광주과학기술원

4. Magnetic Resonance Imaging(4)

Lectures 23, 24

Medical Imaging Systems

Jae Gwan Kim, Ph.D.

jaekim@gist.ac.kr , X 2220

Department of **B**io**M**edical **S**cience and **E**ngineering

Gwangju **I**nstitute of **S**ciences and **T**echnology

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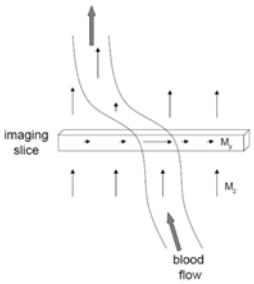
Magnetic resonance angiography

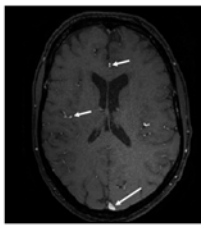
- Unlike X-ray angiography, it is not necessary to use a contrast agent for MRA
- The most common technique of MRA is called time-of-flight (TOF) angiography
- TOF is based on the much shorter T1 of blood due to its flow into and through the imaging slice if the slice is perpendicular to the blood flow
  - T_1 value of water in blood is similar to that in other tissues
  - However, during the TR, a new pool of blood flows into the imaging volume which was not magnetized before
  - Therefore, the protons in a new blood will be fully magnetized (T1 becomes shorter→ $T1_{,eff}$)

Magnetic resonance angiography

- For a given slice thickness (S_{th}) and blood velocity (v), the value of $T1_{,eff}$ of the blood is
  $\frac{1}{T1_{,eff}} = \frac{1}{T1} + \frac{v}{S_{th}}$, $T1_{,eff} = \frac{T1 \cdot S_{th}}{S_{th} + vT1}$, $v \uparrow \rightarrow T1_{,eff} \downarrow$
- For example, if S_{th}=5mm, TR=50ms, blood flow speed > 10cm/s, then the blood will pass the slice before the next phase encoding step → $T1_{,eff}$ is zero

Protons in tissue will have small M_z when TR<<3T1. This small M_z will have small M_y when 90° pulse is applied during imaging sequences. Blood will have full M_z and it will cause large M_y during 90° pulse

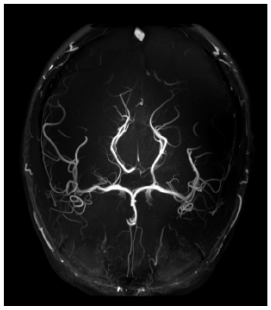


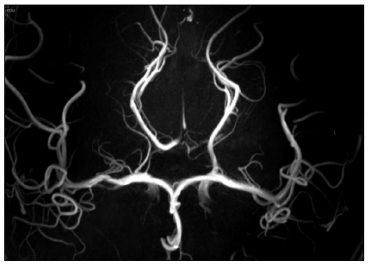


These bright spots are vessels with flow perpendicular to the image slice

Magnetic resonance angiography

- To differentiate between flowing blood and stationary tissue, a very heavily T1-weighted sequence is used with a high tip angle pulse(get max signals from blood), a short TR value (minimize the stationary tissue signals, fast data acquisition) → gradient echo sequence with a large tip angle greater than Ernst angle (multi slice or 3D angiography)





With the use of contrast agents, very small vessels can be also seen

MRI contrast agents

- In many clinical applications, MRI doesn't require the use of contrast agents since there is enough CNR (T_1, T_2 or proton weighted) to distinguish diseased from healthy tissue.
- However, detection of very small lesions may require the use of contrast agent since the partial volume effect can occur.
- In addition, agents can be used in TOF angiography
- Two types of contrast agents
  1. Paramagnetic (positive agent)
  2. Superparamagnetic (negative agent)

Magnetism Types

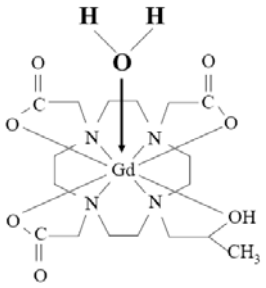
- Ferromagnetism: basic mechanism by which certain materials (such as iron) form permanent magnets, or are attracted to magnets (Fe, Ni, Co)
- Ferrimagnetism: the magnetic moments of the atoms on different sublattices are opposed
- Superparamagnetism: appears in small ferromagnetic or ferrimagnetic nanoparticles and their magnetic susceptibility is much larger than the one of paramagnets
- Paramagnetism: a form of magnetism whereby the paramagnetic material is only attracted when in the presence of an externally applied magnetic field (W, Cs, Al, Li, Mg, Na)
- Diamagnetism: the property of an object which causes it to create a magnetic field in opposition to an externally applied magnetic field, thus causing a repulsive effect (C, Hg, Bs, Pb, Ag, Cu, H_2O)
- Magnetic susceptibility: the degree of magnetization of a material in response to an applied magnetic field

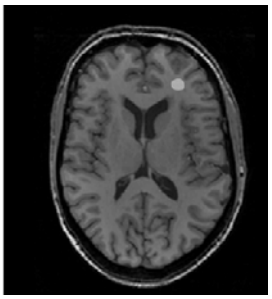
MRI Positive Contrast Agents

- Paramagnetic agents shorten the T_1 of the tissue when they accumulate (250ms, shorter than the T1 of all other tissues except fat)→ increase MR signal on T_1 weighted scans. → Positive agents
- Trade names examples: Omniscan, Prohance and Magnevist
- The differences among them are the ionicity and osmolarity

MRI Positive Contrast Agents

- All the positive agents are based on Gd ion and surrounding a particular chelate.
- Neither Gd ion nor chelate produces an MR signal directly, but via effect on water molecules in tissue which the agent accumulates





MRI Positive Contrast Agents

- Gd^{3+} ion has seven unpaired electrons, and the interaction between water protons and these electrons produces a very efficient T_1 relaxation.
- There are two mechanisms for this relaxation.
  - Inner sphere relaxation: agent is designed to have only one empty binding site. Water molecules temporarily bind to one empty binding site of Gd ion and undergo very rapid T_1 relaxation and then released to be succeeded by a second water molecule, and so on
  - Outer sphere relaxation: water molecules interact with the unpaired Gd electrons at a distance, i.e. by diffusing close to the molecule. This is not as efficient as inner sphere relaxation, but many more water molecules are affected.

MRI Positive Contrast Agents

- Gd based agents are mostly used in the diagnosis of CNS disorders (tumors, lesions, gliomas, meningiomas)
- They pass through a leaky BBB and accumulate in tumors
- Typical Gd agents' dose is ~0.1mmol/kg (10ml at 0.5M)

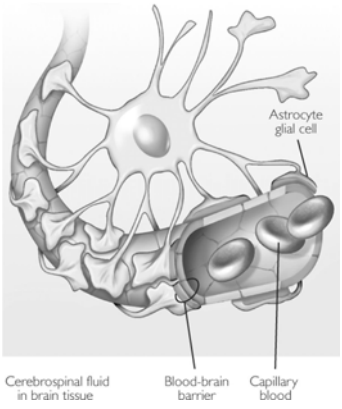
$$\frac{1}{T_1^{CA}} = \frac{1}{T_1} + \alpha_1 C,$$

Where T_1^{CA} is T_1 of tissue after contrast agent administered, T_1 is pre-administration value, and α_1 is the T_1-relaxivity of the contrast agent

- A new agent, Gadovist (2008), is used in magnetic resonance angiography to study peripheral vascular disease, to detect arterial stenosis and plaque formation within arteries
- Until 2005, Gd agents were considered to be safe, but in 2005, Gd based agents are found to increase the risk of nephrogenic systemic fibrosis (NSF)

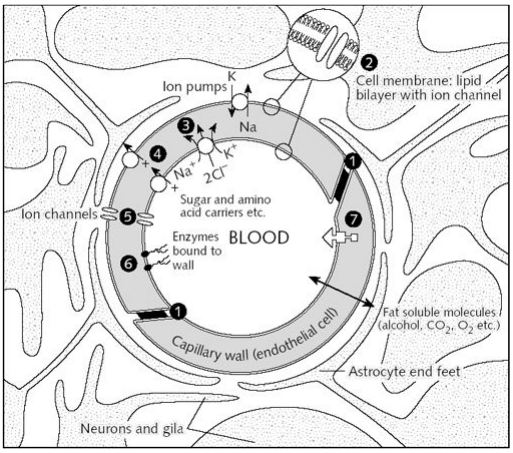
Blood Brain Barrier

- The **blood–brain barrier** (**BBB**) is a separation of circulating blood and the brain extracellular fluid (BECF) in the central nervous system (CNS).
- It occurs along all capillaries and consists of tight junctions around the capillaries that do not exist in normal circulation.
- Endothelial cells restrict the diffusion of microscopic objects (e.g. bacteria) and large or hydrophilic molecules into the cerebrospinal fluid (CSF), while allowing the diffusion of small hydrophobic molecules (O_2, CO_2, hormones).
- Cells of the barrier actively transport metabolic products such as glucose across the barrier with specific proteins.
- This barrier also includes a thick basement membrane and astrocytic endfeet.



Blood Brain Barrier

- *Diagram of a cerebral capillary enclosed in astrocyte end-feet. Characteristics of the blood-brain barrier are indicated: (1) tight junctions that seal the pathway between the capillary (endothelial) cells; (2) the lipid nature of the cell membranes of the capillary wall which makes it a barrier to water-soluble molecules; (3), (4), and (5) represent some of the carriers and ion channels; (6) the 'enzymatic barrier' that removes molecules from the blood; (7) the efflux pumps which extrude fat-soluble molecules that have crossed into the cells*



Read more: http://www.answers.com/topic/blood-brain-barrier#ixzz1cbCfdjcq

MRI Negative Contrast Agents

- Negative contrast agents reduce the MR signal in the tissues where they accumulate→ shortening T2*
- They are used for liver lesions or focal nodular hyperplasia
  - USPIO: ultra-small superparamagnetic iron oxides, less than 30nm diameter
  - SPIO: superparamagnetic iron oxides, 30~100nm diameter
- Feridex/Endorem (~100nm) is approved for worldwide
  - 0.56mg of Fe/kg of body, diluted in 100ml of 5% dextrose solution, given i.v. over 30min
- Resovist (62nm) is approved in EU, Australia and Japan

MRI Negative Contrast Agents

- Negative contrast agents cause very strong inhomogeneities in the local magnetic field → water molecules diffusing through these localized inhomogeneities undergo very fast T_2 and T_2* relaxation → reduction in signal intensity from T_2* weighted gradient echo or T_2 weighted spin echo sequences
- These small particles are taken up primarily by Kuppfer cells (specialized macrophages in the liver) in the liver and also accumulate in the lymph nodes, spleen, and bone marrow
- These particles only enter the healthy Kuppfer cells in the liver and do not accumulate in tumors or other pathological structures.

MRI Negative Contrast Agents

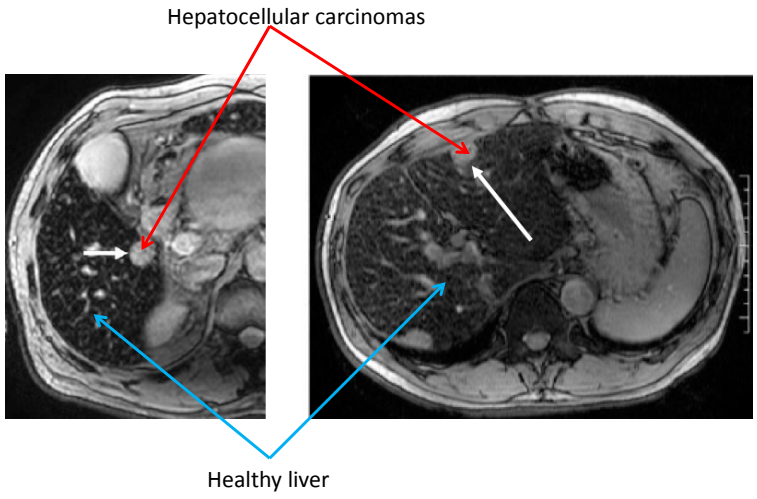


Image characteristics

- Signal to noise
  - B_0 field strength

    $M_0 = \frac{\gamma^2 h^2 B_0 N_{total}}{2\pi^2 kT}$, $\omega = \gamma B_o$, $V_y \propto M_0 \omega_0 sin\omega_o t$

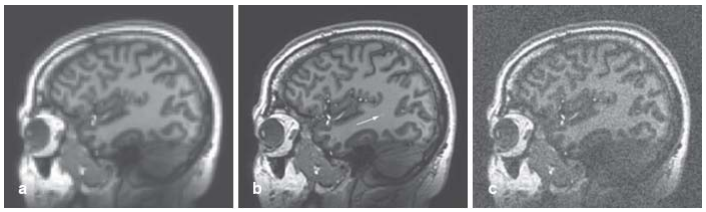
  - Imaging parameters
    1. Too short TR, too high tip angle, too long TE reduces the signal intensity from its optimal value
    2. N times increase of spatial resolution → 2^N times decrease of SNR
    3. SNR ∝ slice thickness
    4. SNR increases by square-root of the number of images

Image characteristics

- Spatial resolution is defined by
  - The slice thickness
  - The field of view in the phase encoded dimension divided by the number of phase encoding steps
  - The field of view in the frequency encoded dimension divided by the number of acquired data points in that dimension

Image characteristics

- Contrast to noise is based on the differences in proton density, T1, T2 relaxation times
- Contrast can be, therefore, modulated by choosing TR and TE times



Safety considerations

- RF electrical field is associated with RF magnetic field which produces currents in conductive tissues
- A key safety consideration in MRI is the power deposition in tissue which is quantified via the local and average specific absorption rate (SAR) values (unit: W/kg)

$$SAR = \frac{\sigma}{2\rho}|E|^2$$

where ρ is the tissue density and σ the tissue conductivity

- Therefore, SAR is proportional to the square of (the amplitude of B_1 field X applied time of B_1 field)

Safety considerations

- SAR limits for MRI (IEC 60601-2033)

	Whole body SAR	Partial body SAR	Head SAR	Local SAR (a)		
Body Region →	whole body	exposed body part	head	head	trunk	extremities
Operating Mode ↓	(W/kg)	(W/kg)	(W/kg)	(W/kg)	(W/kg)	(W/kg)
Normal	2	2–10 (b)	3.2	10 (c)	10	2
1st Level Controlled	4	4–10 (b)	3.2	20 (c)	20	40
2nd Level Controlled	>4	>(4–10) (b)	>3.2	>20 (c)	>20	>40
Short duration SAR	The SAR limit over any 10 s period shall not exceed two times the stated values					

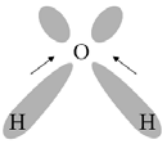
Note: Averaging time of 6 minutes.
(a) Local SAR is determined over the mass of 10 g.
(b) The limit scales dynamically with the ratio "exposed patient mass / patient mass":
NORMAL OPERATING MODE: Partial body SAR = 10 W/kg – (8 W/kg * exposed patient mass / patient mass)
FIRST LEVEL CONTROLLED OPERATING MODE: Partial body SAR = 10 W/kg – (6 W/kg * exposed patient mass / patient mass)
(c) In cases where the orbit is in the field of a small local RF transmit coil, care should be taken to ensure that the temperature rise is limited to 1 °C

Lipid suppression techniques

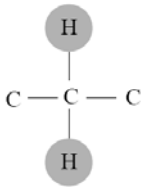
- There are only a few clinical applications that utilize the information of lipid spatial distribution
- Most of cases, therefore, it becomes a mask to prohibit pathological information
- Since lipid has very short T1 and long T2 → appears bright on most images → requires lipid suppression techniques
- Two examples are shown
  1) Chemical shift selective sequence: protons in lipid resonate at a different frequency than those from water→ apply 90° pulse that only tips the protons in lipid, then gradient is applied to dephase the magnetization → destroy the signal→ regular imaging sequence is applied

Signals from lipid

- The majority of protons in lipid are in the form of –CH_2- groups in long-chain fatty acids
- The electron density distribution (shaded area) surrounding protons in water and lipid are shown in figures below
- Proton in water is less shielded due to strong electronegativity of oxygen than carbon in lipid



water



Fatty acid

Signals from lipid

- An electron is a negatively charged particle, so produces a small magnetic field opposite in polarity to the B_0

$$B_{eff}=B_0(1-\sigma)$$

where σ is a shielding constant

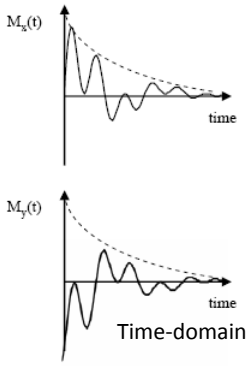
- Therefore, the resonant frequency of the proton is

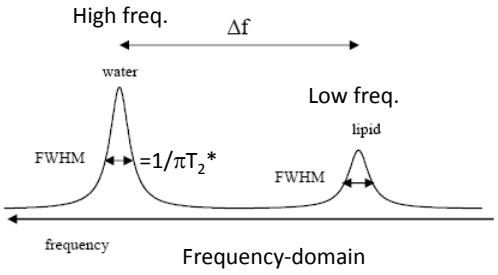
$$\omega = \gamma B_{eff} = \gamma B_0 (1-\sigma)$$

- σ for water is less than that for lipid, therefore, water has a higher resonant frequency (at 3T the difference is about 2500 rad/s or 400Hz

The free induction decay

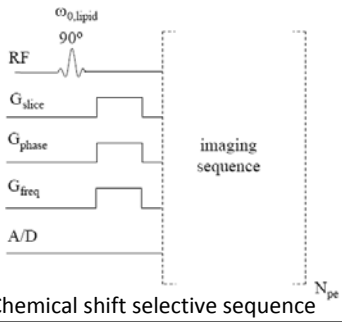
- The signal precesses freely after the RF pulse has been turned off
- This M_x and M_y shows beat patterns which come from the two different resonant frequencies of lipid and water



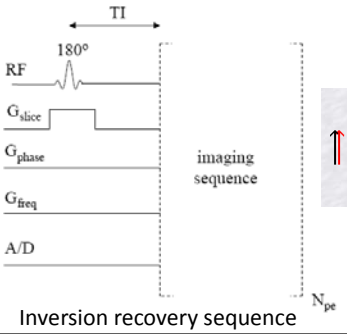


Lipid suppression techniques

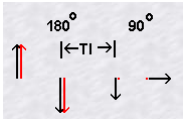
2) Inversion recovery sequence: this is based on the fact that T_1 of lipid protons are much shorter than those in other tissues → apply 180° 'inversion pulse' to have –Mz magnetization of all protons in slice→ then turn off→ protons start to relax back to equilibrium→ after the inversion time 'TI' (protons in lipid have Mz=0), imaging sequence starts



Chemical shift selective sequence

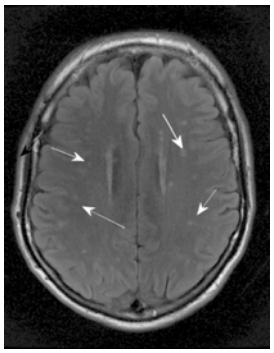


Inversion recovery sequence



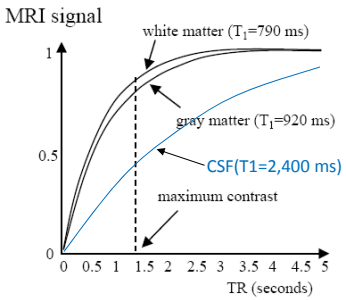
Clinical applications

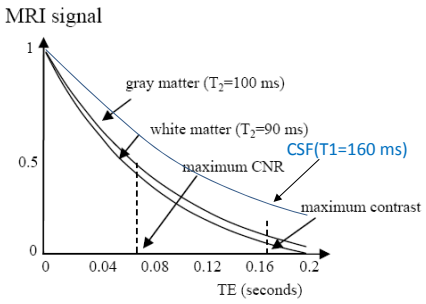
- Neurological applications
  - Acute: stroke, edema
  - Chronic: sclerosis, Alzheimer
  - Intracranial mass lesions
- Most of them require the use of positive contrast agent
- Increased water content (edema) shows high intensity in T_2 weighted sequence



White matter lesions which can be an early indication of multiple sclerosis

MRI signals

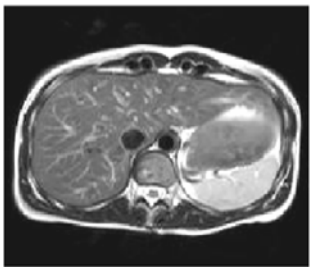




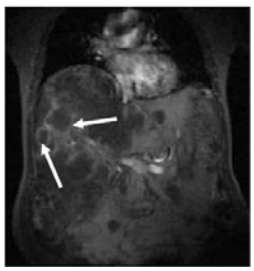
Clinical applications

- Body applications
  - Scans are normally acquired during a single breath-hold (10~20s)
  - Fatty livers, hepatic adenoma, cirrhosis, atrophy
  - Metastases from liver tumors

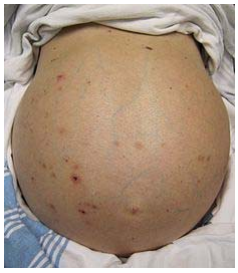
(a) (b)



Fatty liver

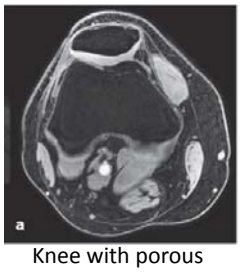


Hemangioma

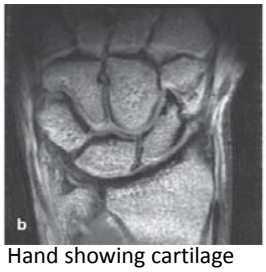


Clinical applications

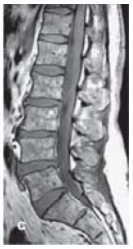
- Musculoskeletal applications
  - Evaluation of cartilage integrity in the knee (rheumatoid- and osteo-arthritis)
  - Hand/wrist
  - Spinal cord degeneration



Knee with porous trabecular bone structure



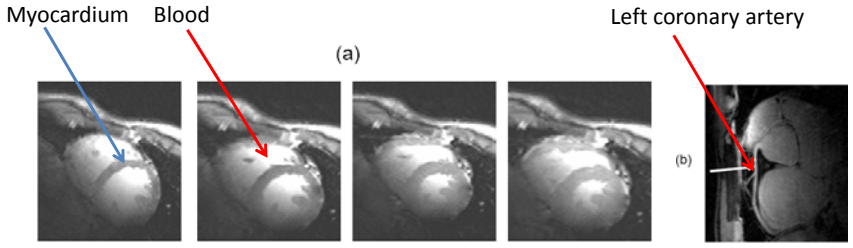
Hand showing cartilage and trabecular bone structure



Spinal cord and vertebral column

Clinical applications

- Cardiology applications
  Ischemic heart disease: T_2 weighted scanning is applied to visualize myocardial infarct since myocardial edema causes high intensity in T_2 images
- Left ventricular and ejection fraction can be measured



See other slides

FUNCTIONAL MRI