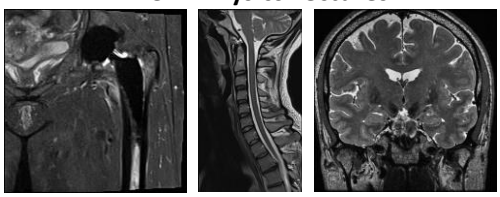
# Magnetic Resonance Imaging

## F.R.C.R. Physics Lectures



Lawrence Kenning PhD

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# Magnetic Resonance Imaging

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FRCR MRI Syllabus

**Magnetic Resonance Imaging (MRI) [2]**

- Gradient echo imaging – basic spoiled and non-spoiled techniques
- Tissue suppression methods – STIR, FLAIR and Fat saturation
- Standard gadolinium contrast agents
- Magnetic Resonance Angiography
- Basic principles of diffusion weighted imaging
- Dynamic contrast enhancement and perfusion imaging
- Principles of magnetic resonance spectroscopy (MRS)

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MRS

# Magnetic Resonance Spectroscopy (MRS)

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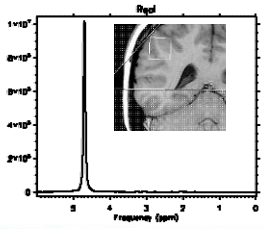
MRS - Metabolism

**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'

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MRS - Metabolism

**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

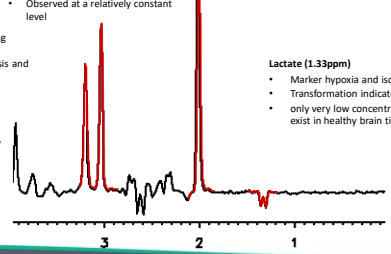
**Choline (3.24ppm)**
- 3 choline containing metabolites
- Membrane synthesis and breakdown

*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

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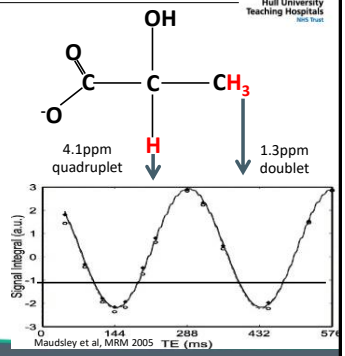
## MRS - Metabolism

**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

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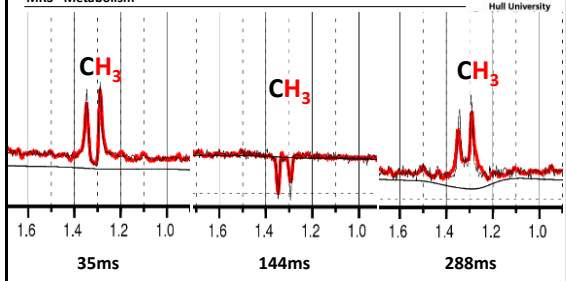
## MRS - Metabolism




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

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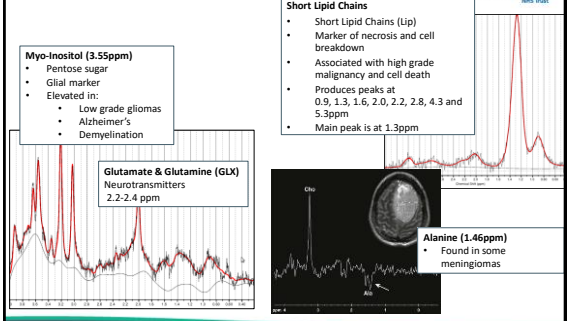
## MRS - Metabolism

**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



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## MRS - Principles

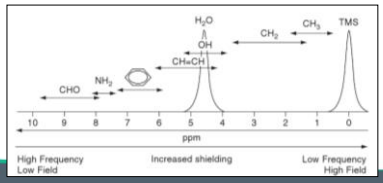
**Chemical Shift**

- MR spectroscopy utilises chemical shift properties of different nuclei
- electron cloud around an atom shields the nucleus from the magnetic field ($\sigma$):

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

- different resonant frequencies for different molecules

$\gamma$ = gyromagnetic ratio, $B_0$ = magnetic field strength, $\omega_0$ = resonant frequency

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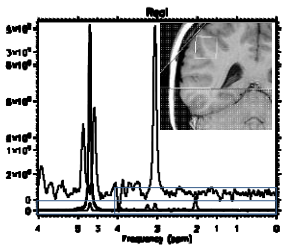
## MRS - Principles

**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

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## MRS - Principles

**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

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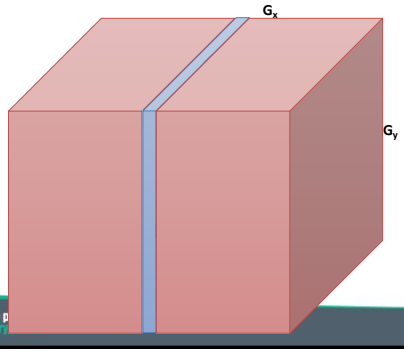
MRS - Principles

Single Voxel Spectroscopy

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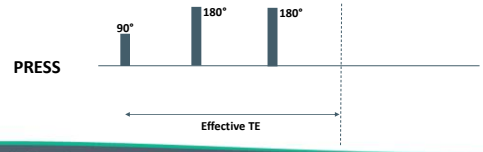
MRS - Principles

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 90º -137º - 137º are used due to the need for a larger bandwidth without breaching the specific absorption ratio (SAR) limit

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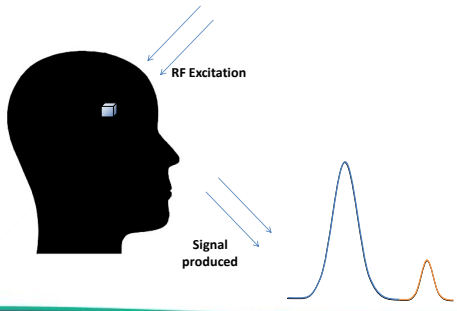
MRS - Principles

Single Voxel Spectroscopy

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MRS - Principles

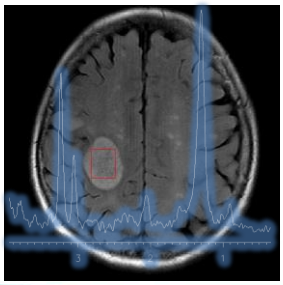
Single Voxel Spectroscopy

**Pros**

- High SNR
- Robust

**Cons**

- Partial volume effects
- No spatial information



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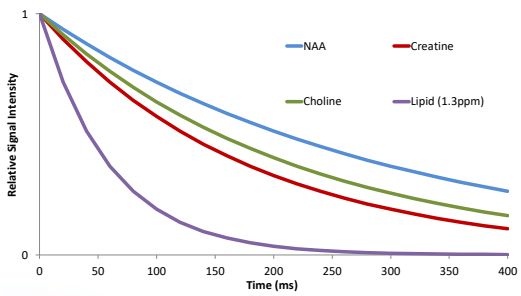
MRS - Principles

$T_2$ Relaxation of Metabolites

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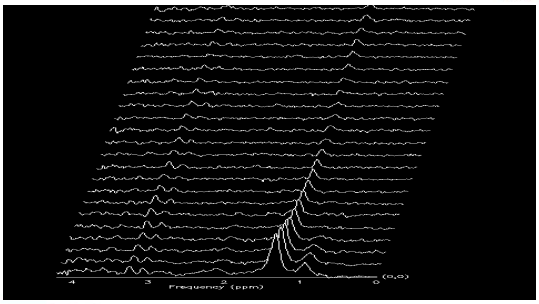
MRS - Principles

$T_2$ Relaxation of Metabolites

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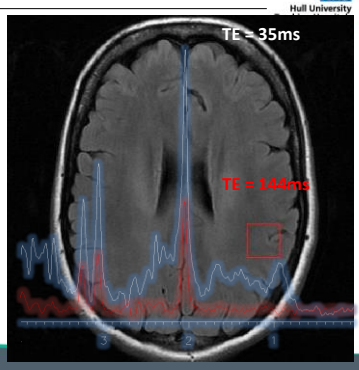
MRS - Principles

**Echo Time (TE)**

**TE = 35ms**
- Higher SNR
- Sensitive to lipids and myo

**TE = 144ms**
- Flatter baseline which improves quantification
- Inverted lactate
- More robust

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MRS - Principles

**Sample Protocols**

| SVS | 2D MRSI |
|---|---|
| • TR=1200ms | • TR=1000ms |
| • TE=35/144ms | • TE=144ms |
| | • FOV=16cm |
| | • PE=16x16 |
| | • Slice Thickness=10mm |
| • NEX=192 | • NEX=1.6 |
| • Voxel Size = 20x20x20mm$^3$ | • Voxel Size = 10x10x10mm$^3$ |
| • **Scan Time = 4.20min** | • **Scan Time = 7.00min** |

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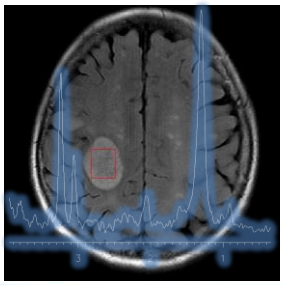
MRS - Principles

**Spectroscopic Planning**

- Representative of the abnormality
- Minimise normal tissue contamination
- Avoid oedema
- Use ADC/CBF maps to identify targets



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MRS - Principles

**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

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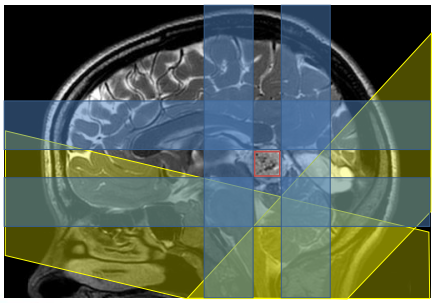
MRS - Principles

**Spectroscopic Planning**



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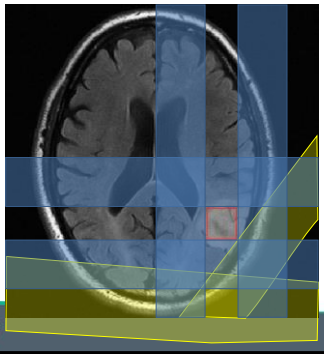
MRS - Principles

**Spectroscopic Planning**



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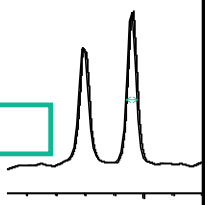
MRS - Principles

**Acquisition**

**Auto Prescan**

- optimize the transmit / receiver gains
- the centre frequency
- the shim
- the power of the water suppression pulses

R1:11 R2:29 AX:63855957
**LnWdth:5** Flip Ang:145 **Supp Lvl: 98**



**Line Width**

- Less than 15Hz

**Water Suppression Level**

- Between 90 and 99%

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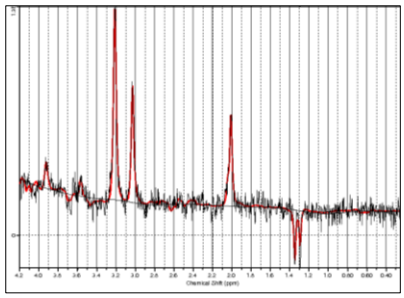
MRS - Principles

**5 MINUTES LATER.....**



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MRS - Principles

**Magnetic Resonance Spectroscopic Imaging (MRSI)**

single voxel spectroscopy

+

phase encoding steps

=

multivoxel spectroscopy

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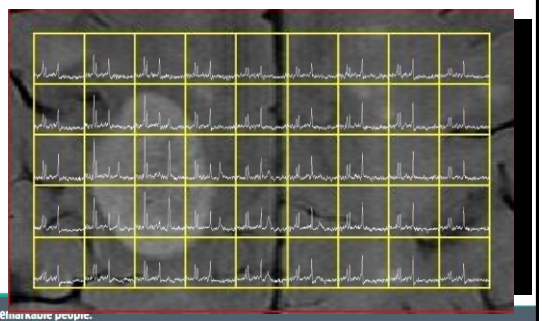
MRS - Principles

**Multivoxel Spectroscopy**



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MRS - Principles

**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 |

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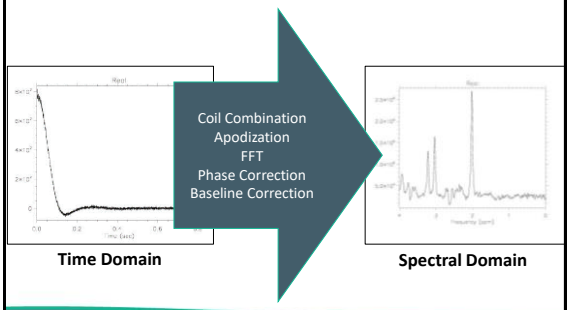
MRS - Processing

**Spectral Processing**

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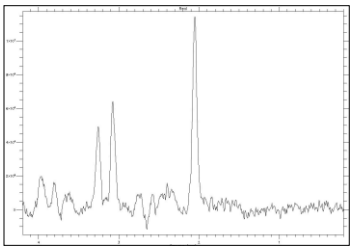
## MRS - Processing

**Quantification**

- Peak Height
- Peak Area
- Individual metabolites
- Ratios of metabolites i.e Choline:NAA
- User defines peak position and integration width



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## MRS - Processing

**Quantification**

- Spectral fitting using linear combination models (LCModel)
- Combines pure compound spectra
- Converts to metabolite concentration
- Fully automated
- User independent
- Minimal pre-processing. Only spatial apodization and zero order phase correction used.
- Cramer Lower Bounds describe the certainty that a peak is real
  - Useful in noisy data

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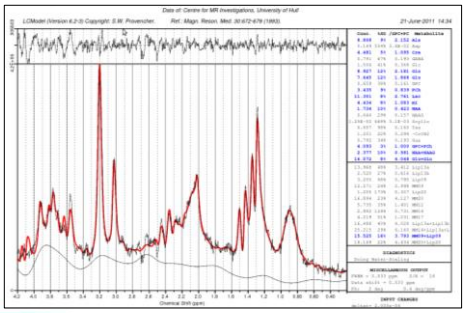
## MRS - Processing

**Quantification**



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## MRS - Processing

**Quantification**

| Conc. | %SD | /GPC+PC | Metabolite |
|---|---|---|---|
| 8.808 | 9% | 2.152 | Ala |
| 0.149 | 504% | 3.6E-02 | Asp |
| 4.481 | 5% | 1.095 | Cre |
| 0.791 | 67% | 0.193 | GABA |
| 1.504 | 41% | 0.368 | Glc |
| 8.927 | 12% | 2.181 | Gln |
| 7.645 | 12% | 1.868 | Glu |
| 0.659 | 38% | 0.161 | GPC |
| 3.435 | 9% | 0.839 | PCh |
| 11.301 | 8% | 2.761 | Lac |
| 4.434 | 8% | 1.083 | mI |
| 1.734 | 10% | 0.423 | NAA |
| 0.644 | 29% | 0.157 | NAAG |
| 1.25E-02 | 668% | 3.1E-03 | Scyllo |
| 0.657 | 98% | 0.160 | Tau |
| 1.201 | 22% | 0.294 | -CrCH2 |
| 0.792 | 34% | 0.193 | Gua |
| 4.093 | 3% | 1.000 | GPC+PCh |
| 2.377 | 10% | 0.581 | NAA+NAAG |
| 16.572 | 8% | 4.048 | Glu+Gln |

| | | | |
|---|---|---|---|
| 16.572 | 8% | 4.048 | Glu+Gln |
| 13.968 | 48% | 3.412 | Lip13a |
| 2.520 | 27% | 0.616 | Lip13b |
| 3.255 | 98% | 0.795 | Lip09 |
| 12.271 | 24% | 2.998 | MM09 |
| 1.255 | 173% | 0.307 | Lip20 |
| 16.894 | 23% | 4.127 | MM20 |
| 5.735 | 35% | 1.401 | MM12 |
| 2.992 | 124% | 0.731 | MM14 |
| 4.219 | 51% | 1.031 | MM17 |
| 16.488 | 40% | 4.028 | Lip13a+Lip13b |
| 25.215 | 29% | 6.160 | MM14+Lip13a+L |
| 15.525 | 16% | 3.793 | MM09+Lip09 |
| 18.149 | 22% | 4.434 | MM20+Lip20 |

DIAGNOSTICS

Doing Water-Scaling

MISCELLANEOUS OUTPUT

FWHM = 0.033 ppm S/N = 18

Data shift = 0.033 ppm

Ph: 2 deg 0.4 deg/ppm

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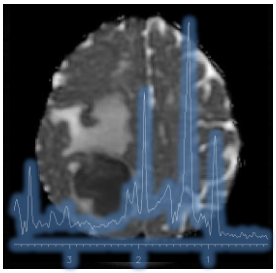
## MRS - Applications

**Abscess**

**Key Features**

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



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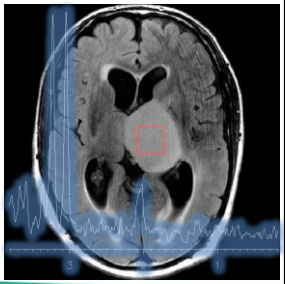
## MRS - Applications

**Astrocytic Tumours (WHO II/III)**

**Key Features**

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



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MRS - Applications

**Oligodendroglial Tumours (WHO II/III)**

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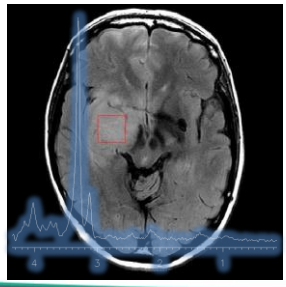
**Key Features**

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



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MRS - Applications

**Glioblastoma Multiforme (WHO IV)**

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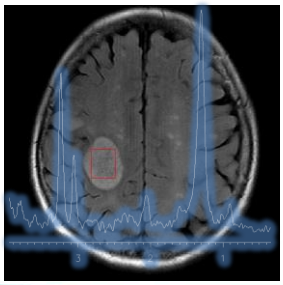
**Key Features**

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



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MRS - Applications

**Metastases**

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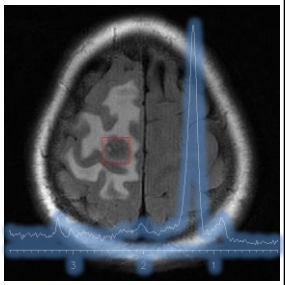
**Key Features**

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



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MRS - Applications

**Quantification**

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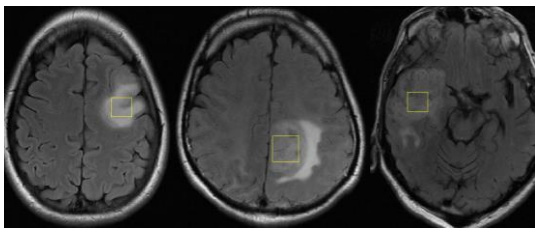

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MRS - Applications

**Glioblastoma Multiforme**

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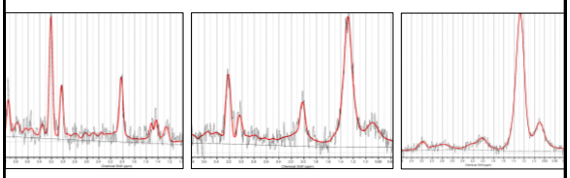

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MRS - Applications

**Recurrent Glioblastoma Multiforme?**

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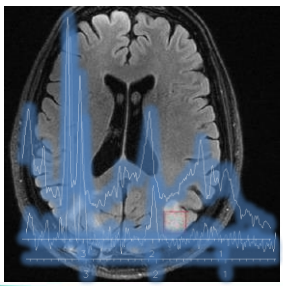
**Astrocytic Appearance**

- Lipid increase
- Choline/creatine increase
- NAA decrease



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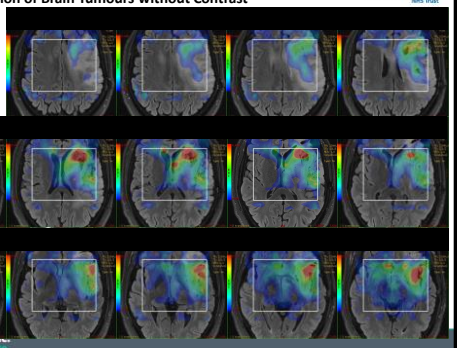
MRS - Applications

Characterisation of Brain Tumours without Contrast

3D MRSI

Choline/NAA



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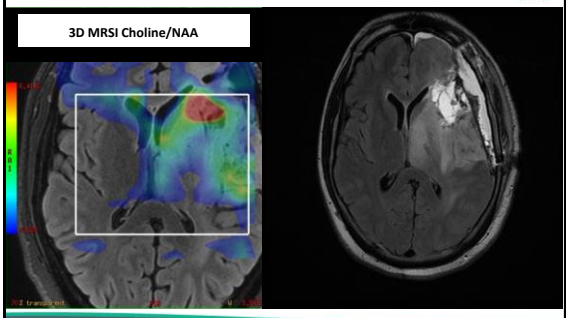
MRS - Applications

Characterisation of Brain Tumours without Contrast

3D MRSI Choline/NAA



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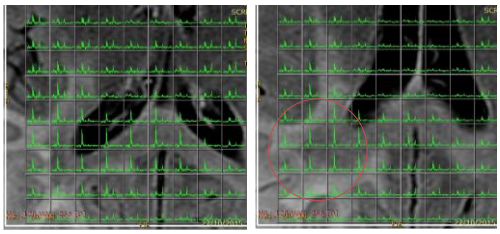
Extraordinary place.

MRS - Applications

Characterisation of Extensive $T_2$ Abnormalities



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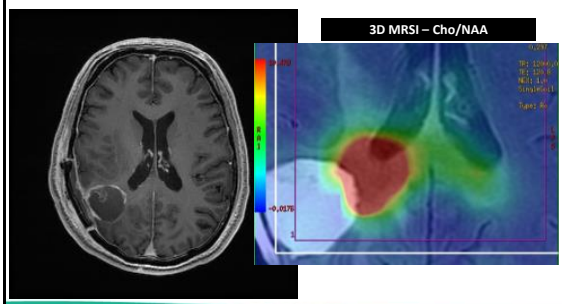
Glioblastoma (WHO IV)

3D MRSI – Cho/NAA



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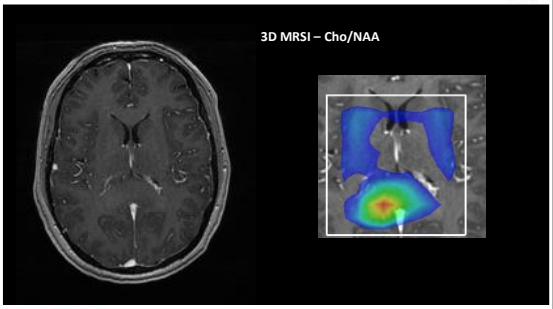
3D MRSI – Cho/NAA



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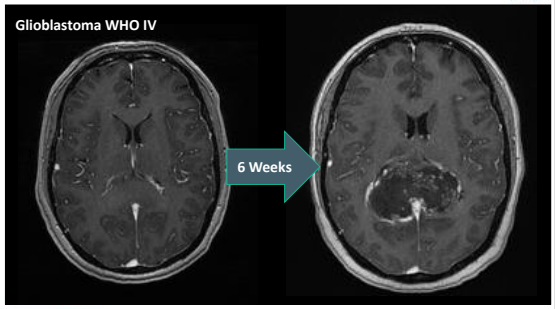
Glioblastoma WHO IV

6 Weeks



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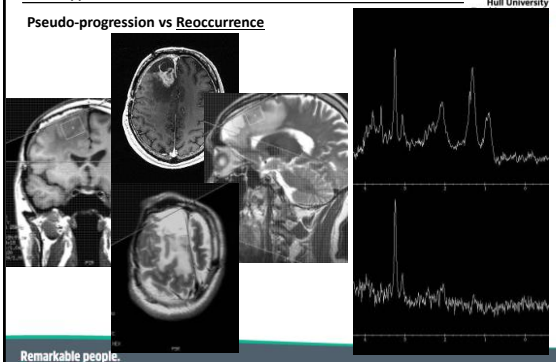
Pseudo-progression vs Reoccurrence



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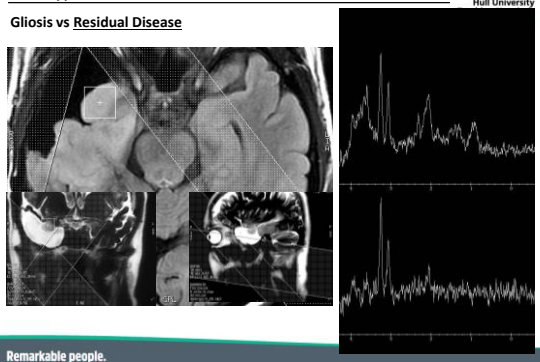
Gliosis vs Residual Disease



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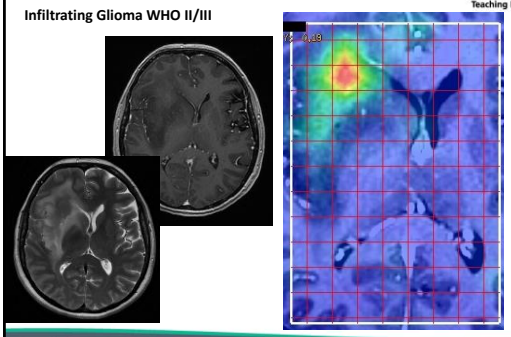
Infiltrating Glioma WHO II/III



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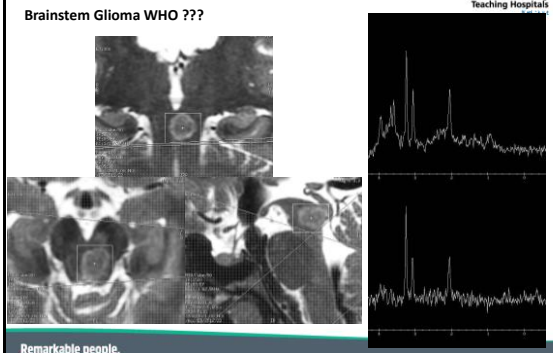
Brainstem Glioma WHO ???



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Metastasis vs Meningioma



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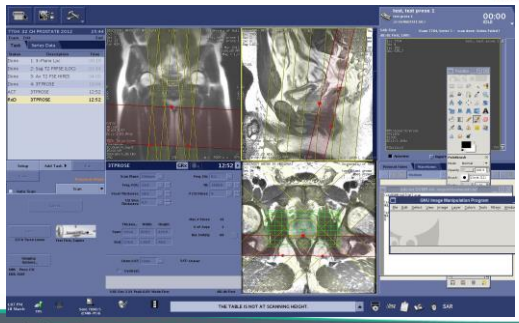
MRS - Applications

Prostate Spectroscopy



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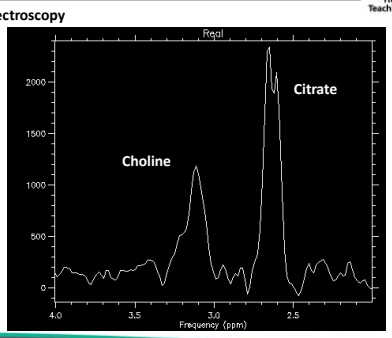
MRS - Applications

Prostate Spectroscopy

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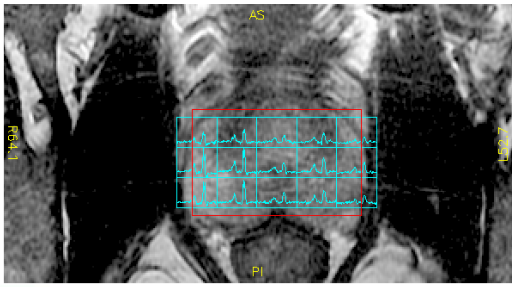
Prostate Spectroscopy

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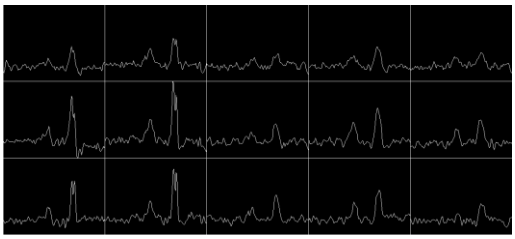
Prostate Spectroscopy



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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.

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Other Nuclei – Relative Sensitivities

| Nucleus | Spin | γ Rad/T/s (x$10^8$) | 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% |

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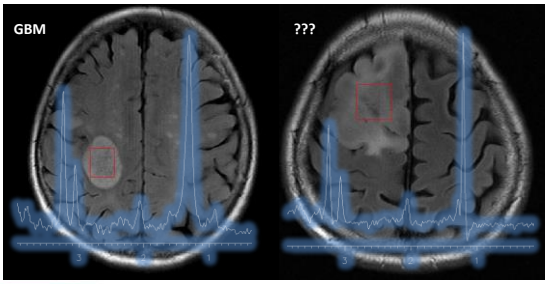
Mystery Case

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**MRS - Applications**

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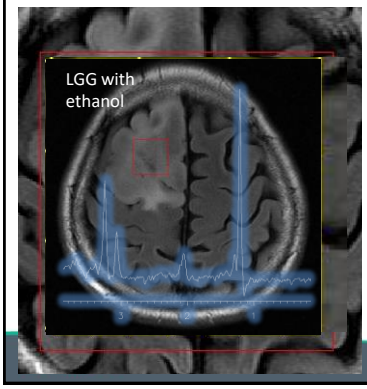


**Key Points**

- 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

**MRS - Applications**

Hull University Teaching Hospitals NHS Trust

- MR Spectroscopy can provide metabolic information non-invasively in additional to conventional imaging sequences
- The 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
  - Examine planning images for partial volume effects.

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**Question**
Pulse sequences in MR

A. Chemical shift imaging utilises the subtle Larmor frequency differences for hydrogen contained in molecules to distinguish those molecules

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