March 2002

# Spinning Protons Presents: The Basics of MRI: T1 vs. T2

Frank Minja, Harvard Medical School Year III
Gillian Lieberman, MD

# From Voxels to Spinning Protons

- A Voxel is a small volume element = approx 3 $mm^3$
- A Voxel

- A proton is a single positive charge in the nucleus of an atom
- A cloud of positive charge

- Protons are constantly spinning about their axes
- A spinning charge results in a magnetic moment
- Thus, spinning protons can be thought of as tiny magnetic moments
- A tiny magnetic moment

# Spinning Protons a.k.a Tiny Magnetic Moments

- Each magnetic moment is a *vector* with a finite size and direction
- The net magnetic moment is the *vectorial* sum of these tiny magnetic moments
- At random these magnetic moments cancel each other out leaving a net magnetic moment of zero
- Note the protons continue to spin!

- Spinning Protons a.k.a Tiny Magnetic Moments

Frank Minja, HMS III
Gillian Lieberman, MD

# Enter the External Magnetic Field: Alignment of Spinning Protons

- The external magnetic field causes the spinning protons (tiny magnetic moments) to align themselves: parallel or anti-parallel to the external magnetic field
- Parallel alignment is the low energy state
- Parallel alignment
- Anti-parallel alignment is a high energy state
- Antiparallel alignment
- More spinning protons prefer the low energy state
- Thus, the net magnetic moment of all spinning protons is parallel to the external magnetic field
- Net Magnetic Moment
- External Magnetic Field in the z-axis

# The Other Spin - Precession

- The external magnetic field exerts a *torque* on the tiny magnetic moments causing them to *precess* around the vertical axis.
- Thus the tiny magnetic moments, parallel or anti-parallel, are not fixed in space, but are in constant *precession* around the vertical axis of the external magnetic field.
- The rate of precession (Larmor frequency) is proportional to the strength of the external magnetic field.
- Precession around the vertical axis

# A Pulse of Radiofrequency

- Once the tiny magnetic moments are in equilibrium with the external magnetic field, they will continue to be aligned and precess about the vertical axis.
- A pulse of radiofrequency (RF) will disrupt the equilibrium causing the tiny magnetic moments to fall out of alignment with the external magnetic field.
- Following the RF pulse, the tiny magnetic moments will tend towards their original state of alignment and precession around the vertical axis
- As the magnetic moments re-align themselves, they release energy in the form of radiowaves.
- These radiowaves are the MRI signals!
- A Pulse of Radiofrequency (RF)

# T1 relaxation

- The parallel and anti-parallel magnetic moments will fall onto the transverse plane when pulsed by a 90 degree RF
- The net magnetic moment aligned with the External Magnetic Field
- Enter a 90 degree RF pulse

- The transverse plane is a high energy state
- The Magnetic moments will ‘relax’ back to the vertical plane - low energy state
- T1 Relaxation back to the vertical plane
- The energy (radiowaves) emitted during this relaxation gives the T1 signal
- T1 relaxation curve
- The net magnetic moment re-aligned with the External Field

Frank Minja, HMS III
Gillian Lieberman, MD

# T2 decay

- When the parallel and anti-parallel magnetic moments fall onto the transverse plane they continue to precess around the vertical axis
- Precession about the vertical axis
- At time zero, all magnetic moments are in phase -Maximum T2 signal
- The local environment (local magnetic fields) will cause some magnetic moments to precess faster and some to precess slower. The magnetic moments fall out-of-phase (de-phasing)
- Faster forward precession
- Slower forward precession (reverse precession)
- *Since the net magnetic moment depends on direction, as more magnetic moments fall out of phase - the more they cancel each other out - the T2 signal decays.* This rate of cancellation = T2 decay
- Complete de-phasing of magnetic moments
- T2 decay curve
- T1 RELAXATION AND T2 DECAY TOGETHER (repeat again!)

# Spinning Protons Are Not Equal

- The have the same mass and charge $^{1}_{0}H$
- Each spinning proton aka tiny magnetic moment is influenced by its local magnetic environment
- This local environment is the tissue!
- Different tissues have different local electro-magnetic environments
- Different local environments cause the protons to respond differently to pulses of RF
- Different reponses to RF pulses = contrast in MRI
- *(Mass density is the basis for contrast in CT)*

# Weighting Inequalities - RF Pulse sequences

- To enhance the contrast of MRI signals we can accentuate how the aligned spinning protons experience T1 relaxation and/or T2 decay.
- T1 Weighting - accentuating T1 relaxation
- T2 Weighting - accentuating T2 relaxation
- Proton-density weighting - accentuating the number of protons

# T1 Weighting

- Different tissues have different T1 and T2 time constants
- Table of T1 and T2 constants
- To obtain an MRI image the voxel of interest must be pulsed several times with RF.
- The time in between RF pulses is the repetition time (TR).
- If the repetition time is long enough, *all* spinning protons will re-align themselves with the vertical axis = no contrast
- If the repetition time is short, some spinning protons will re-align faster than others = Bingo! contrast!
- T1 relaxation
- 90 degree RF pulse followed by a T1 signal
- Thus, T1 weighting = short TR (repetition time)

Frank Minja, HMS III
Gillian Lieberman, MD

# T2 Weighting

- T2 is the rate of decay of precession as a result of magnetic moments falling out of phase.
- This rate of decay again depends on the local environment, thus the T2 signal depends also on the local environment (different tissues have different T2 constants)
- A special pulse of RF is used to measure the T2 signal. This pulse reverses the precessing magnetic moments by 180 degrees.
- Reversing the plane of precession
- The reversal results in an ‘echo’ signal
- 180 degree RF pulse followed by an ‘echo’ T2 signal
- The maximal echo signal is the T2 signal
- The time between echoes = TE
- The longer the time between echoes = the better the T2 contrast
- Thus, T2 weighting = Long TE (Echo Time)

# T1 weighting vs. T2 weighting

| | T1 Weighting | T2 Weighting |
|---|---|---|
| TR Repetition time | Short | Long |
| TE Echo time | Short | Long |

Frank Minja, HMS III
Gillian Lieberman, MD

# T1 Weighting

- Short TR + Short TE
- TR < 600ms
- TE < 20 ms

- Dark Eyeballs! (TR/TE = 450/14 ms)
- Dark Eyeballs! (TR/TE = 450/14 ms)

- Dark Lesion (TR/TE = 450/14 ms)
- Dark Lesion (TR/TE = 450/14 ms)

Frank Minja, HMS III
Gillian Lieberman, MD

# T2 Weighting

- Long TR + Long TE
- TR = 2000 - 3500 ms
- TE = 70 - 150 ms

- Bright Eyeballs! (TR/TE = 5500/105 ms)
- Bright Eyeballs! (TR/TE = 5500/105 ms)

- Bright Lesion! (TR/TE = 5500/105 ms)
- Bright Lesion! (TR/TE = 5500/105 ms)

Frank Minja, HMS III
Gillian Lieberman, MD

# Proton (Spin) Density Weighting

- The signal depends on the number of spinning protons
- The greater the density of protons = the stronger the signal
- The smaller the density of protons = the weaker the signal
- A Long TR repetition time will blunt the T1 signal
- A Short TE echo time will blunt the T2 signal
- By default contrast must now depend on the proton density
- Differences in proton density = contrast!
- Proton (Spin) Density weighting = Long TR + Short TE
- TR = 1500 - 3500 ms
- TE = 20 -35 ms

# Flow

- Flow adds a fourth dimension: space in time
- In moving fluids e.g Blood the spinning protons are not stationary
- Thus the previous three signals: T1, T2 and proton density are constantly changing at a given point in space, at a given point in time
- Changing signals = contrast!
- This is the basis of MR angiography

Frank Minja, HMS III
Gillian Lieberman, MD

# MR Angiography

- MR Angiography, an example

# The Fifth Element

- MR contrast agents
- Gadolinium (Gd) is a paramagnetic metal ion that causes fluctuating magnetic fields around protons.
- Gd alters T1 and T2 values of tissues.
- Tissues that are vascular will have a brighter signal compared to non-vascular tissues.
- Difference in signal = MR contrast!!
- Gd is typically chelated to lessen its toxicity.
- MR contrast agents are very safe to use in patients with renal insufficiency or allergies to CT contrast

# MR w/ Gadolinium contrast

- Gadolinium oral contrast

# The Five Elements of Contrast in MRI

- T1 relaxation
- T2 decay
- Proton density
- Flow
- MR Contrast agents

# The Lesser Traits of MRI

- Cost
- Claustrophobia
- Motion artifacts
- Long Image Acquisition Times

# The Future of MRI

- Technology will gradually improve cost, claustrophobia, motion artifacts and image acquisition times.
- Different RF pulse sequences will further enhance the weighting capabilities for T1,T2 and proton density.
- Computing power will enhance the detection and resolution of MRI signals = even better images.
- Functional MRI (tumor vs. normal tissue).

Frank Minja, HMS III
Gillian Lieberman, MD

# Timeline of MRI

- Fifty years of MR
- 1946 - Discovery of the MR phenomenon
- 1996 - Hyperpolarized $^{129}Xe$ imaging
- 2046??

# References


- **Bushberg JT, Siebert JA, Leidholdt EM, Boone JM.** Chapter 11, The Essential Physiscs of Medical Imaging**, 1994.**
- **Hornak JP** http://www.cis.rit.edu/htbooks/mri
- **Margaret M. King, RT** http://www.erads.com/mrimod.htm
- Oral MR Contrast Image : http://www.utdallas.edu/~balkus/pcyc2.gif

# Acknowledgements

Many Thanks to

Gillian Lieberman, MD

Ivan Pedrosa, MD

Eric Niendorf, MD

Michelle Swire, MD

Dan Cornfeld, MD

Pamela Lepkowski

Mike Larson - Media Lab

Our Webmasters: Larry Barbaras and Cara Lyn D’amour