Centre for the Clinical Application of Particles

# Nuclear diagnostics and Magnetic Resonance Imaging

## Lecture 11: Magnetic Resonance Imaging: contrast

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# Outline

1. **Generating contrast in MRI**
   - Introduction
   - Worked example 1: spin-echo sequence for proton-density weighted image
   - Worked example 2: spin-echo sequence for $T_1$-weighted image
   - Worked example 3: spin-echo sequence for $T_2$-weighted image
   - Comparison of $T_1$, $T_2$, and proton-weighted images
   - Inversion recovery
   - Questions

2. **Lecture summary**

Section 1

# Generating contrast in MRI

# Generation of an MRI image

Tissue specificity in MRI is generated principally by three physical quantities:

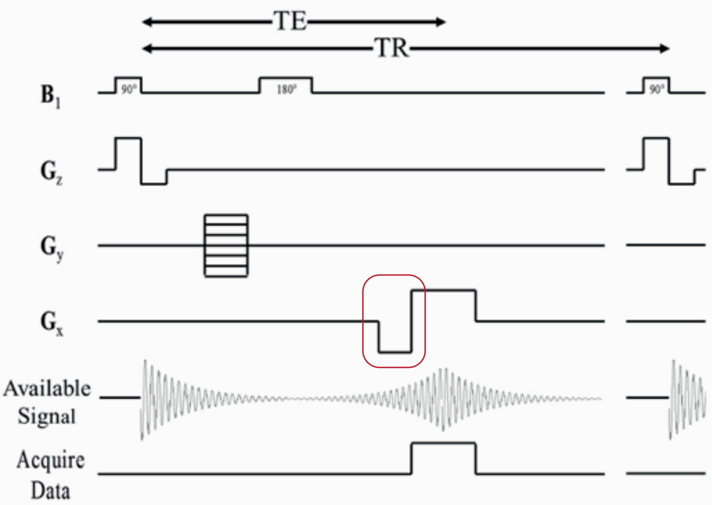
- The net magnetisation at equilibrium, $M_{\mathrm{eqm}}$:
  - This is a measure of "proton density";
  - Often referred to as proton density and $M_{\mathrm{eqm}}$ expressed as the fraction its value for water
- $T_1$: the spin-lattice relaxation time constant; and
- $T_2$: the spin-spin relaxation time constant

In a spin-echo sequence the time to repetition, TR, and the time to echo, TE, are adjusted to enhance the sensitivity of the signal amplitude to these three basic characteristics

The instantaneous signal intensity is proportional to the instantaneous magnitude of the magnetisation transverse to $\mathbf{B}_0$

This statement is **important** to get to grips with the generation of contrast in MRI

# Pulse sequence; reminder



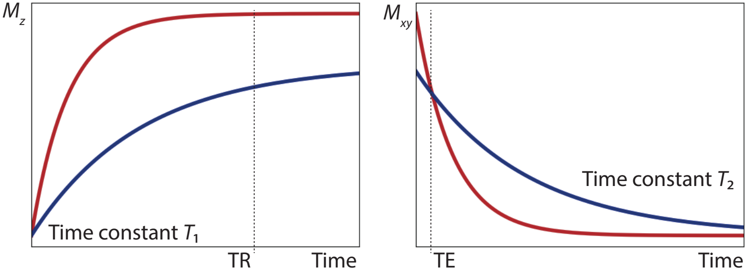

Note presence of "pre-winding pulse" circled in red

- Phase-encoding pulse causes phase to be position dependent
- Incoherence induces causes a loss of signal, so
- "Negative" gradient pulse applied in frequency encoding direction to "pre-wind" spins and cause an echo re-enforcing the signal at readout

# Values of the basic parameters for a variety of tissues

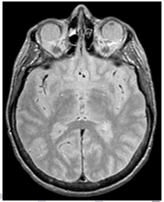
| Tissue | Proton density | 1.5 T | | 3 T | |
|---|---|---|---|---|---|
| | | $T_1$ ms | $T_2$ ms | $T_1$ ms | $T_2$ ms |
| Cartilage | 0.94 | 1024 | 42 | 1168 | 37 |
| Skeletal muscle | 0.95 | 1084 | 37 | 1416 | 41 |
| Blood | 0.97 | 1441 | 308 | 1932 | 275 |
| Fat | 0.94 | 343 | 160 | 380 | 130 |
| CSF | 1.00 | 4550 | 60 | 4550 | 30 |
| Brain matter (white) | 0.99 | 688 | 81 | 833 | 68 |
| Brain matter (grey) | 1.00 | 1195 | 97 | 1436 | 93 |

# Proton-density weighted image




$B_0 = 3\,\mathrm{T}$; set $\mathrm{TR} = 2500\,\mathrm{ms}$ and $\mathrm{TE} = 10\,\mathrm{ms}$

| | $T_1$ (ms) | $\frac{\mathrm{TR}}{T_1}$ | $T_2$ (ms) | $\frac{\mathrm{TE}}{T_2}$ | Relative brightness |
|---|---|---|---|---|---|
| Blood | 1932 | 1.29 | 275 | 0.04 | Medium |
| CSF | 4550 | 0.55 | 30 | 0.33 | Low |
| White matter | 833 | 3.00 | 68 | 0.15 | High |
| Grey matter | 1436 | 1.74 | 83 | 0.12 | Medium |



# Proton-density weighted image

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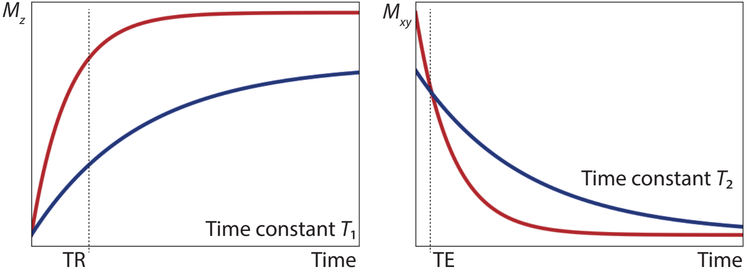
Proton-density weighted image:

- TR long: long enough that $M_{\mathrm{eqm}}$ is restored between repetitions
- TE short: such that effects of different $T2$ are not allowed to evolve

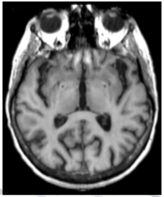
Such images have strong signal from all tissues, but relatively low contrast between them

# $T_1$ weighted image




$B_0 = 3\,\mathrm{T}$; set $\mathrm{TR} = 500\,\mathrm{ms}$ and $\mathrm{TE} = 10\,\mathrm{ms}$

| | $T_1$ (ms) | $\frac{\mathrm{TR}}{T_1}$ | $T_2$ (ms) | $\frac{\mathrm{TE}}{T_2}$ | Relative brightness |
|---|---|---|---|---|---|
| Blood | 1932 | 0.25 | 275 | 0.04 | Low/Medium |
| CSF | 4550 | 0.11 | 30 | 0.33 | Low |
| White matter | 833 | 0.60 | 68 | 0.15 | High |
| Grey matter | 1436 | 0.35 | 83 | 0.12 | Medium/Low |



# $T_1$ weighted image

| Tissue | Proton density | 1.5 T | | 3 T | |
|---|---|---|---|---|---|
| | | $T_1$ ms | $T_2$ ms | $T_1$ ms | $T_2$ ms |
| Cartilage | 0.94 | 1024 | 42 | 1168 | 37 |
| Skeletal muscle | 0.95 | 1084 | 37 | 1416 | 41 |
| Blood | 0.97 | 1441 | 308 | 1932 | 275 |
| **Fat** | 0.94 | 343 | 160 | 380 | 130 |
| CSF | 1.00 | 4550 | 60 | 4550 | 30 |
| **Brain matter (white)** | 0.99 | 688 | 81 | 833 | 68 |
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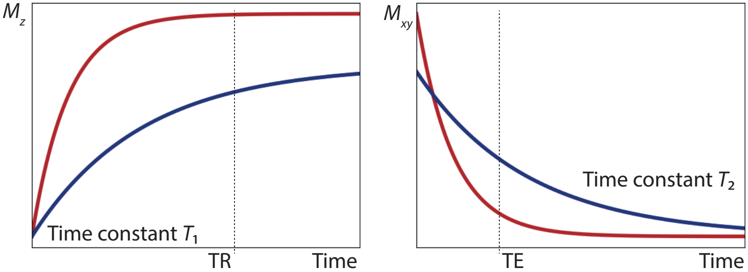
$T_1$ weighted image enhancing signal from e.g. fat, white mater:

- TR short: such that $M_{\rm eqm}$ can only recover fully between repetitions in tissues with low $T_1$
- TE short: enough that the effects of different $T2$ are not allowed to evolve

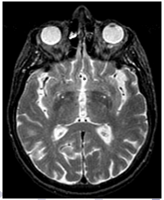
Tissues such as fat appear bright in such images

# $T_2$-weighted image




$B_0 = 3\,\mathrm{T}$; set $\mathrm{TR} = 2500\,\mathrm{ms}$ and $\mathrm{TE} = 100\,\mathrm{ms}$

| | $T_1$ (ms) | $\frac{\mathrm{TR}}{T_1}$ | $T_2$ (ms) | $\frac{\mathrm{TE}}{T_2}$ | Relative brightness |
|---|---|---|---|---|---|
| Blood | 1932 | 1.29 | 275 | 0.4 | Medium |
| CSF | 4550 | 0.55 | 30 | 3.3 | High |
| White matter | 833 | 3.00 | 68 | 1.5 | Low |
| Grey matter | 1436 | 1.74 | 83 | 1.2 | Medium/Low |



# $T_2$-weighted image

| Tissue | Proton density | 1.5 T | | 3 T | |
|---|---|---|---|---|---|
| | | $T_1$ ms | $T_2$ ms | $T_1$ ms | $T_2$ ms |
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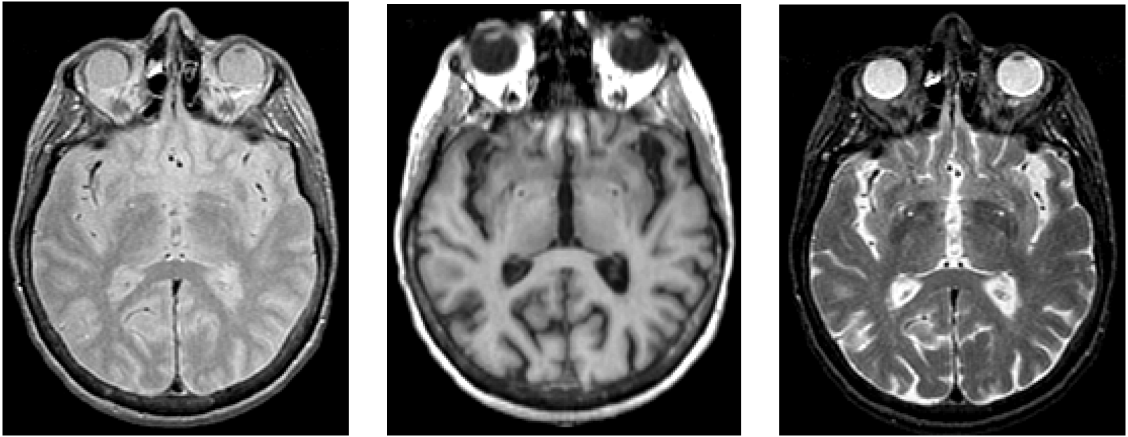
$T_2$ weighted image enhancing signal from e.g. blood and CSF:

- TR long: long enough that $M_{\rm eqm}$ is restored between repetitions
- TE long: enough that the decay rates determined by $T2$ **are** allowed to evolve

"Tissues" such as blood & CSF appear bright in such images

# Comparison of $T_1$, $T_2$, and proton-density weighting

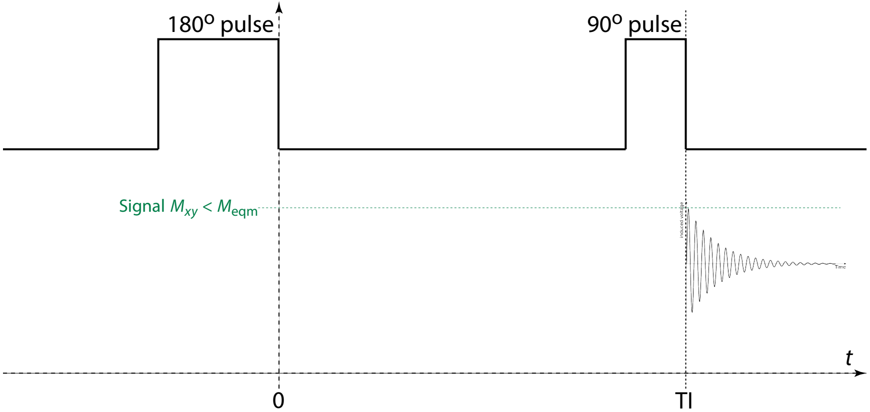


Proton-density weighted

$T_1$ weighted

$T_2$ weighted

# Inversion recovery pulse sequence; reminder

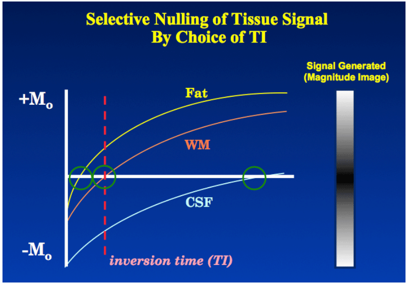


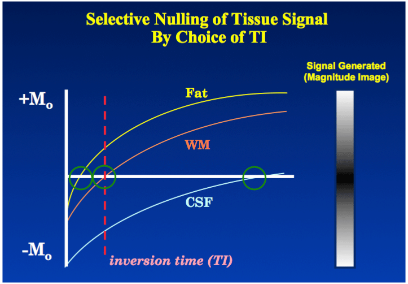

$$M_z(\mathrm{TI}) = M_{\mathrm{eqm}} \left[ 1 - 2\exp\left( -\frac{\mathrm{TI}}{T_1} \right) \right]$$

# Advantages of inversion recovery

Inversion recovery provides contrast in three ways:

1. Suppress ("null") the signal from particular tissues
2. Enhanced $T_1$ contrast
3. Additive (rather than competitive) $T_1$ and $T_2$ effects



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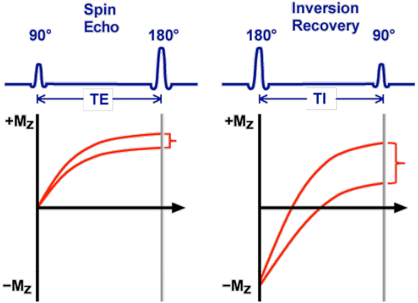


$$M_z(\mathrm{TI}) = M_{\mathrm{eqm}}\left[1 - 2\exp\left(-\frac{\mathrm{TI}}{T_1}\right)\right]$$

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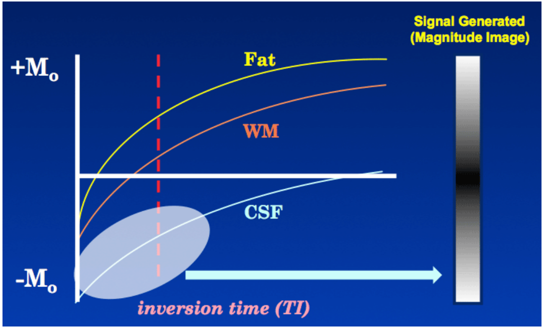
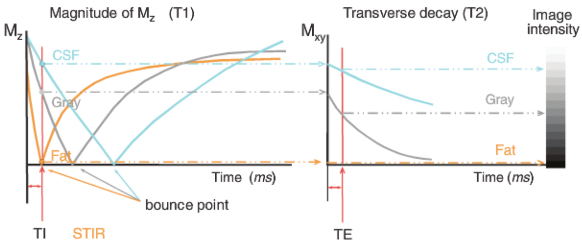


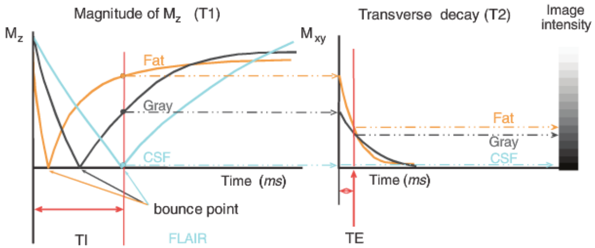

When TI is less than the "null point", the net magnetisation is the magnetisation of the tissues with long $T_1$ will remain inverted and enhance the transverse magnetisation the decay of which is characterised by $T_2$

# Inversion recovery

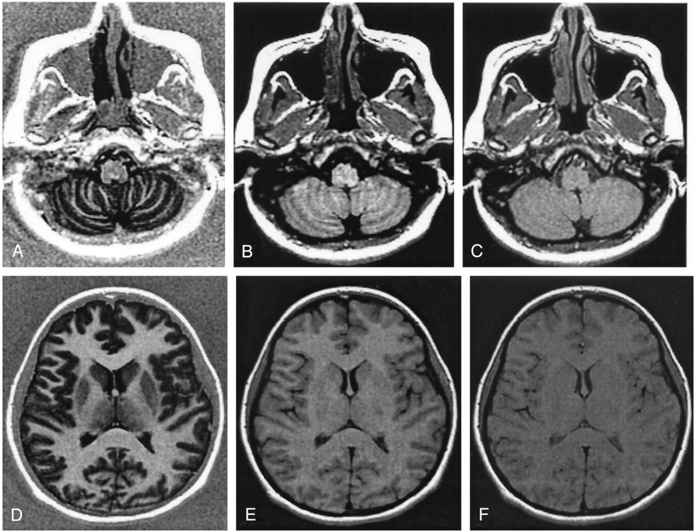



Short TI inversion recovery

Fluid attenuated inversion recovery



# Inversion recovery image of brain



# Question 1

What is the optimal TR to get maximum $T_1$ contrast between two tissues $A$ and $B$ for which the $T_2$ values are very similar and for which the $T_1$ values are $T_{1A} = 700\,\text{ms}$ and $T_{1B} = 900\,\text{ms}$?

# Answer 1

We know:

$$M_z(\mathrm{TR}) = M_{\mathrm{eqm}}\left[1 - \exp\left(-\frac{\mathrm{TR}}{T_1}\right)\right]$$

and

$$M_{xy}(\mathrm{TE}) = M_{\mathrm{eqm}}\exp\left(-\frac{\mathrm{TE}}{T_2}\right)$$

So, the signal $S$ may therefore be written:

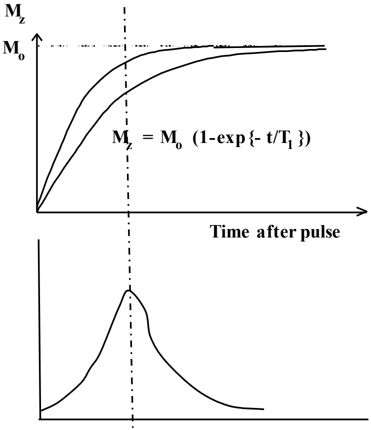
$$S\left(\mathrm{TR}, \mathrm{TE}\right) = S_0\left[1 - \exp\left(-\frac{\mathrm{TR}}{T_1}\right)\right]\exp\left(-\frac{\mathrm{TE}}{T_2}\right)$$

Can now write down the difference between the signals from tissues $A$ and $B$:

$$\Delta S = S_A - S_B$$

The maximum contrast will be when $\Delta S$ is maximised.

# Answer 1, continued




So, evaluate:

$$\frac{\partial \Delta S}{\partial \mathrm{TR}} = 0$$

And solve for $\mathrm{TR}_{\mathrm{max}}$ to show that:

$$\mathrm{TR}_{\mathrm{max}} = \ln\left(\frac{T_{1B}}{T_{1A}}\right)\frac{T_{1A}T_{1B}}{T_{1B}-T_{1A}} = 791.6\,\mathrm{ms}$$

# Question 2

What inversion time, TI, should be used to “null” the response of a tissue for which $T_1 = 700\,\mathrm{ms}$?

# Answer 2

We know:

$$M_z(\mathrm{TI}) = M_{\mathrm{eqm}} \left[1 - 2\exp\left(-\frac{\mathrm{TI}}{T_1}\right)\right]$$

So, $M_{xy}$ crosses zero when TI is equal to $\mathrm{TI}_0$ given by:

$$\left[1 - 2\exp\left(-\frac{\mathrm{TI}_0}{T_1}\right)\right] = 0$$

This occurs when:

$$\mathrm{TI}_0 = T_1 \ln 2 = 0.69 \times 700 = 483\,\mathrm{ms}$$

Section 2

# Lecture summary

# Summary

The contrast of an MRI image is flexible, to find optimal settings require:

- Knowledge of tissue properties to determine sequence timings
- The impact of disease on relaxation time constants;

$T_1$ contrast is introduced through TR setting

$T_2$ contrast is introduced through TE setting

Inversion recovery sequence has advantages, for example in allowing selective de-excitation of tissue, at the cost of longer patient time in scanner