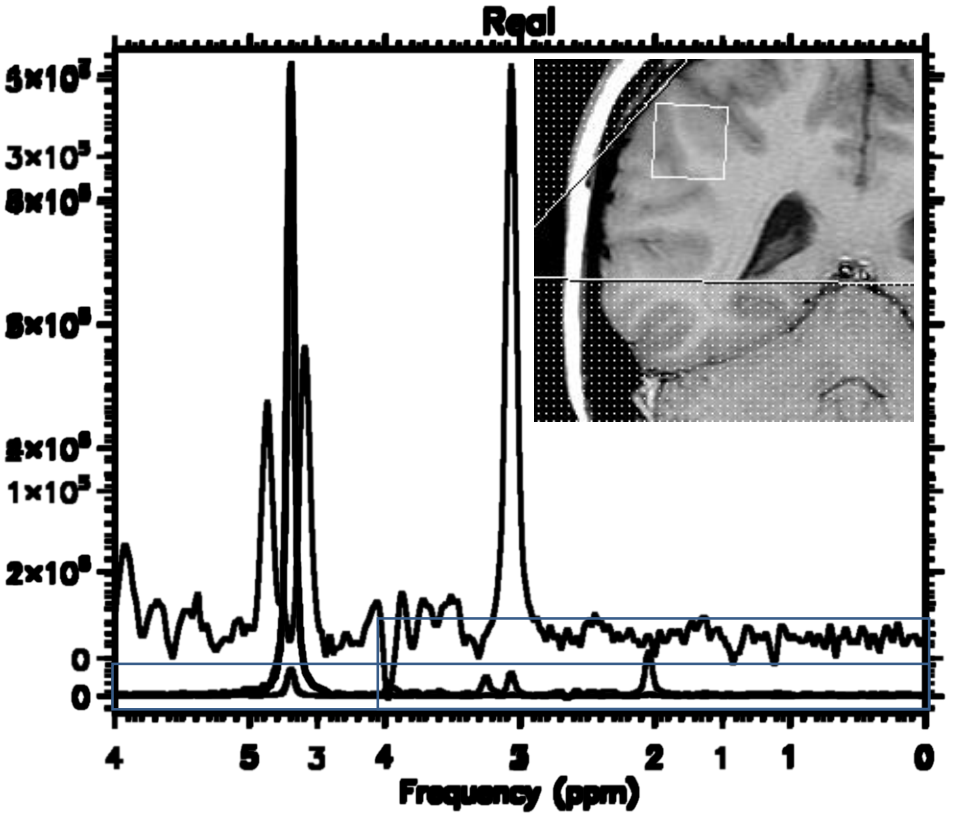
- different resonant frequencies for different molecules

γ = gyromagnetic ratio, B_0 = magnetic field strength, ω_0 = resonant frequency



Water Suppression

- Given the brain consists predominantly of water
- spectra are also dominated by water
- chemical shift selective (CHESS) pulse used first prior to acquisition



Awareness of MR spectroscopy (MRS) and appropriate TEs for particular clinical questions

Hull University Teaching Hospitals NHS Trust

Creatine (3.06ppm)

- Involved in energy metabolism via the creatine kinase reaction which generates ATP
- Metabolically active tissues (brain, muscle)
- Observed at a relatively constant level

NAA (2.02ppm)

- N-acetylaspartate (NAA)
- Largest signal in normal adult brain
- Neuronal cell marker
- Changes are non-specific
- Decreases in MS, tumour and infarct

Choline (3.24ppm)

- 3 choline containing metabolites
- Membrane synthesis and breakdown

Free choline

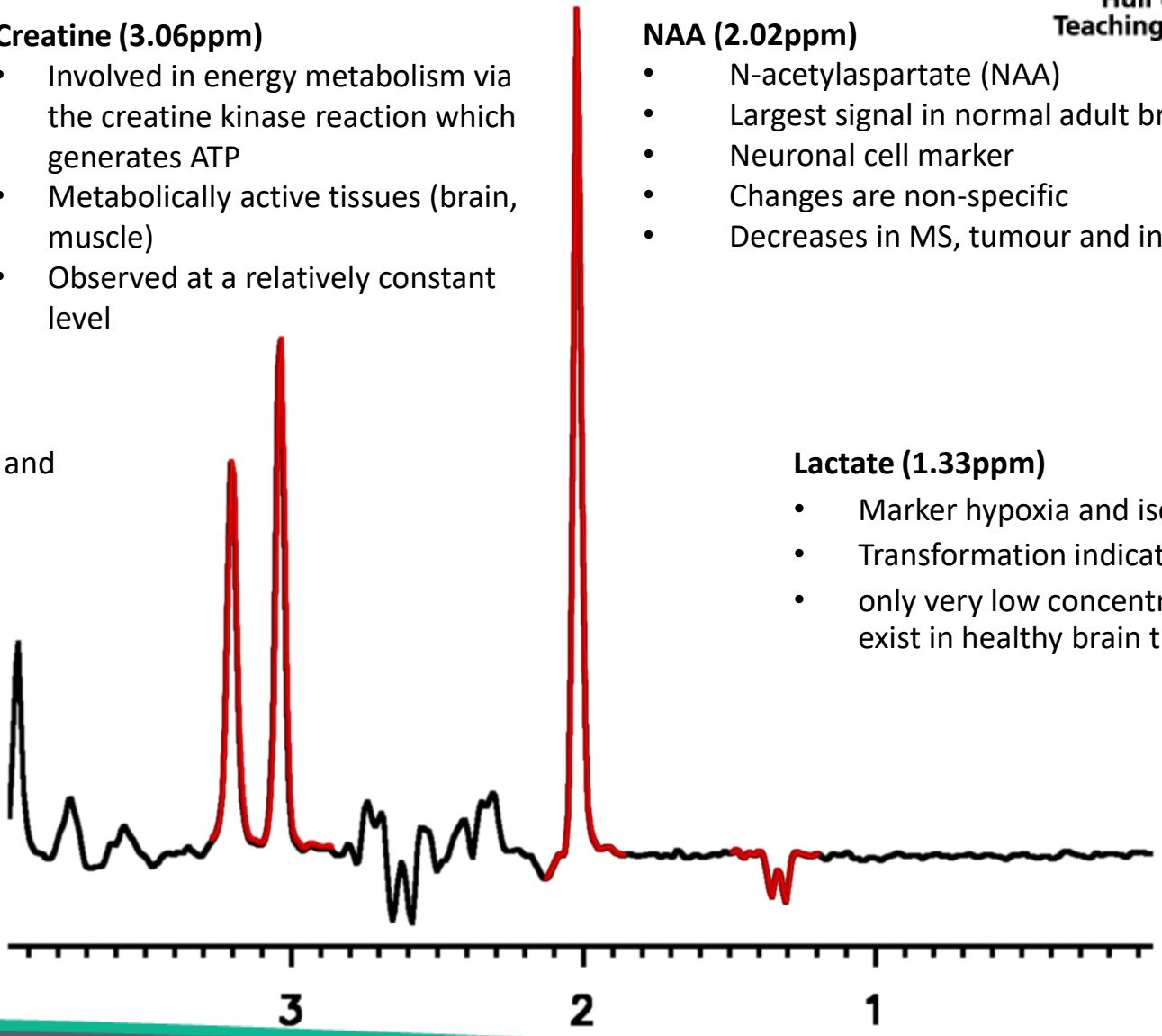
- cell breakdown

Phosphocholine

- cell density

Glycerophosphocholine

- proliferation

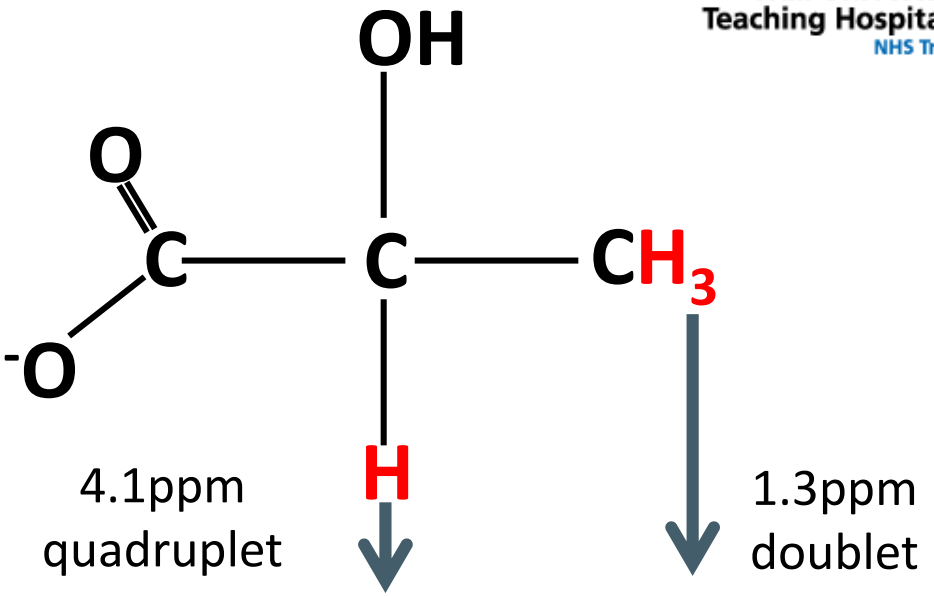


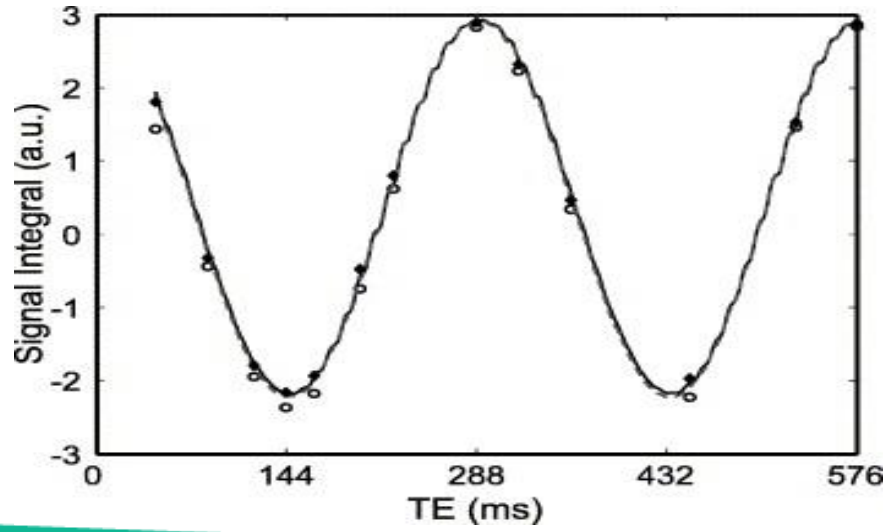
Lactate (1.33ppm)

- Marker hypoxia and ischemia
- Transformation indicator
- only very low concentrations exist in healthy brain tissue

Lactate

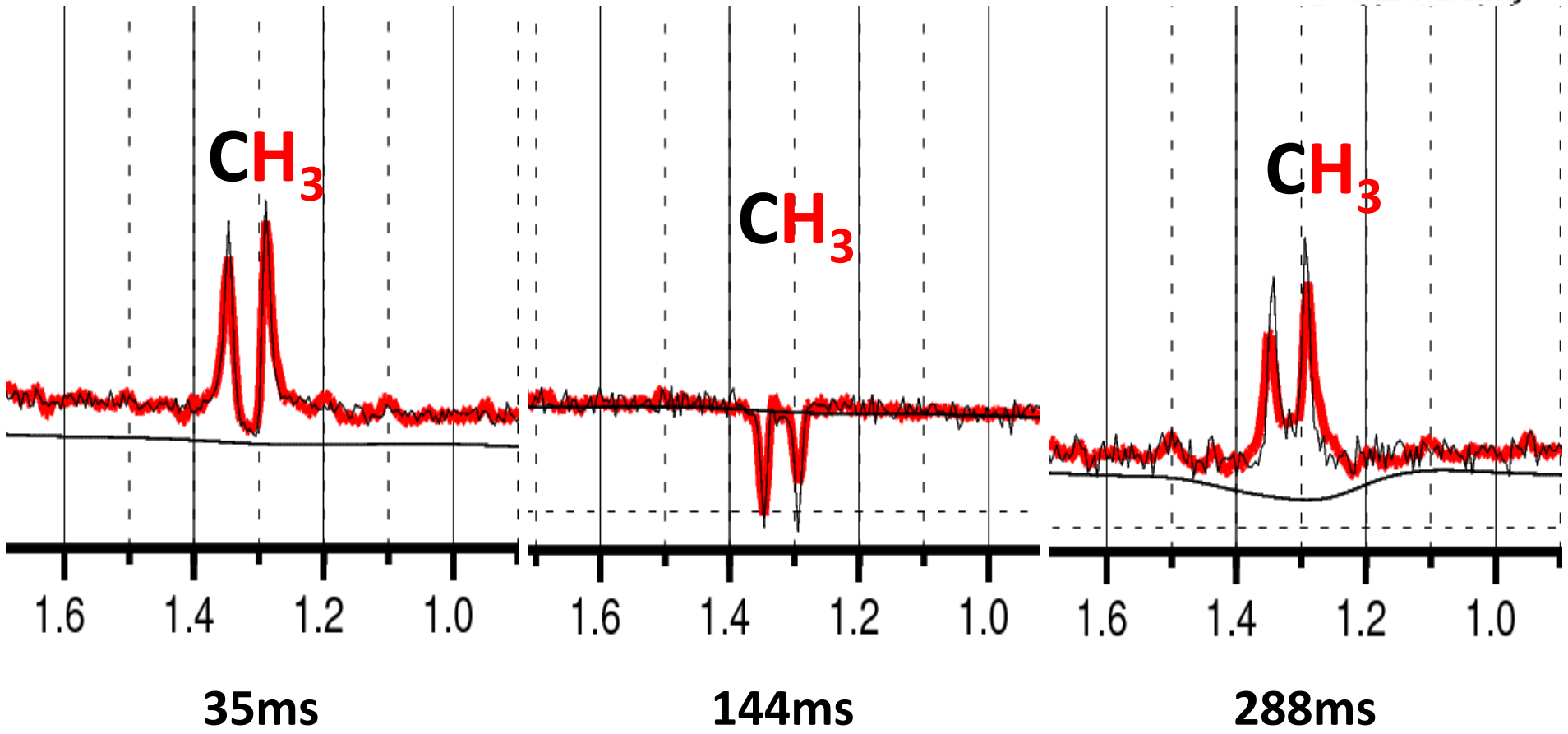
- AX_3 coupled metabolite
- weak interactions
- only very low concentrations exist in healthy brain tissue
- AX coupling causes the signal produced to modulate as function of echo time





http://www.bmrb.wisc.edu

Maudsley et al, MRM 2005



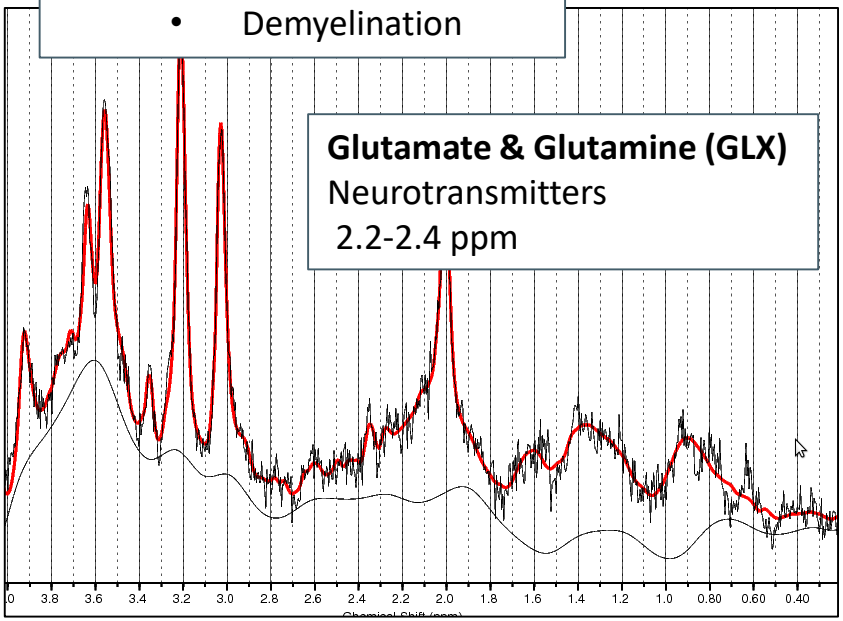
35ms **144ms** **288ms**

- Larger signal from water, obscures smaller, lower SNR - 4.1ppm quadruplet of lactate

Awareness of MR spectroscopy (MRS) and appropriate TEs for particular clinical questions

Myo-Inositol (3.55ppm)

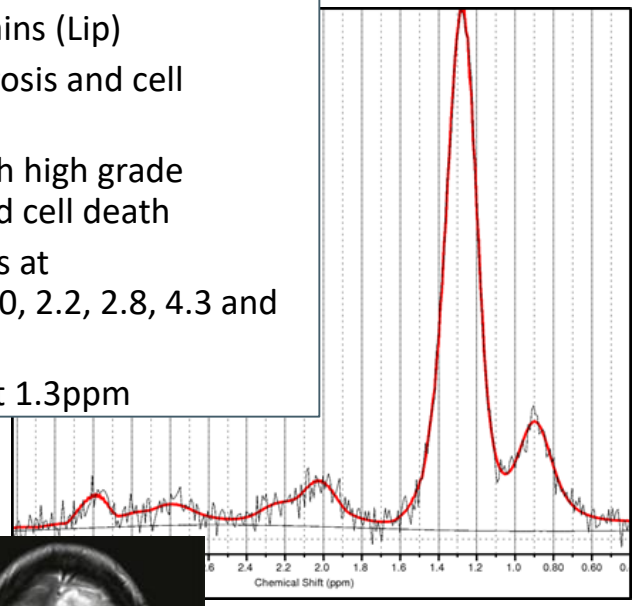
- Pentose sugar
- Glial marker
- Elevated in:
  - Low grade gliomas
  - Alzheimer's
  - Demyelination

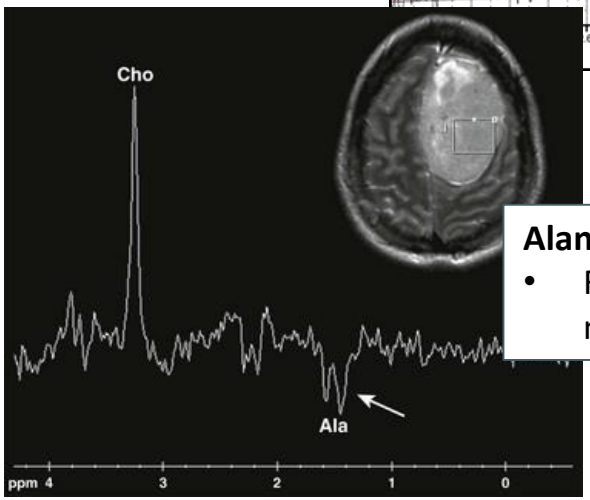


Glutamate & Glutamine (GLX)
Neurotransmitters
2.2-2.4 ppm

Short Lipid Chains

- Short Lipid Chains (Lip)
- Marker of necrosis and cell breakdown
- Associated with high grade malignancy and cell death
- Produces peaks at 0.9, 1.3, 1.6, 2.0, 2.2, 2.8, 4.3 and 5.3ppm
- Main peak is at 1.3ppm





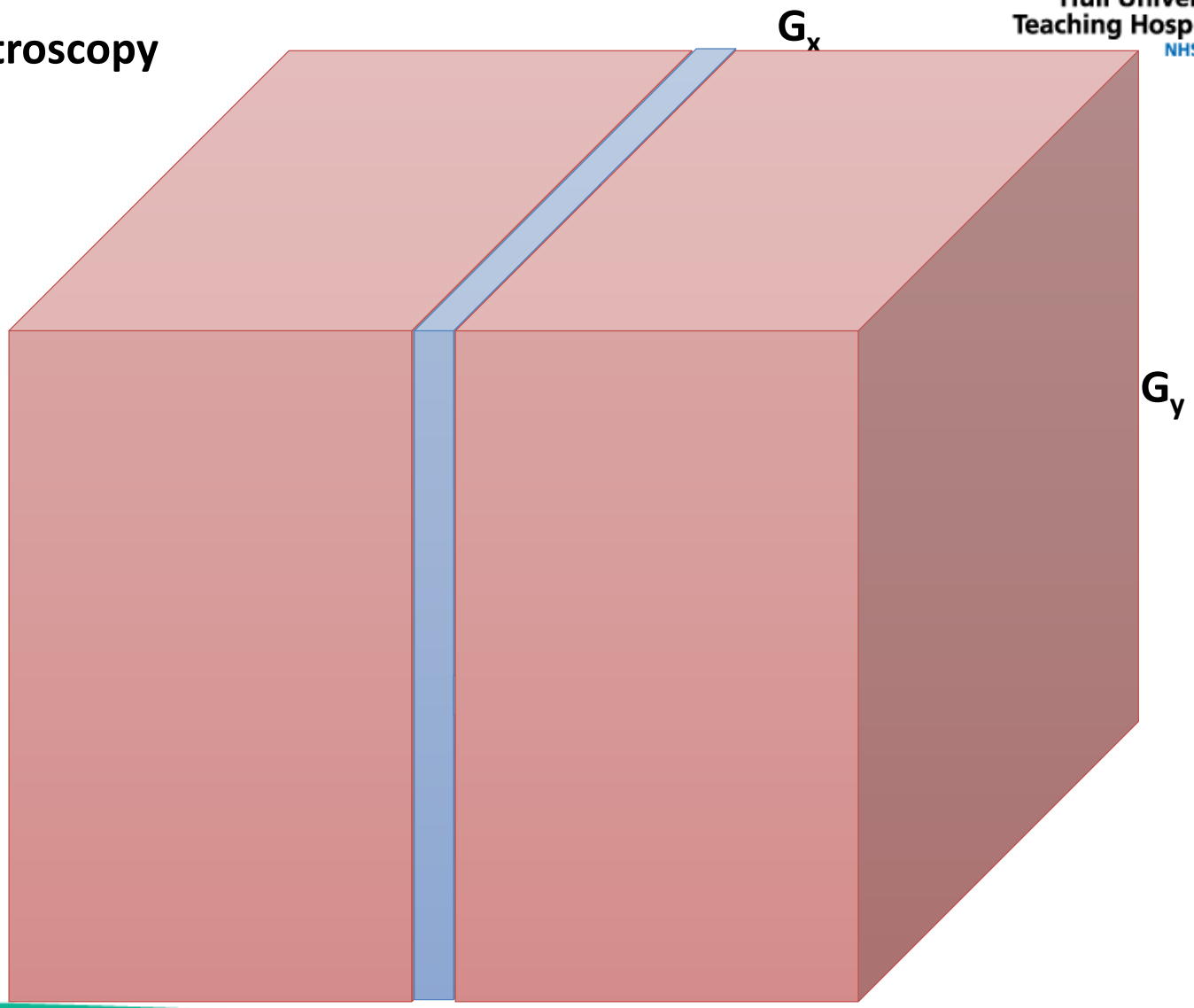
Alanine (1.46ppm)

- Found in some meningiomas

Acquisition

- Simplest method to acquire spectroscopic data is in the form of a single localised voxel (single voxel spectroscopy (SVS)
- Three slice selective pulses to excite the volume of tissue
- Outer volume suppression is used to stop unwanted signal from outside of the voxel

Single Voxel Spectroscopy



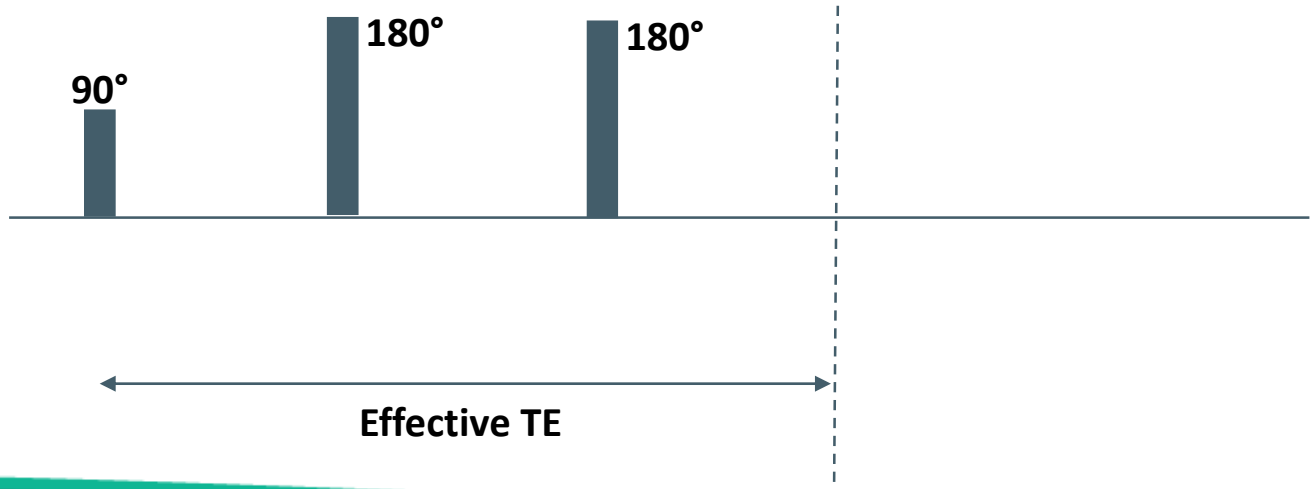
PRESS

- **P**oint **Res**olved **S**pectroscopy (90°-180°-180°)

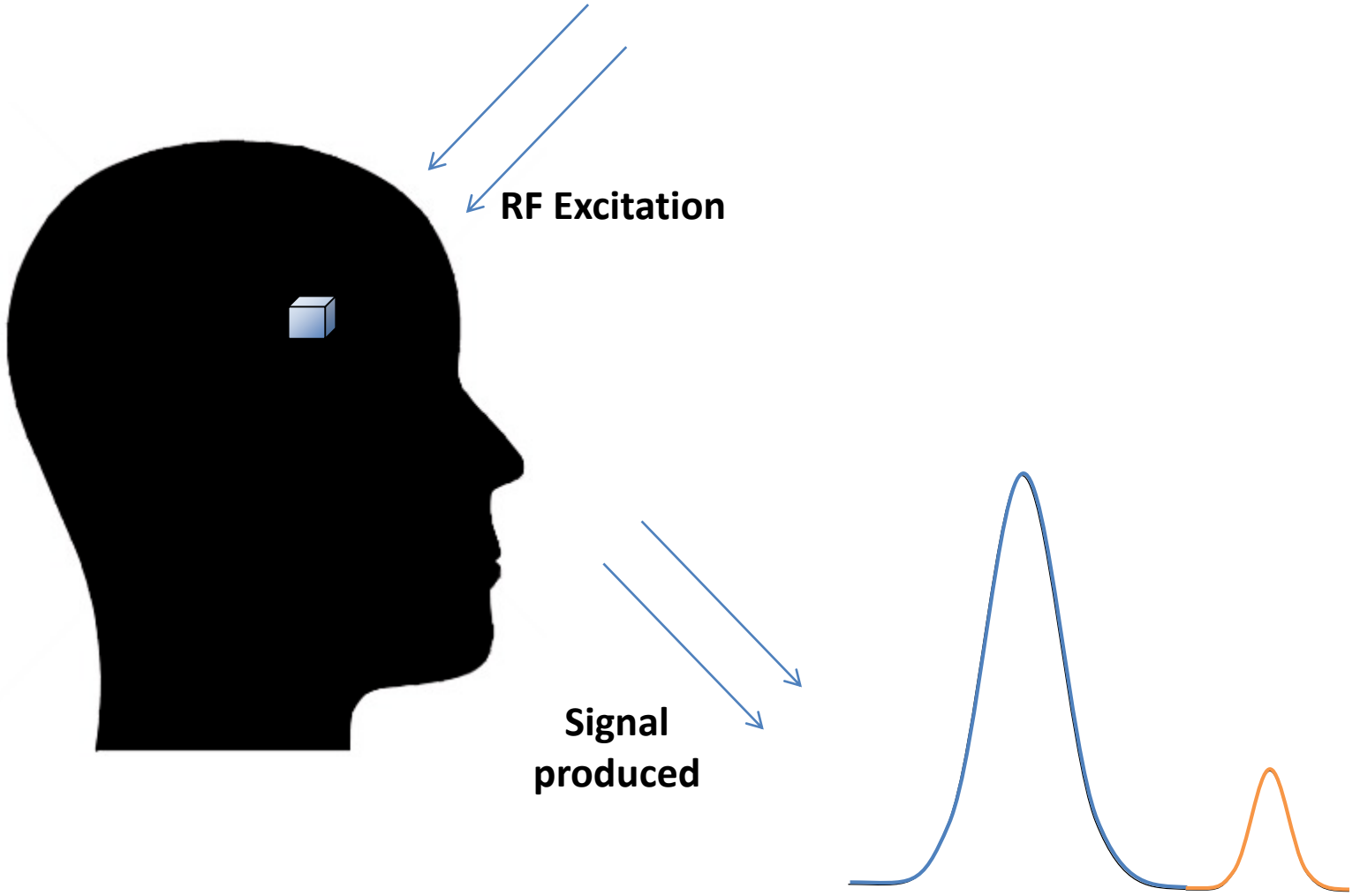
- Based on a Spin Echo sequence, and was designed by Paul Bottomley in 1987 while working for General Electric

- At field strengths 3.0T, flip angles of 90° -137° - 137° are used due to the need for a larger bandwidth without breaching the specific absorption ratio (SAR) limit

PRESS



Single Voxel Spectroscopy



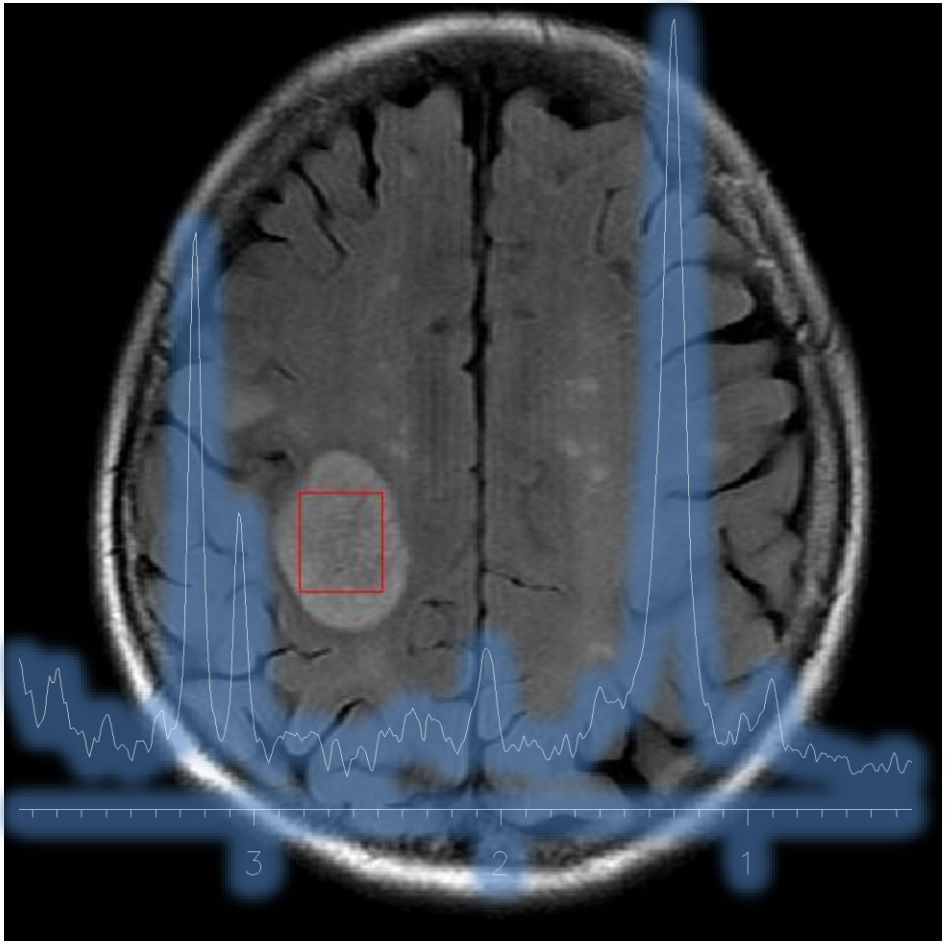
Single Voxel Spectroscopy

Pros

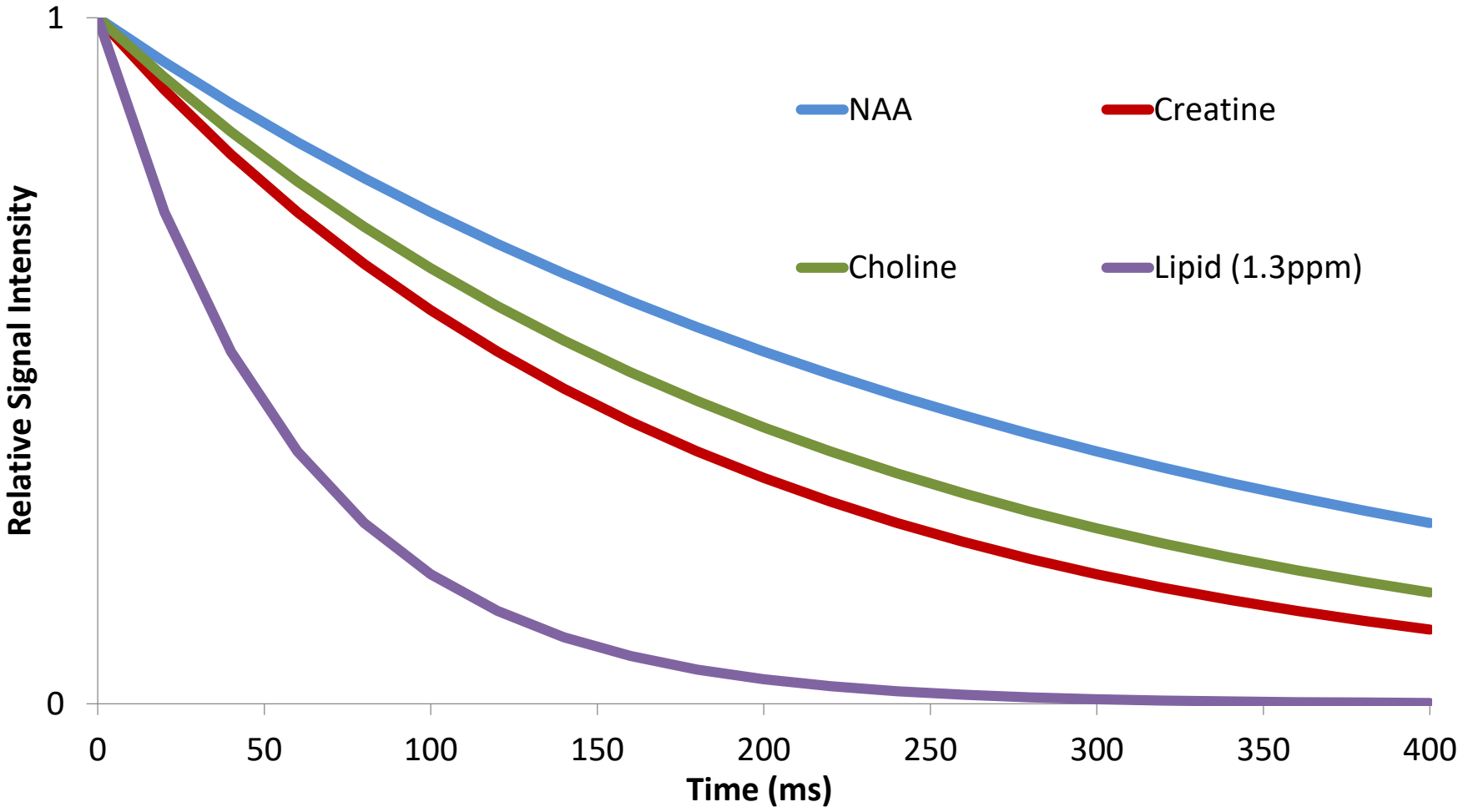
- High SNR
- Robust

Cons

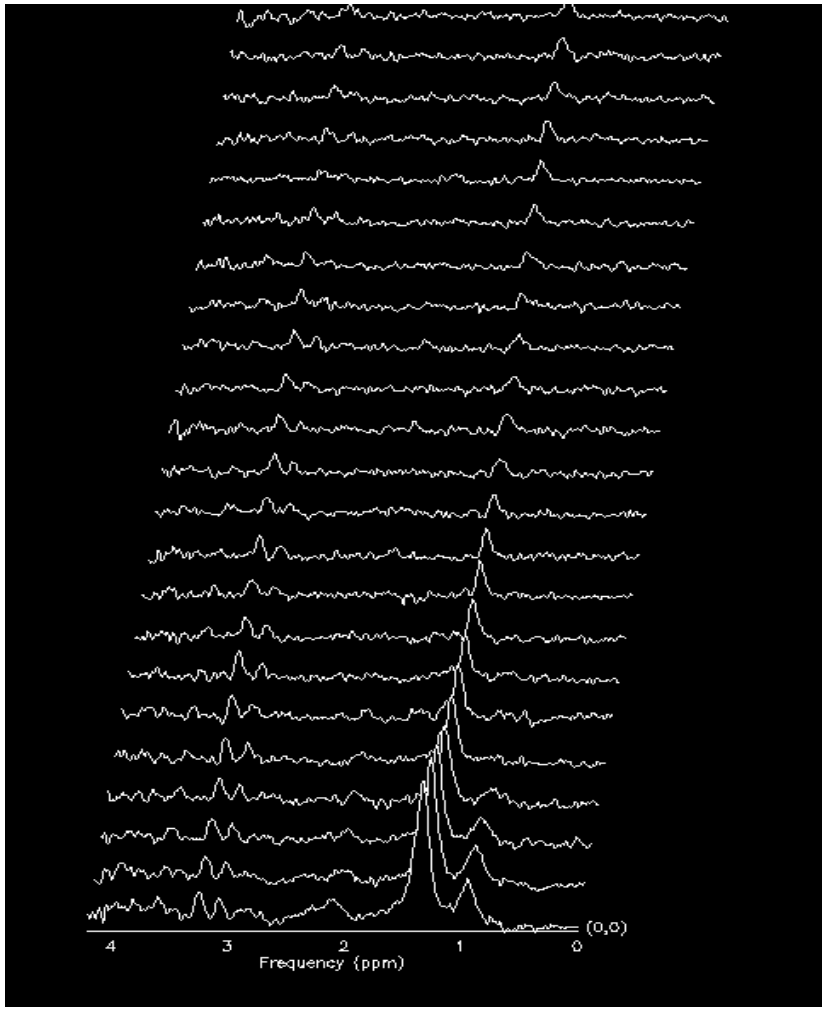
- Partial volume effects
- No spatial information



T_2 Relaxation of Metabolites



T_2 Relaxation of Metabolites



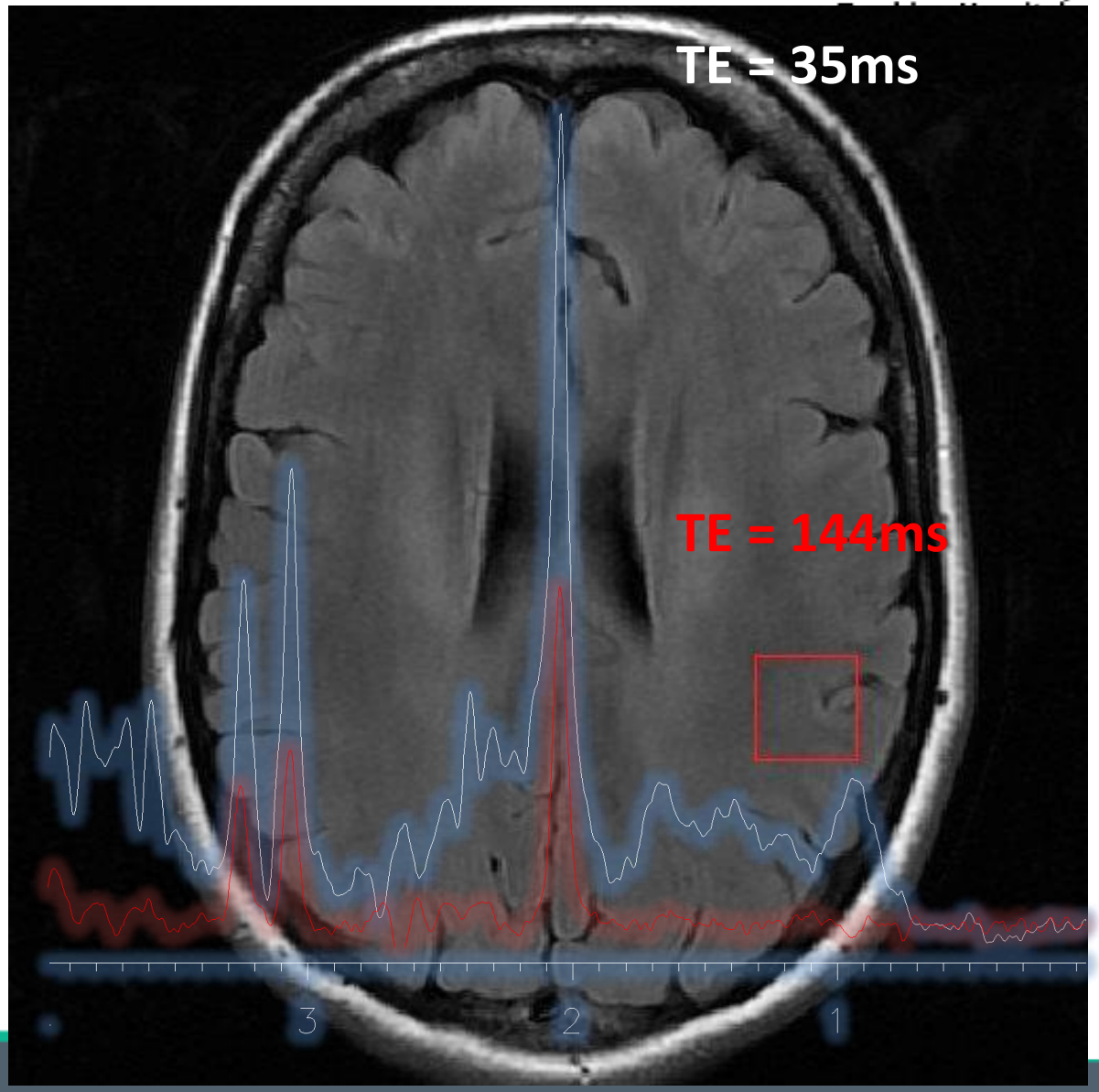
Echo Time (TE)

TE = 35ms

- Higher SNR
- Sensitive to lipids and myo

TE = 144ms

- Flatter baseline which improves quantification
- Inverted lactate
- More robust



Single Voxel Spectroscopy

- 2 different echo times (144ms and 35ms) should be acquired
- 144ms provides a simpler more robust spectrum, with an inverted lactate if present
- 35ms has double the SNR but more complicated to interpret, will show presence of lipids
- Useful to have both! Once the first echo time is setup, copy and duplicate the position for second sequence

Magnetic Resonance Spectroscopic Imaging (MRSI)

single voxel spectroscopy

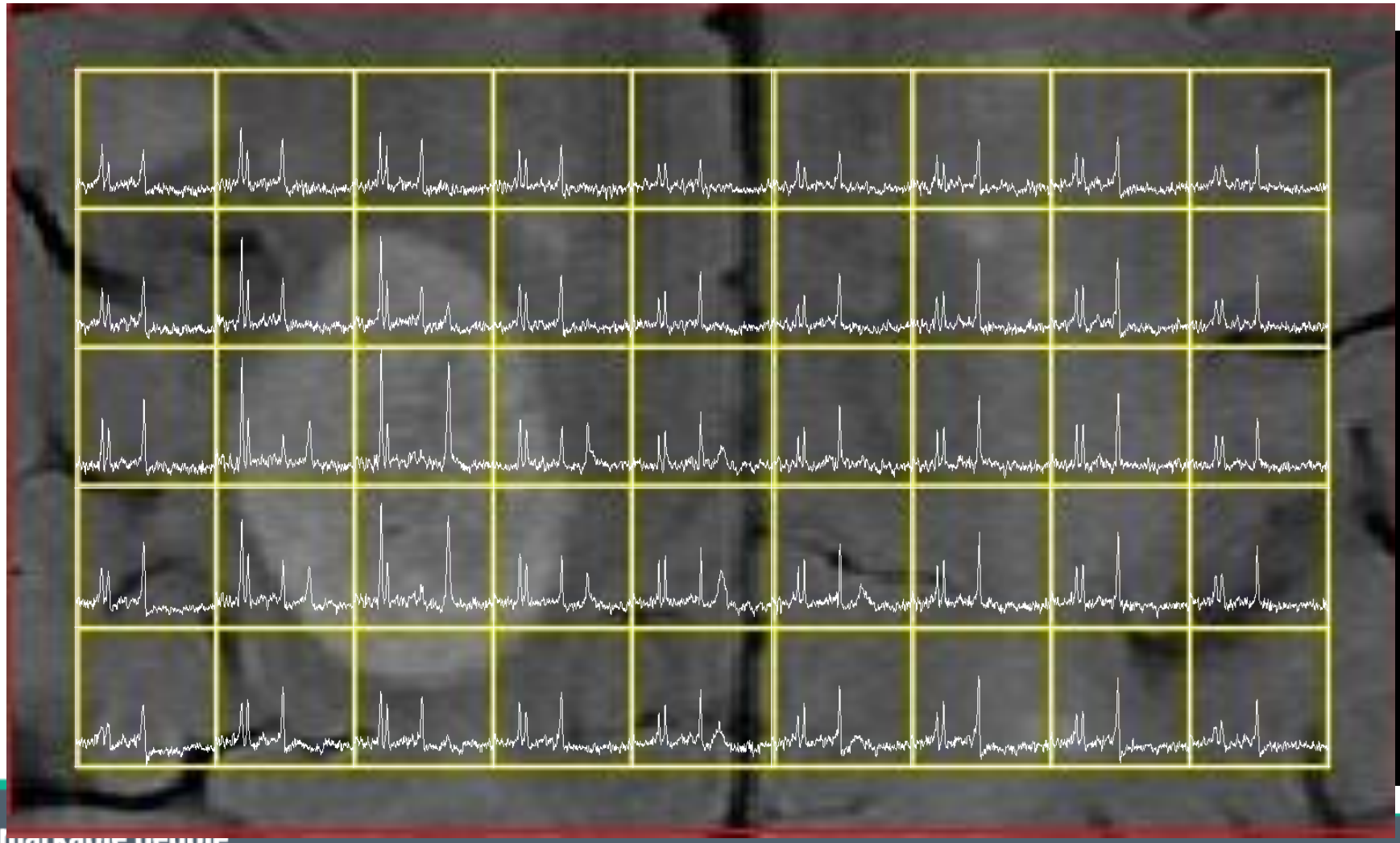
+

phase encoding steps

=

multivoxel spectroscopy

Multivoxel Spectroscopy



Single or Multi- voxel Spectroscopy ???

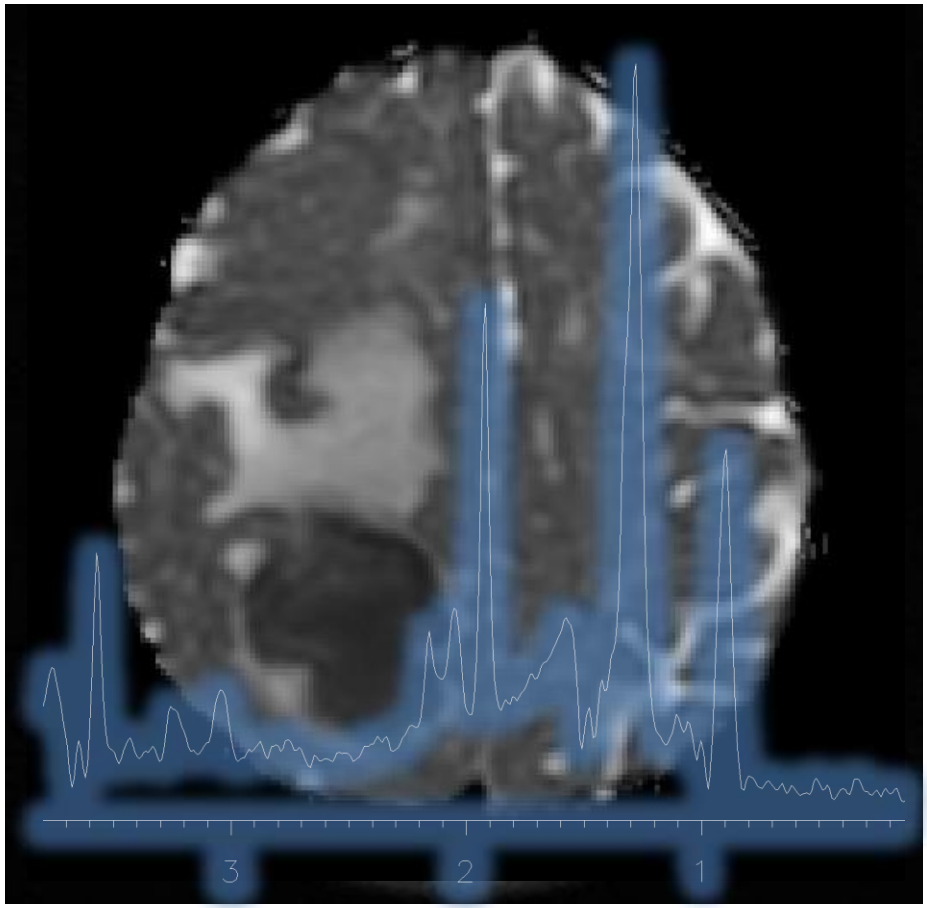
- Check card for question
- Location and suspected pathology will determine choice of spectroscopic sequence

• Diagnostic question - focal lesions larger than 15mm	SVS
• Biopsy targeting	2D/3D MRSI
• Tumour transformations	2D/3D MRSI
• Tumour Reoccurrence/radionecrosis	2D/3D MRSI
• Small lesions less than 15mm diameter	2D MRSI
• Temporal lobe, brain stem or lesions close to skull	SVS
• Systemic diseases	2D/3D MRSI

Abscess

Key Features

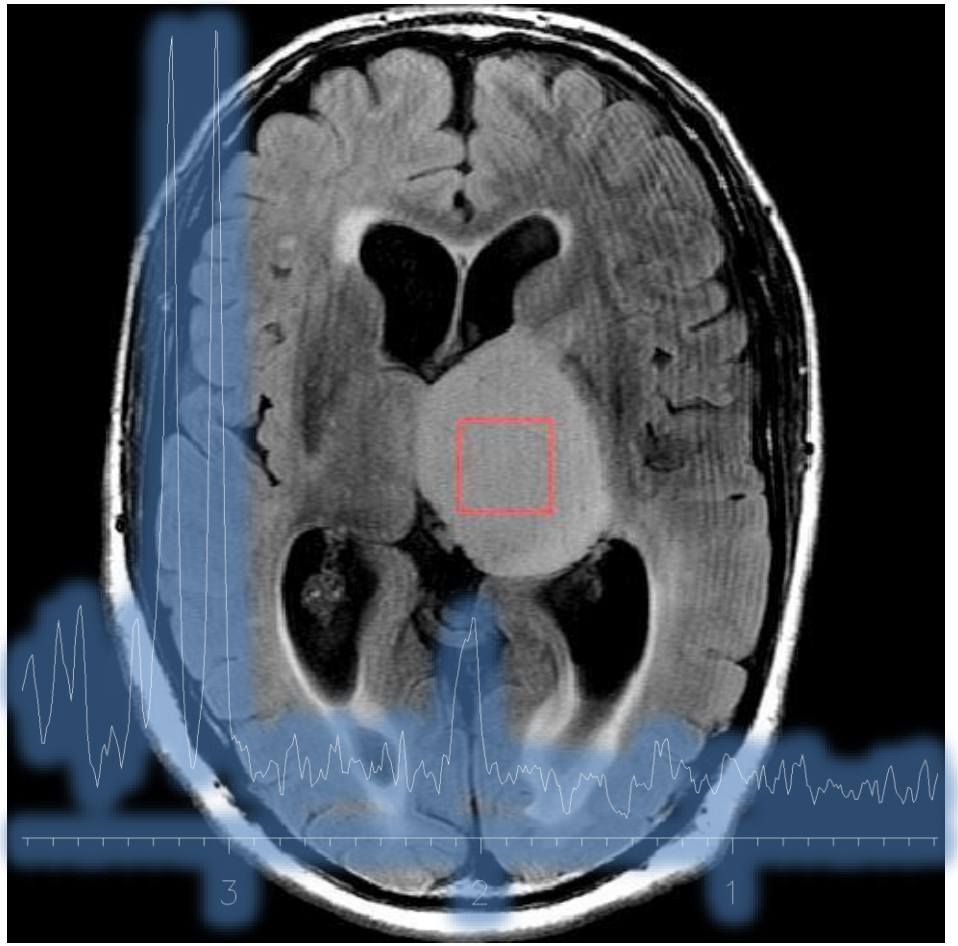
- Choline/Creatine =
- NAA ↓↓
- Acetate (1.9ppm) ↑
- Lipids ↑
- Succinate (2.4ppm) ↑



Astrocytic Tumours (WHO II/III)

Key Features

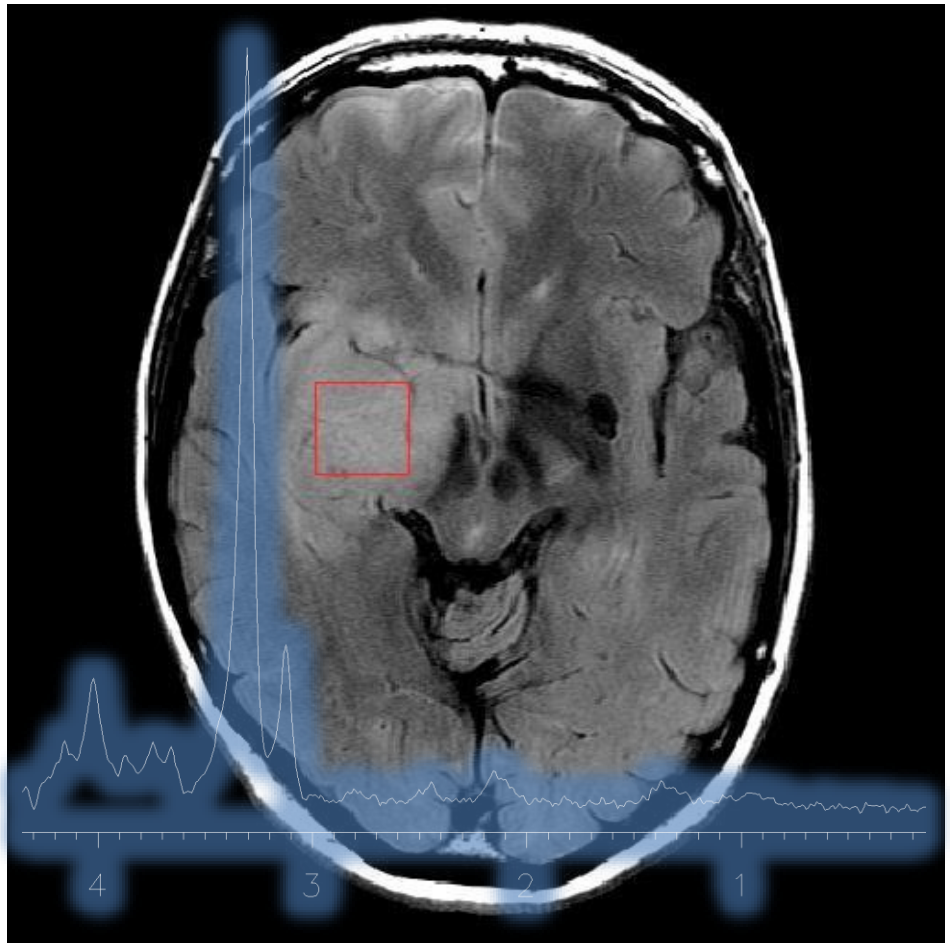
- Choline/Creatine ↑
- NAA ↓
- Lipid (Grade III) ↑



Oligodendroglial Tumours (WHO II/III)

Key Features

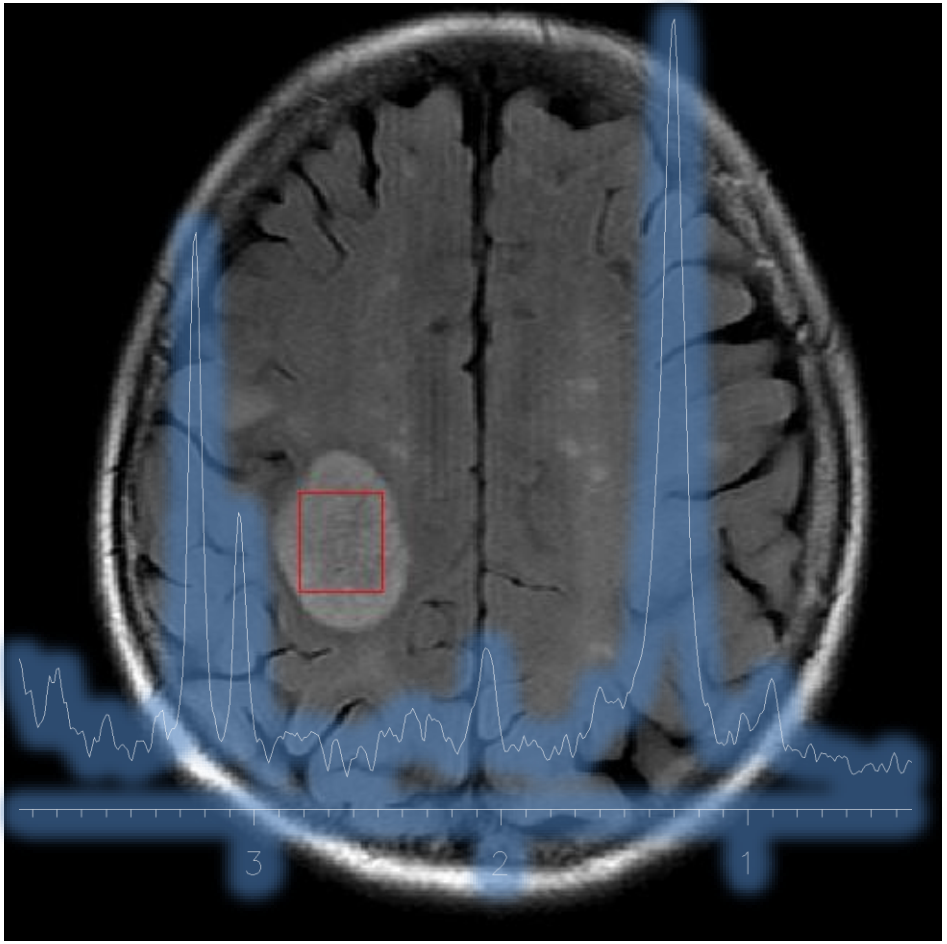
- Choline/Creatine ↑↑
- NAA ↓↓
- Lipid (Grade III) ↑



Glioblastoma Multiforme (WHO IV)

Key Features

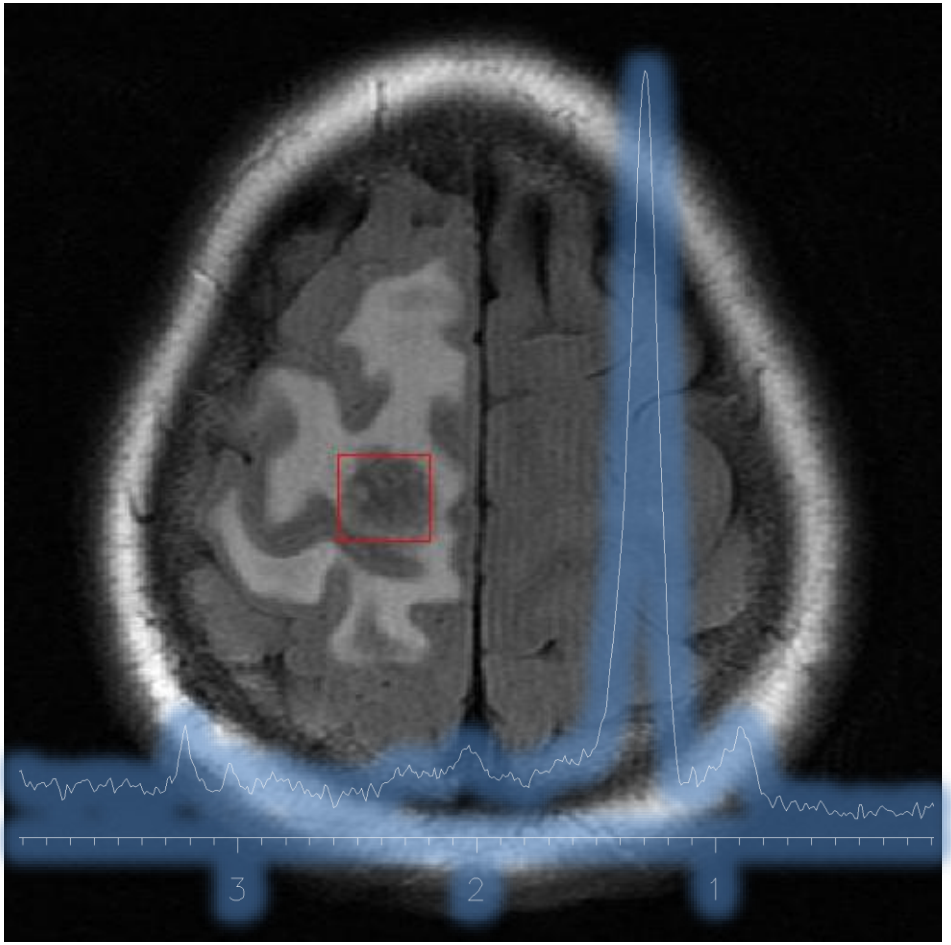
- 1.3ppm Lipid ↑↑
- Choline/Creatine ↑
- NAA ↓



Metastases

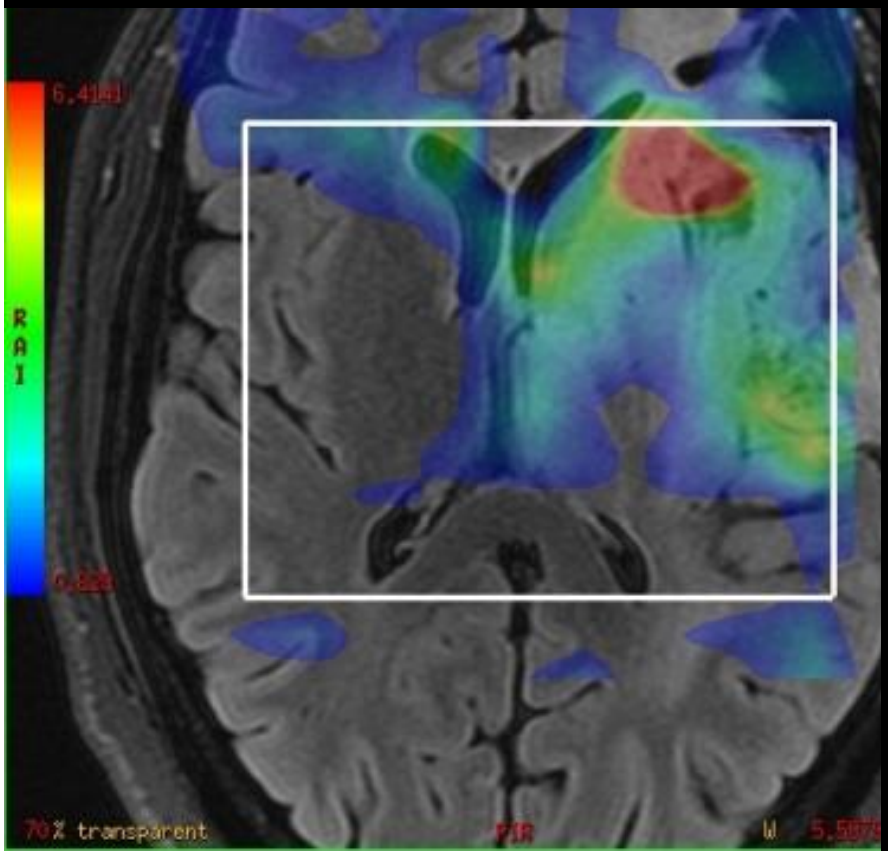
Key Features

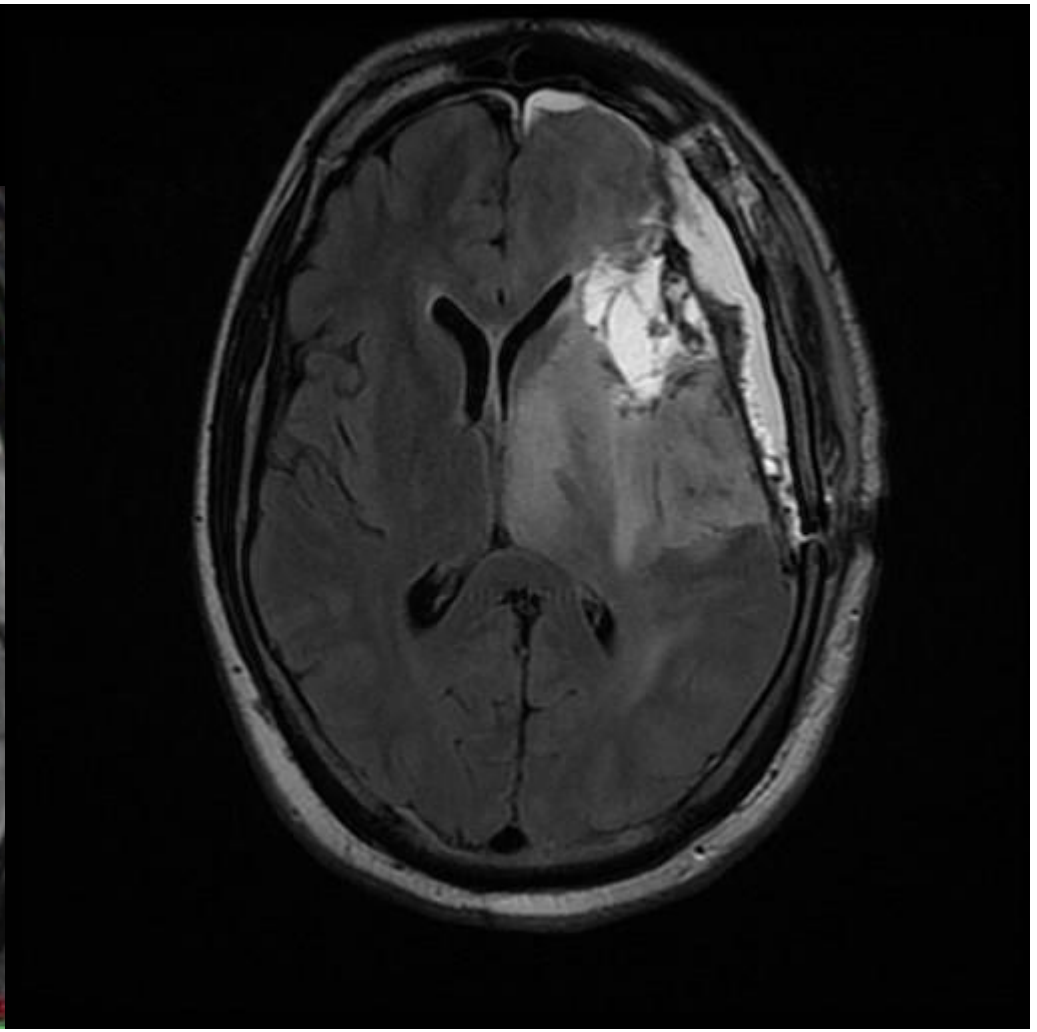
- 1.3ppm Lipid ↑↑↑
- Choline/Creatine ↑
- NAA ↓↓



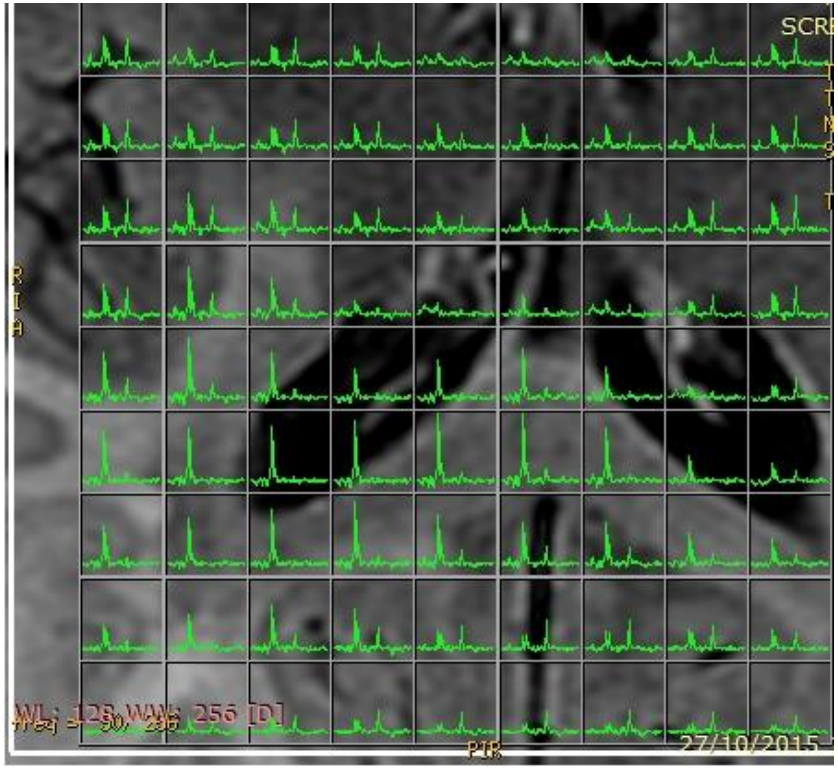
Characterisation of Brain Tumours without Contrast

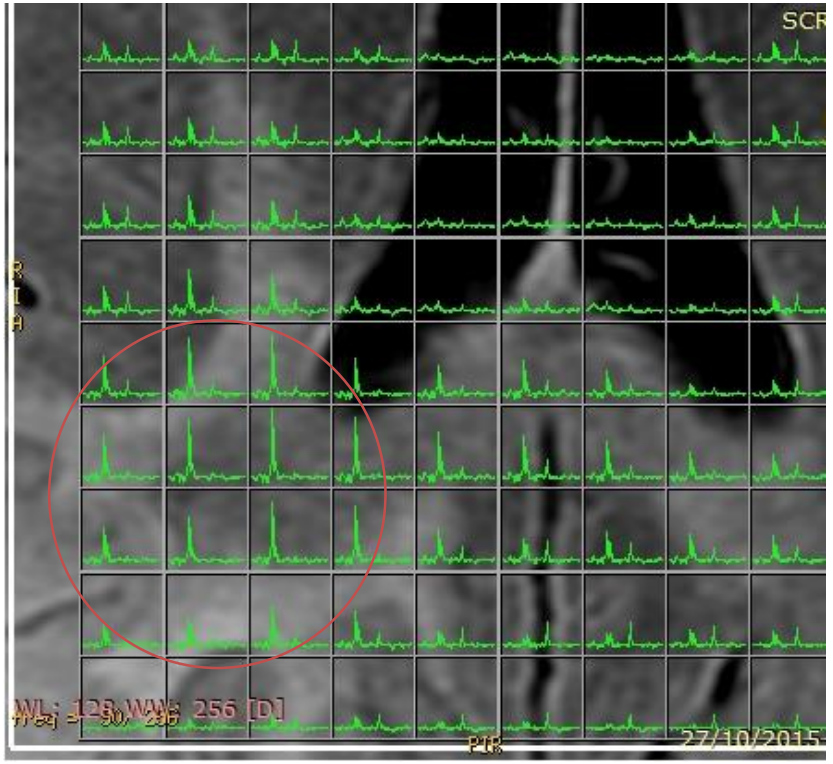
3D MRSI Choline/NAA



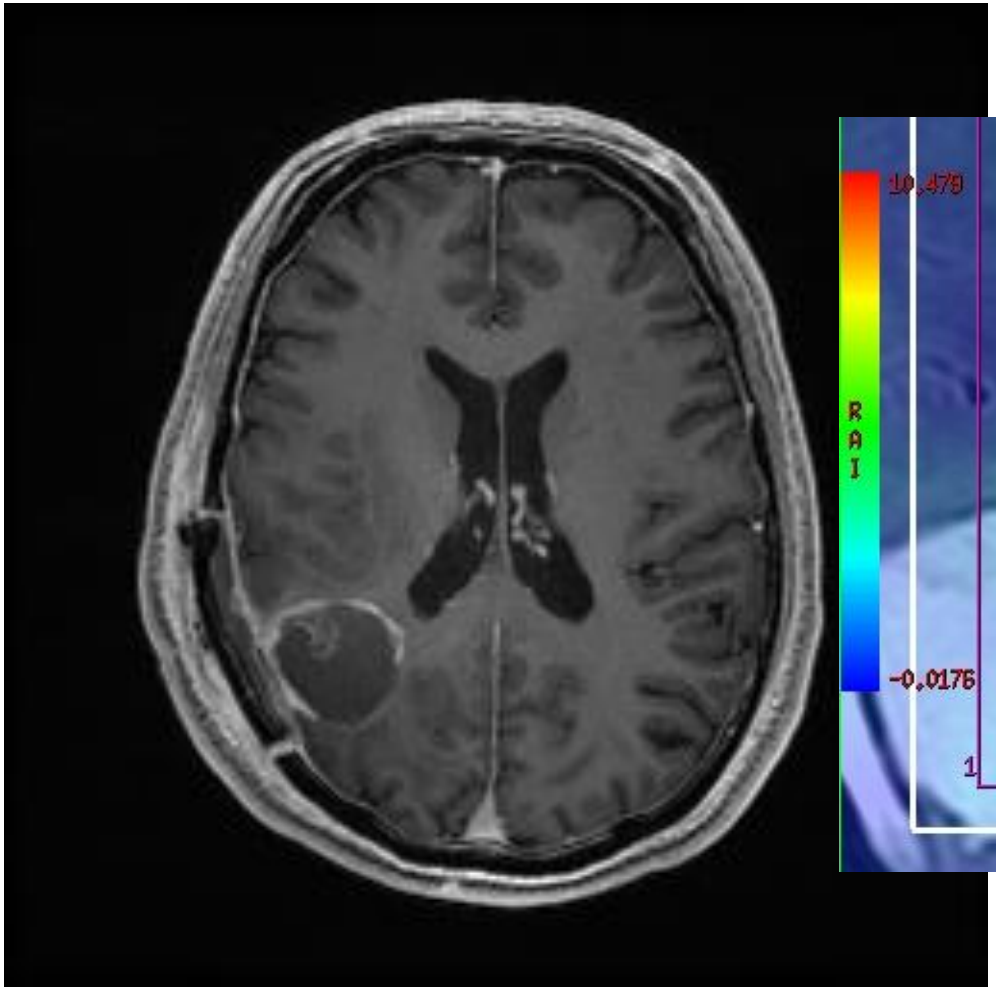


Characterisation of Extensive T_2 Abnormalities

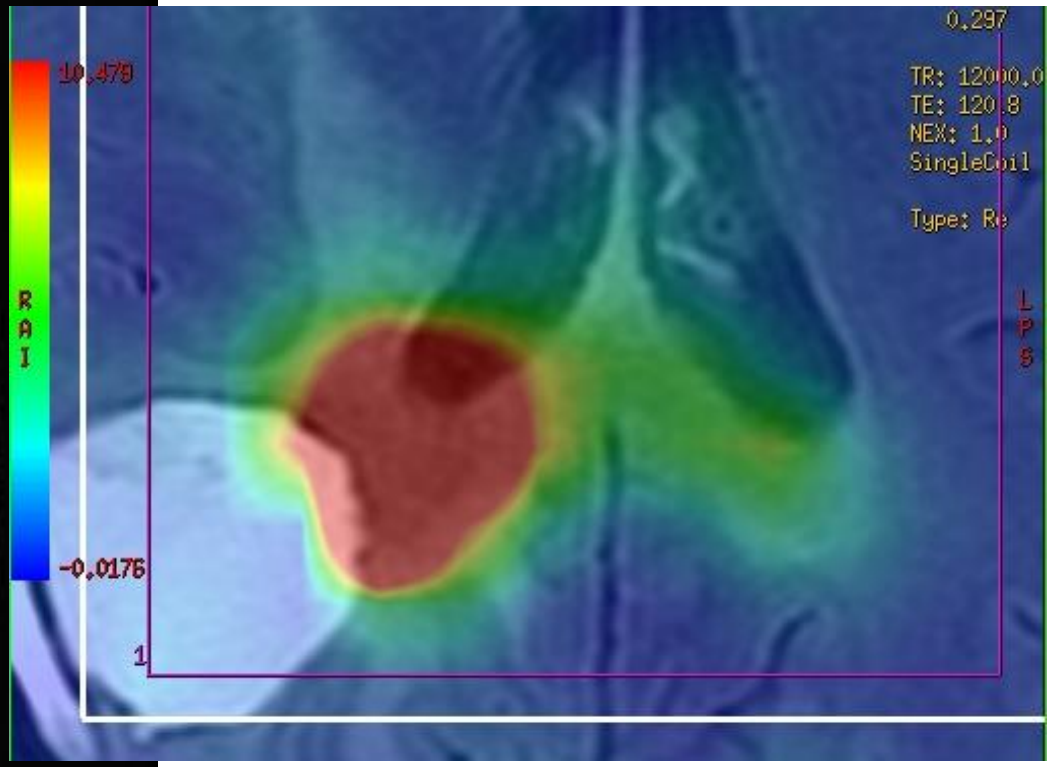


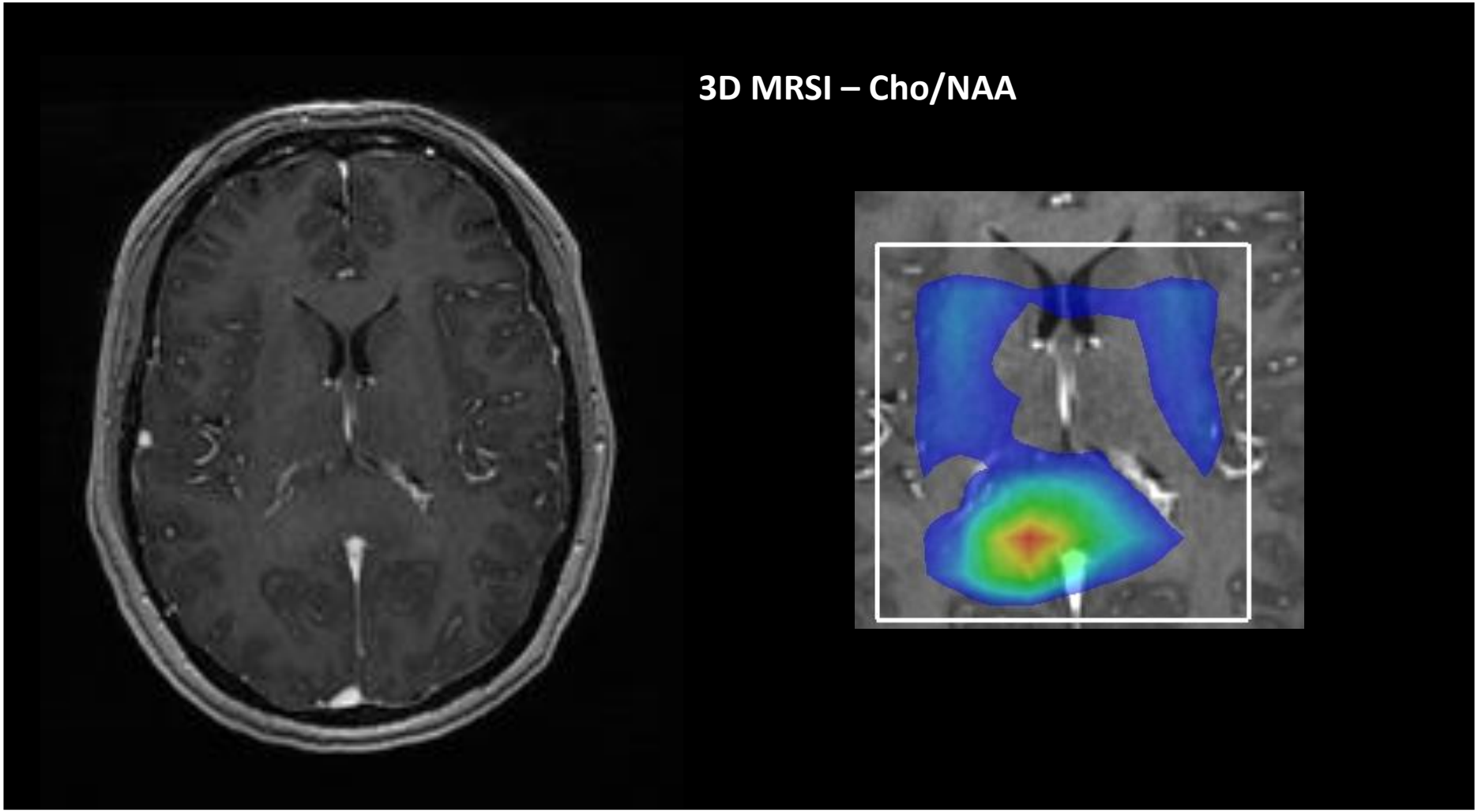


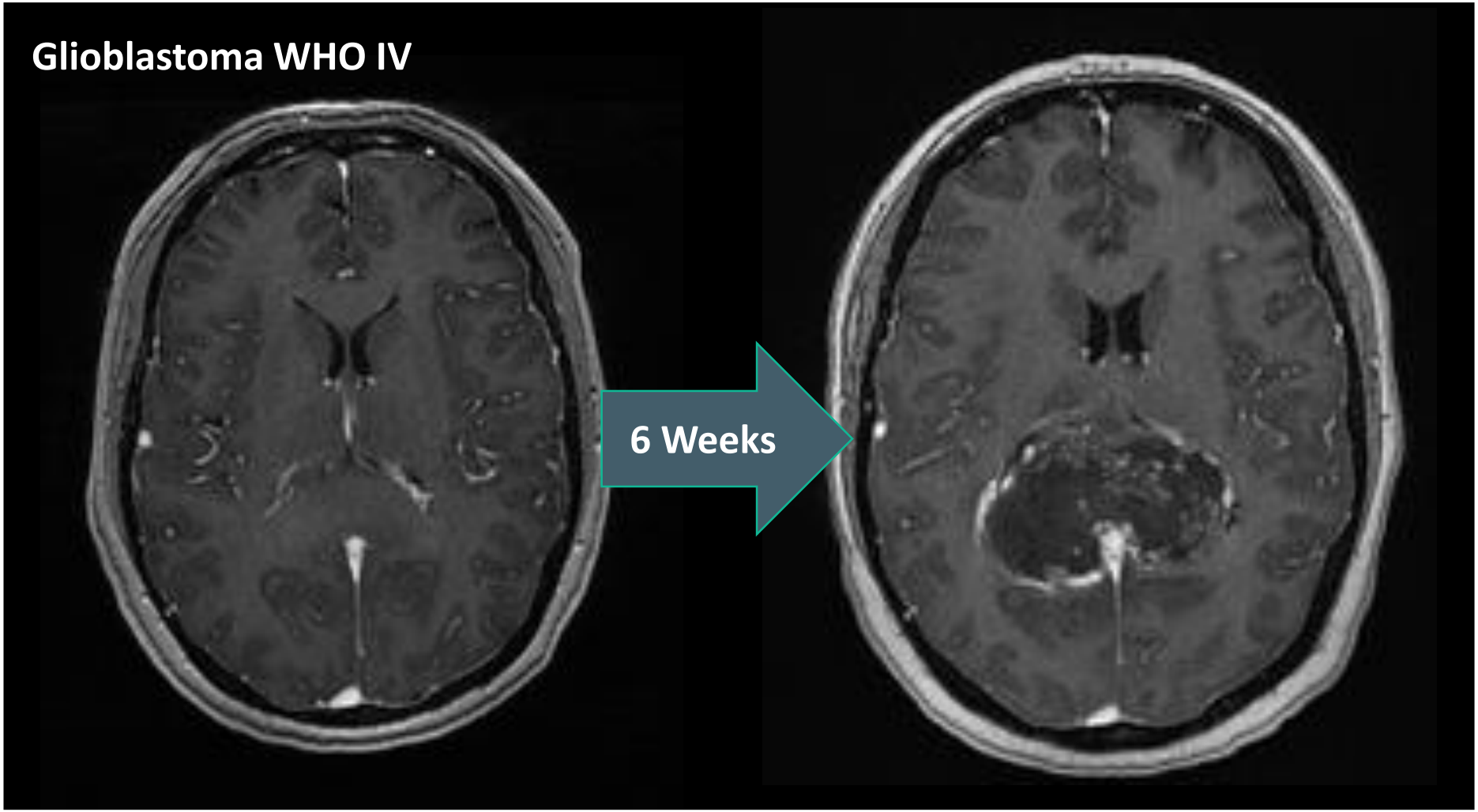
Glioblastoma (WHO IV)



3D MRSI – Cho/NAA

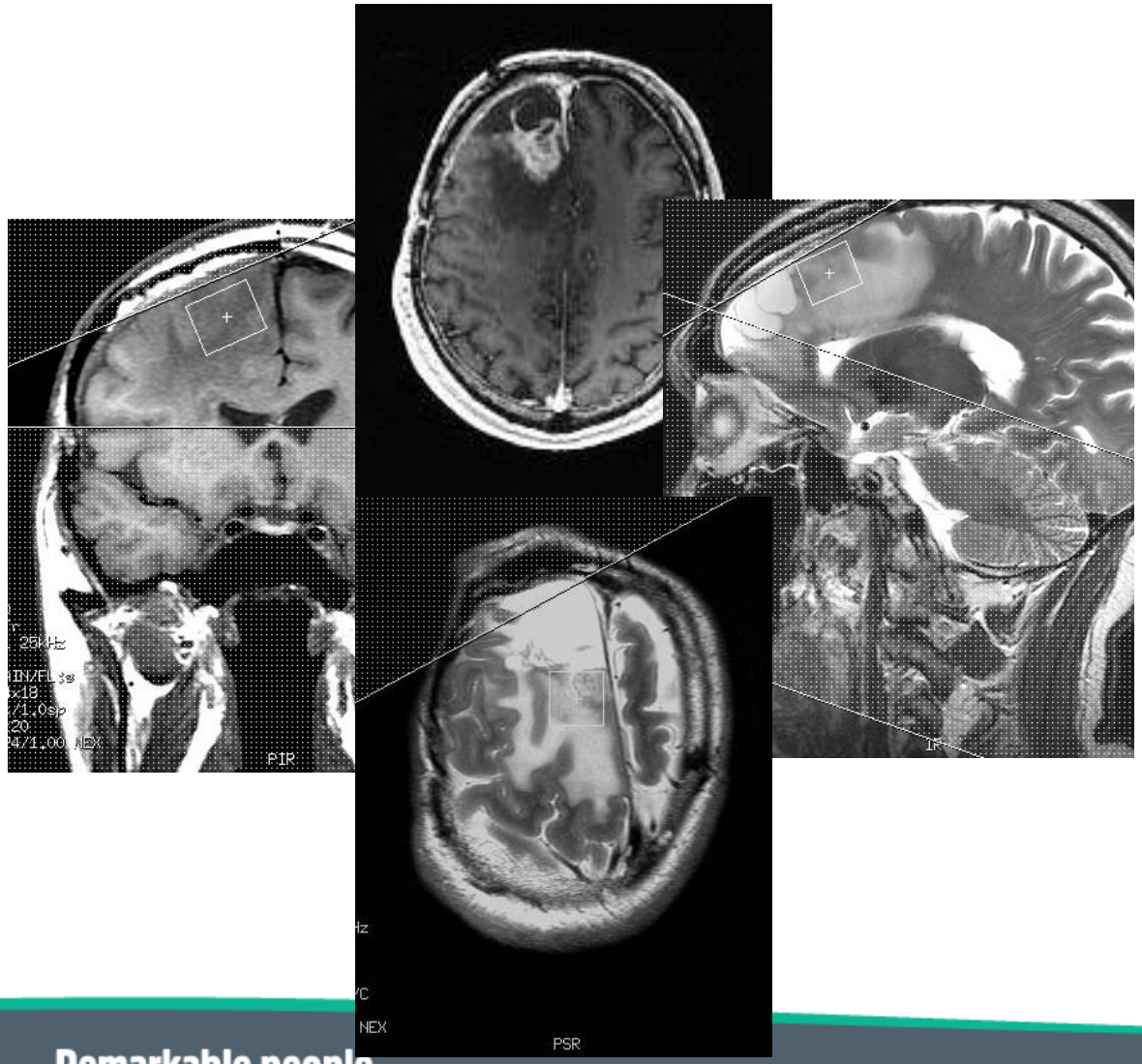


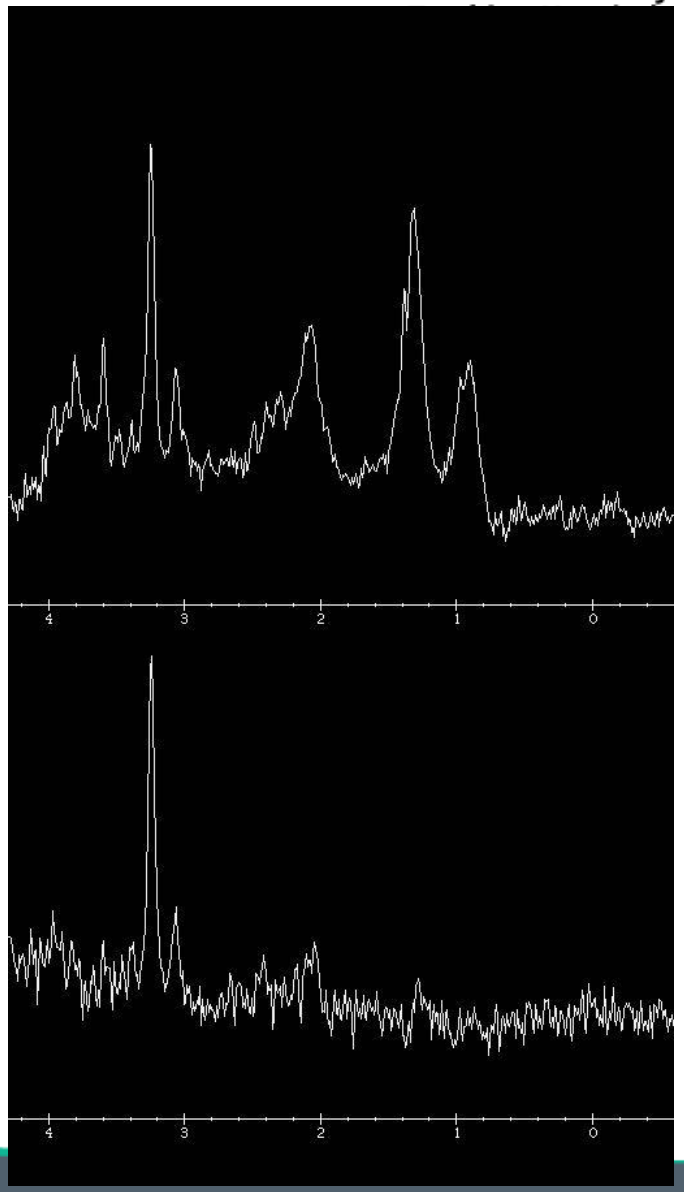

3D MRSI – Cho/NAA


Glioblastoma WHO IV
6 Weeks

NHS
Hull University

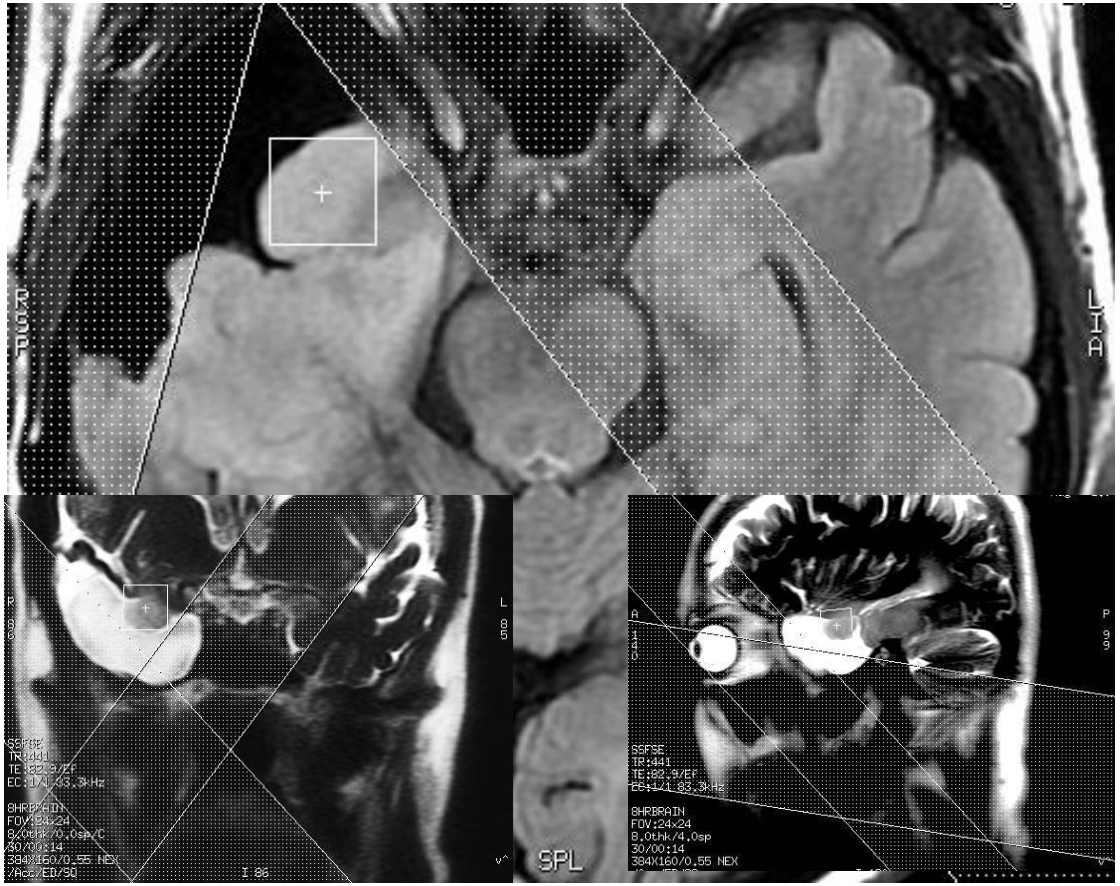
Pseudo-progression vs Reoccurrence

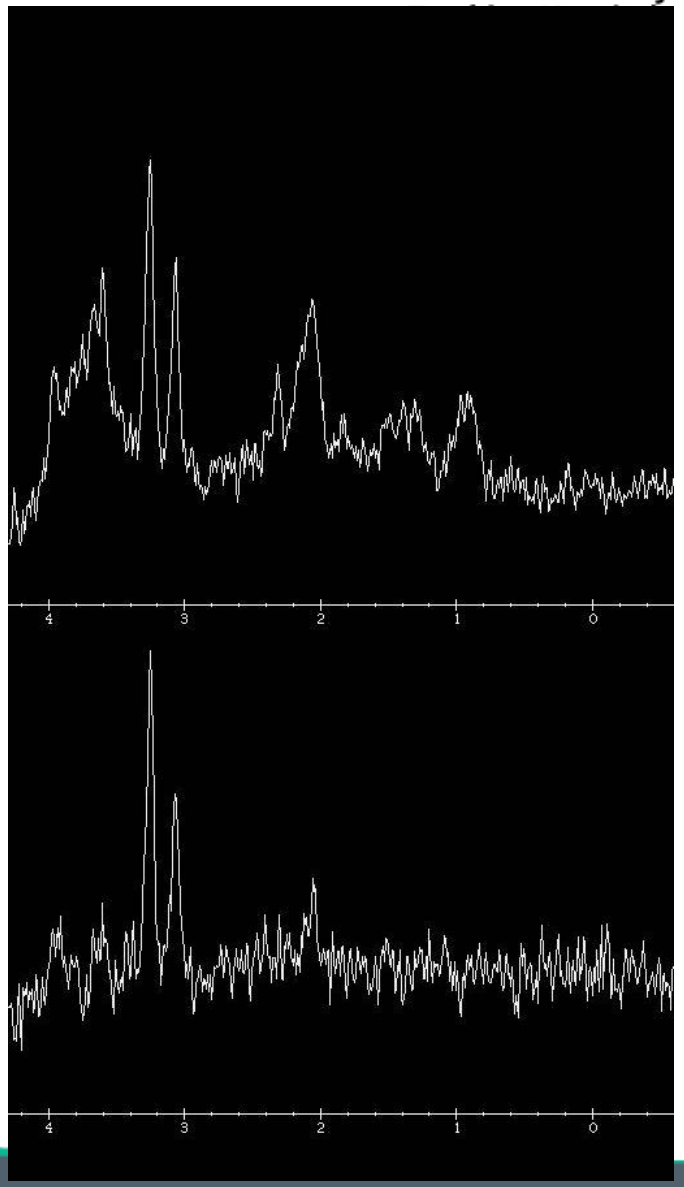




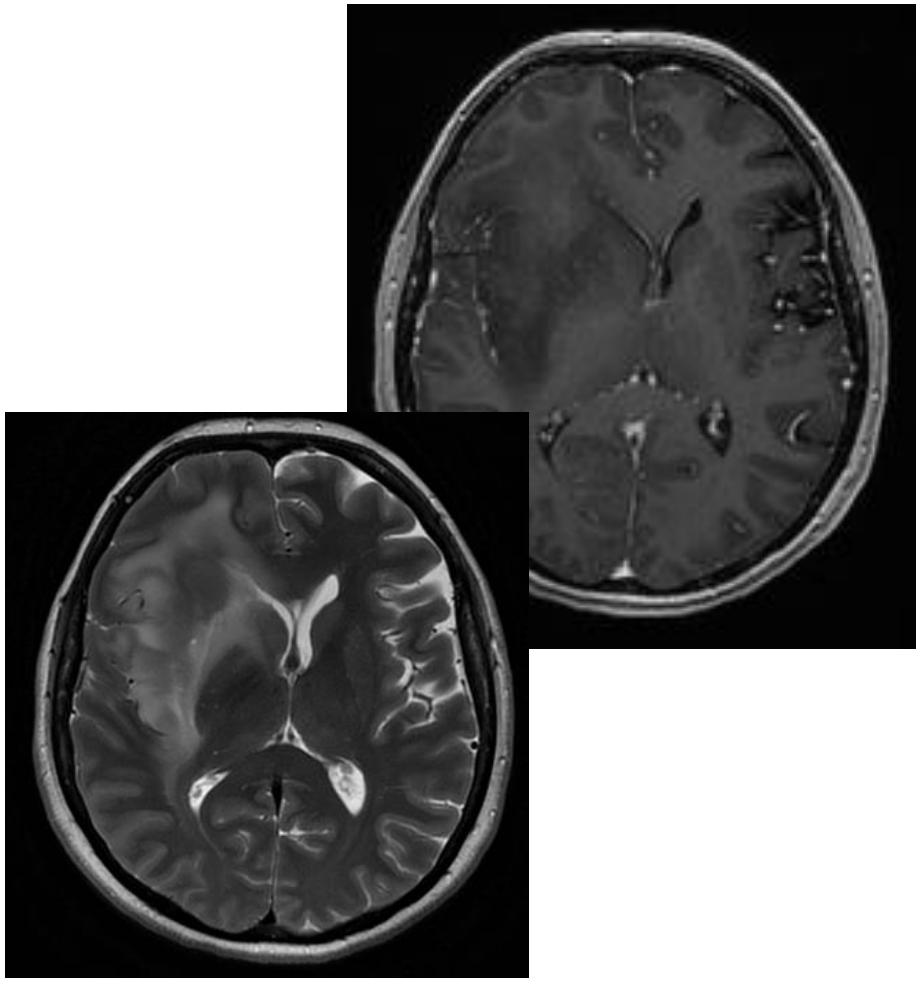
NHS
Hull University

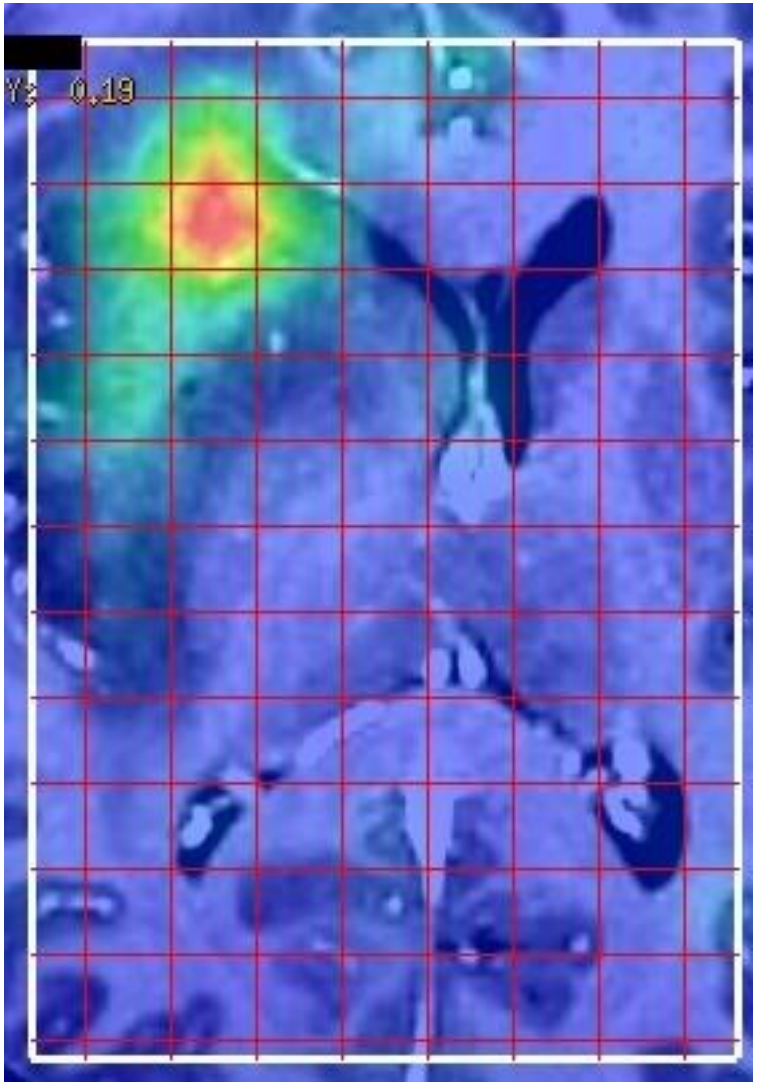
Gliosis vs Residual Disease



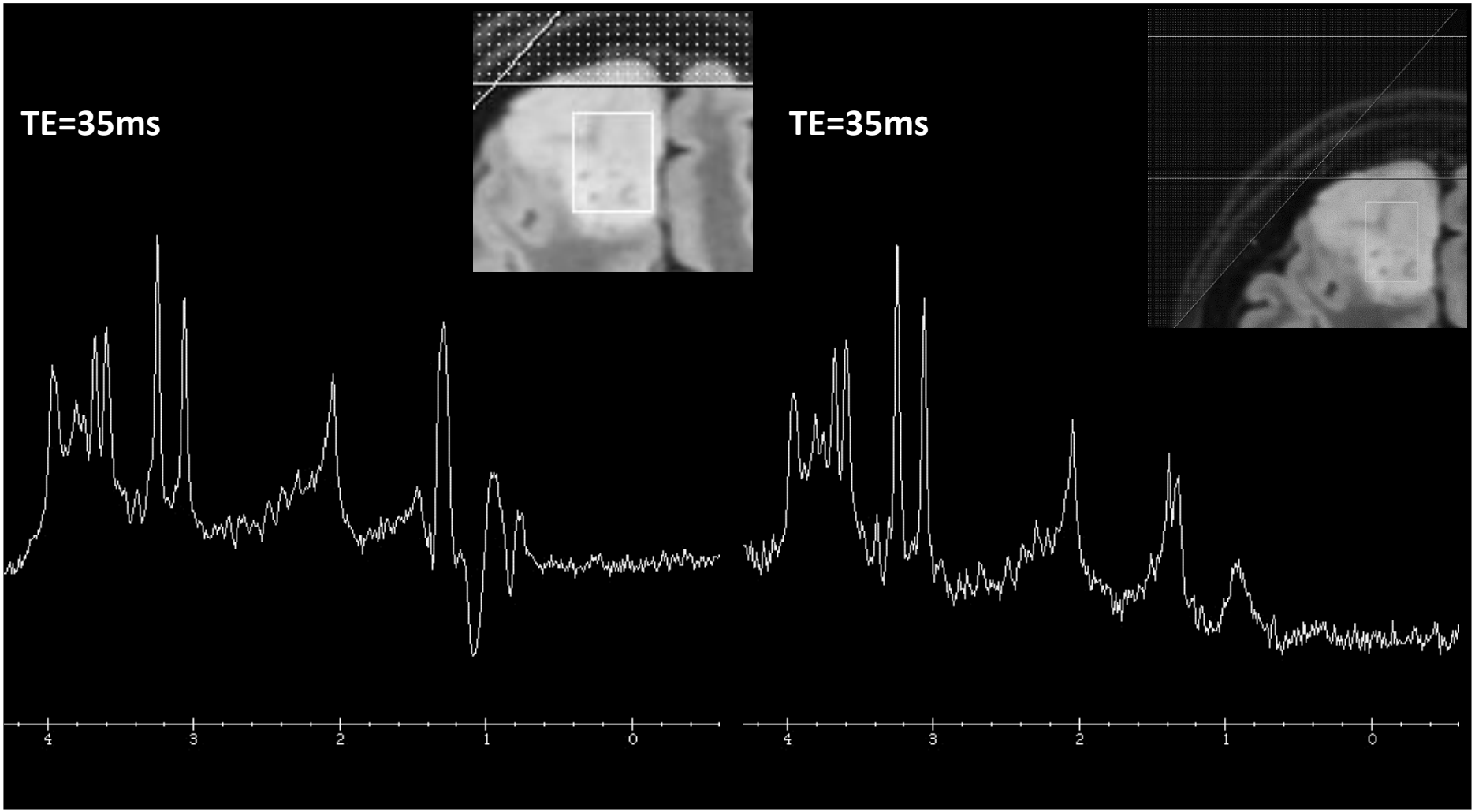


Infiltrating Glioma WHO II/III

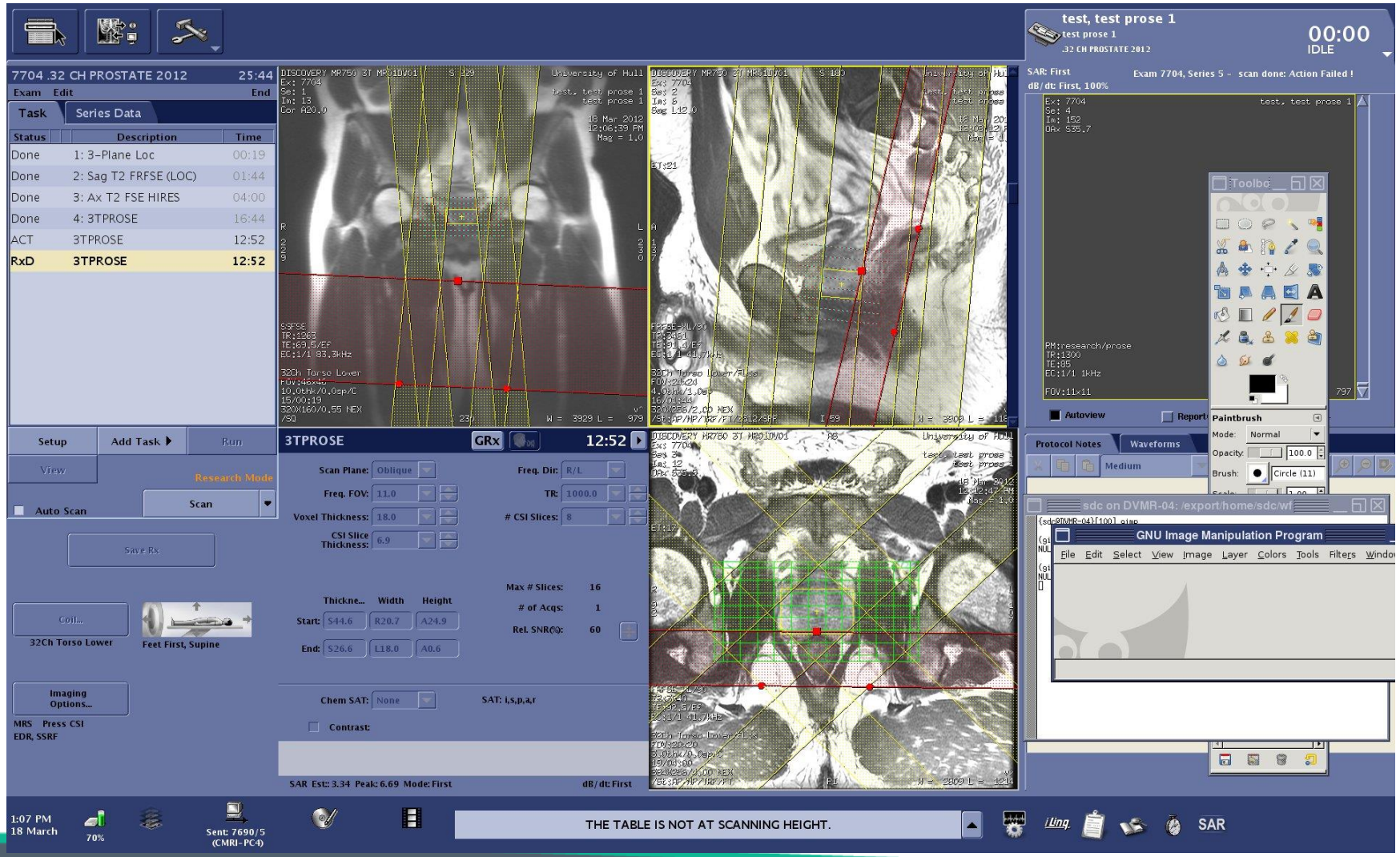




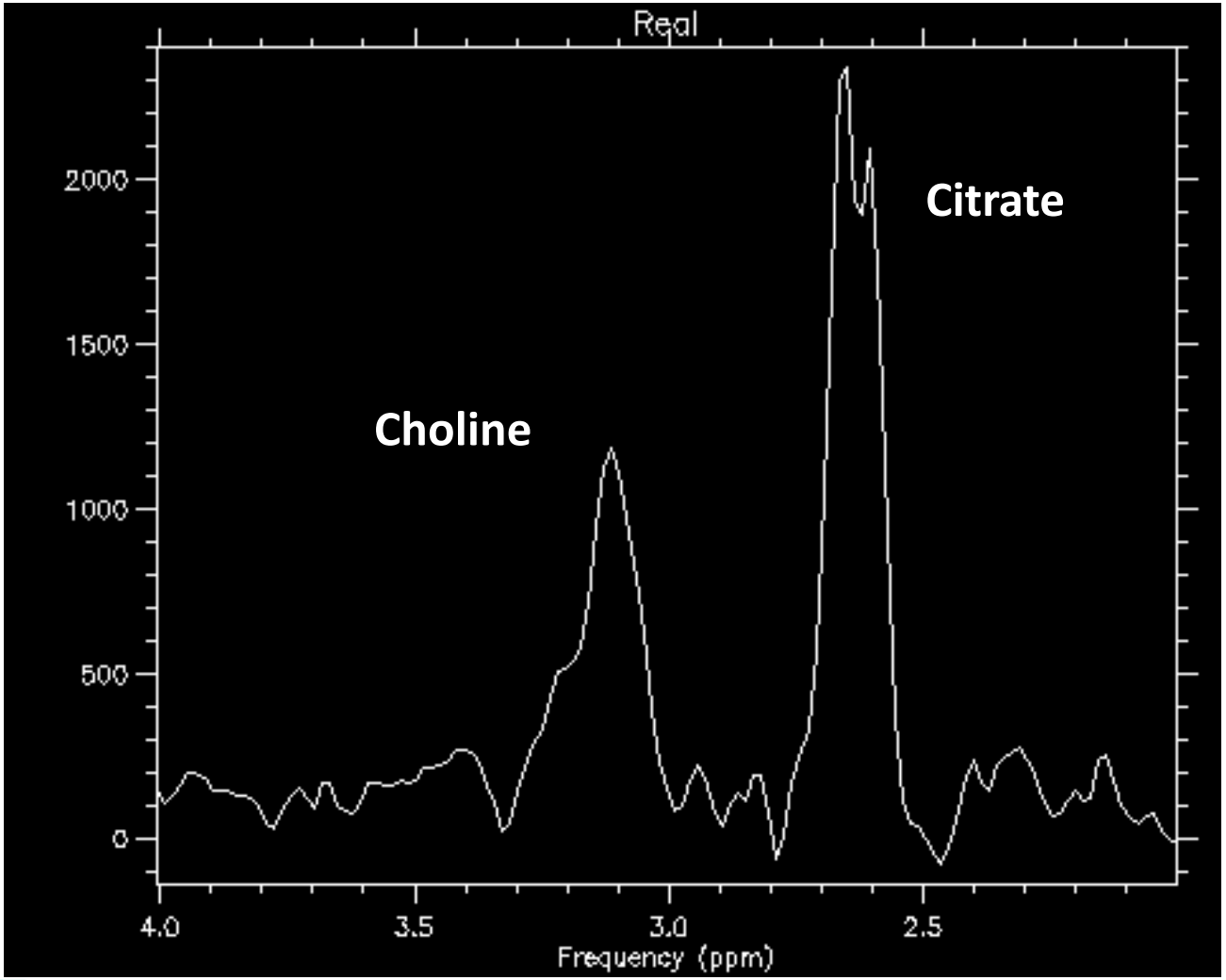
Flow Artefact



Prostate Spectroscopy



Prostate Spectroscopy



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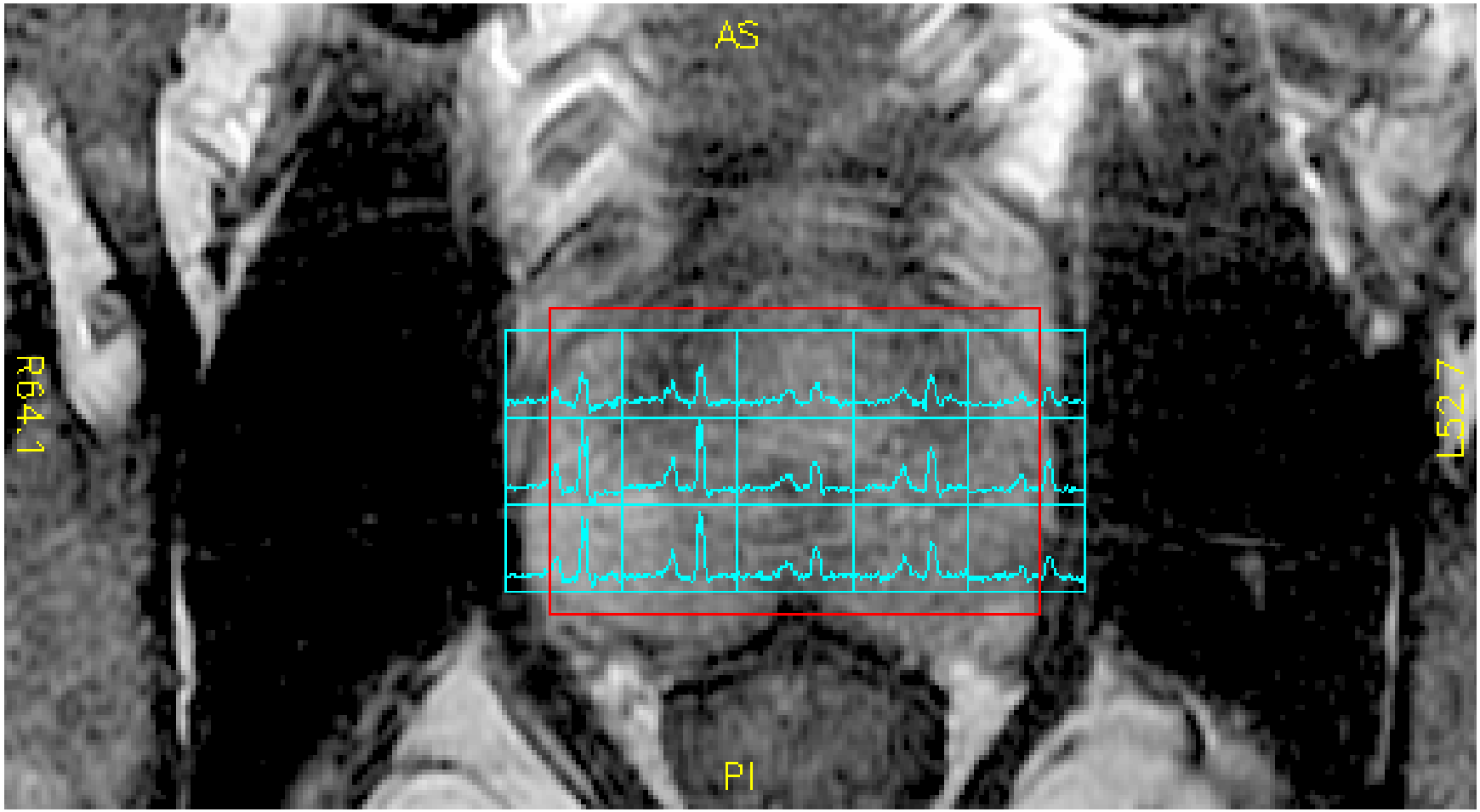
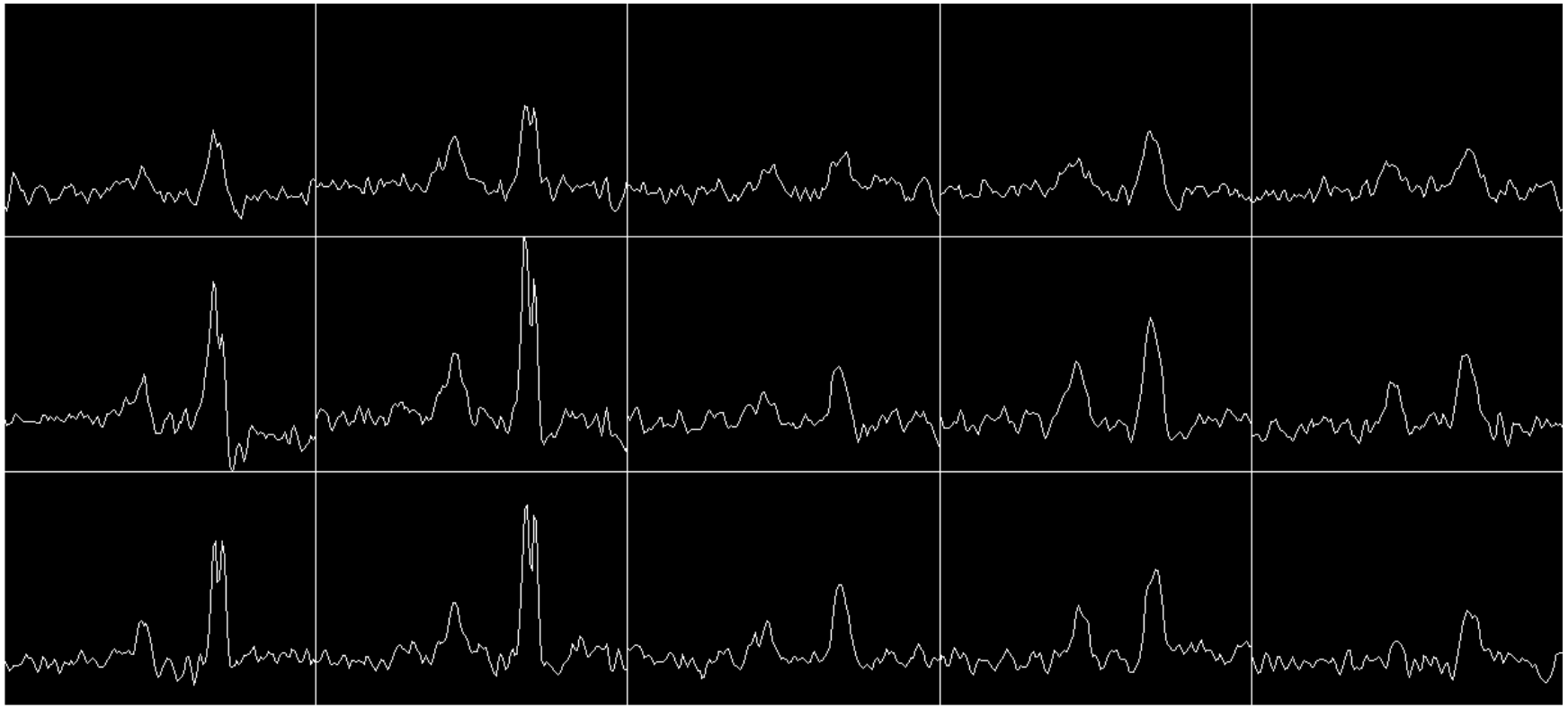


Prostate Spectroscopy



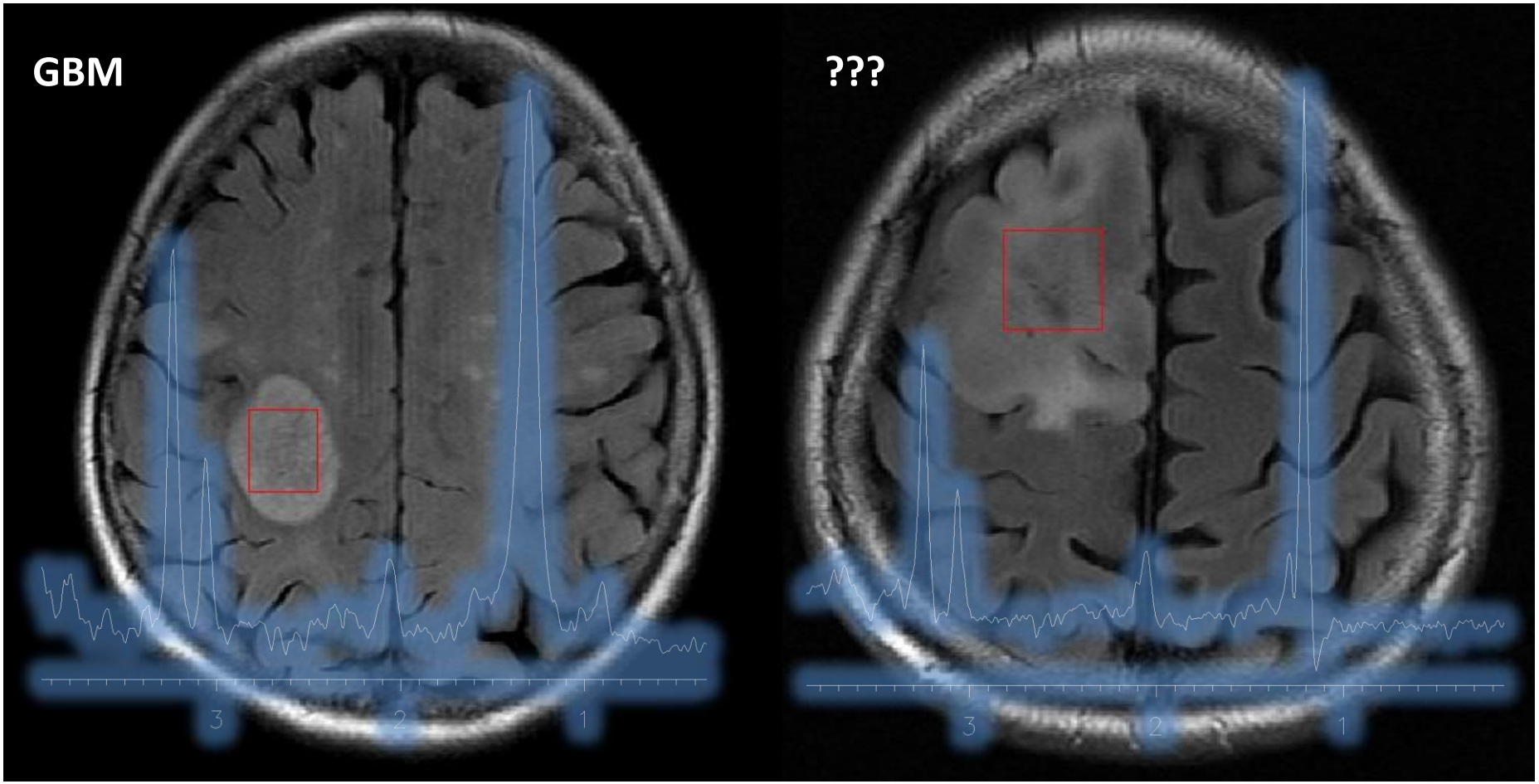
Other Nuclei

- Spectroscopy also possible with other nuclei, e.g. ^{31}P and ^{13}C.
- Phosphorus is less abundant than protons, so SNR poor. Since phosphorus major component in adenosine triphosphate (ATP), consumed and renewed during conversion of sugars to energy, ^{31}P often used to study muscle metabolism.
- By labelling glucose with ^{13}C, it is possible to study glucose metabolism in the brain.
- ^{23}Na has been used to measure intra and extracellular levels of sodium ions.

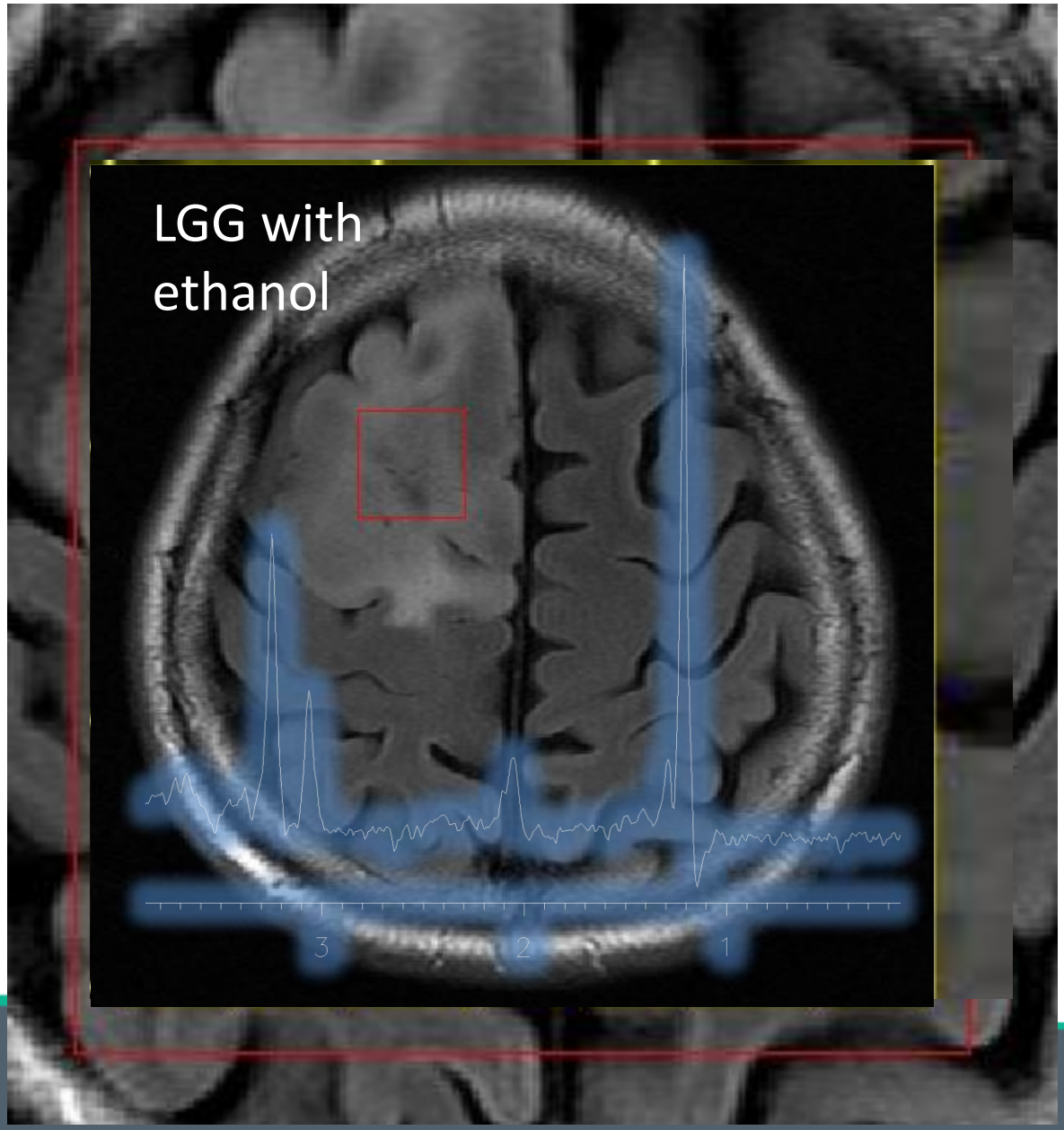
Other Nuclei – Relative Sensitivities

Nucleus	Spin	γ Rad/T/s ($x10^8$)	Frequency @1.5T (MHz)	Natural abundance	Relative Sensitivity
^{1}H	1/2	2.675	63.6	100%	100%
^{19}F	1/2	2.517	59.8	100%	83%
^{31}P	1/2	1.083	25.7	100%	0.663%
^{23}Na	3/2	0.708	16.8	100%	0.925%
^{13}C	1/2	0.673	16.0	1.1%	0.0176%

Mystery Case



NHS
Hull University Teaching Hospitals
NHS Trust



Key Points

- In high enough concentrations, ethanol can be visible in the brain
- Ethanol produces a triplet at 1.2ppm
- Lipid produces a multiplet at 1.3ppm and 0.9ppm

7.4 Frequency-dependant techniques

- Understanding of chemical shift: fat & water
  - *The two dominate fat peaks (1.3ppm and 0.9ppm) experience a lower local magnetic field (B_0) due to the electron shielding compared to water. Fat precesses at a lower frequency than water. Chemical shift is 3.5ppm*
  - *Δf = (64 MHz)(3.5 ppm) = (64 x 10^6 Hz)(3.5 x10^{-6}) ≈ 220 Hz @ 1.5T*

- Fat saturation
  - *CHESS (Chemical Shift Selective) aka 'fat sat'. Narrowband RF pulse applied to fat peak. Quick but not very robust.*

- In-phase & out-of-phase TEs, Dixon
  - *Fat-water will be in/out of phase every 2.2ms @ 1.5T*
  - *Generate water or fat only image*
  - *In-phase image is a normal T_1/T_2/P.D.*
  - *Dixon - Very robust fat-nulling. Time penalty.*

7.4 Frequency-dependant techniques

- Awareness of MR spectroscopy (MRS) and appropriate TEs for particular clinical questions
  - *MR Spectroscopy can provide metabolic information non-invasively in additional to conventional imaging sequences.*
  - *Key to good spectroscopic data is careful positioning and planning.*
  - *Considerations:*
    - *The clinical question*
    - *Whether single or multivoxel methods are required*
    - *The echo time of spectra (lactate inverted doublet at 144ms)*
    - *Examine planning images for partial volume effects.*