# Magnetic Resonance Imaging

## A. Basic Concepts

1. All nuclei have neutrons and protons.

    ● The protons are positively charged.

    ● Neutrons have a charge distribution but a net charge of zero.

    ● The net charge of the nucleus is positive.

    ● The protons and neutrons behave as if they spin on their axes.

    ● Spinning charges are like an electrical current flowing through a loop of wire.

    ● Ampère's law states that an electrical charge flowing through a wire loop creates a magnetic field.
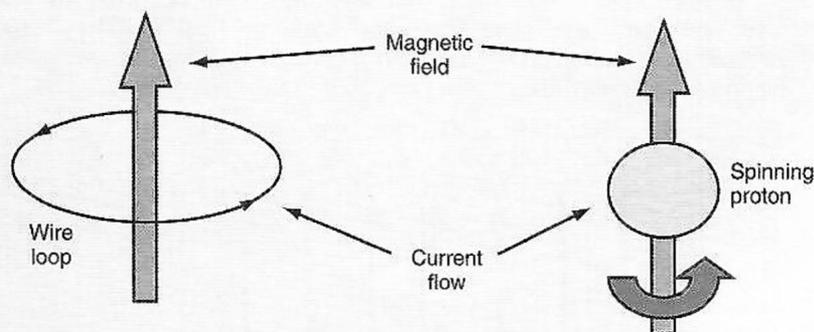
    ● If a proton in the nucleus pairs with another proton with spin in the opposite direction, the combined magnetic moment of a pair of protons is zero (see figure on next page). This pairing also occurs with neutrons.

    ● Single neutrons have a smaller magnetic moment than a proton, but paired neutrons have no net magnetic moment.

    ● Hence, nuclei with an even number of protons and neutrons have no magnetic moment. *Nuclei with an odd number of protons have the largest magnetic moment.*

    ● *Hydrogen is the most important nucleus for magnetic resonance imaging (MRI).* Hydrogen is found throughout the body in various molecules such as water and has an single (odd) proton that produces a strong magnetic moment.

No net magnetic moment

Pair of protons spinning
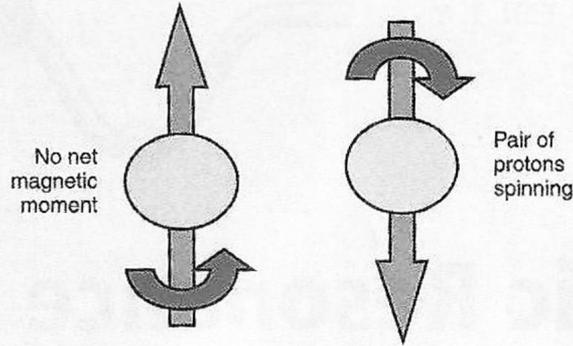
2. Without the presence of a magnetic field, the magnetic moments of the various nuclei randomly point in all directions. Hence, the **net** magnetic moment of the biologic sample is zero.

3. **If a strong magnetic field is present**, a population of nuclei align so that slightly more than 50% are along the magnetic field (low energy state) and slightly fewer than 50% are antiparallel (high energy state) to the magnetic field.

   - The nuclei aligned along the magnetic field are at a lower energy.

   - It requires some input of energy, such as a radiofrequency (RF) wave, to cause the nuclei to flip antiparallel to the applied magnetic field.

   - The percentage difference between the number of nuclei aligned along the magnetic field and the number opposed to the magnetic field is small (of the order of parts per million) and depends on the temperature of the sample.

   - The nuclei are not exactly parallel and opposed to the magnetic field. They are at a slight angle to the magnetic field.

   - If nuclei are slightly misaligned with an external applied magnetic field (B_0), nuclei precess or the nuclear magnetic moment moves in a circular pattern around the applied magnetic field lines.

   - Because the precession (rotation) about the magnetic field is random, there is no net magnetization perpendicular to the applied main magnetic field, B_0. However, there is a net magnetization along the field from the hydrogen nuclei in the tissue because slightly more nuclei are aligned with the applied magnetic field than are opposed to the field.

   - The rate of precession is the Larmor frequency.

Motion of nuclear magnetic moment

Applied magnetic field = B_0
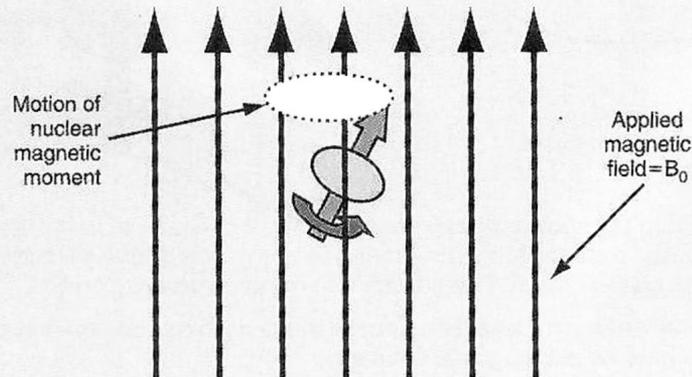
4. **Larmor's equation** yields the rate of precession or precessional frequency (ω) of the nuclear magnetic moment.

$$\omega = \gamma B_0$$

where γ = gyromagnetic ratio and B_0 = applied external magnetic field.

- The gyromagnetic ratio (γ) depends on the element and isotope involved, as shown in the table. It is different for nuclei that have different numbers of protons and neutrons.

ATOM	GYROMAGNETIC RATIO (MHz/tesla)
$_1H^1$	42.58
$_6C_{13}$	10.71
$_9F^{19}$	40.05
$_{11}Na^{23}$	11.26
$_{15}P^{31}$	17.34

5. To provide the energy needed to flip a nucleus from being aligned to the applied magnetic field to being opposed to it, an RF pulse is required whose frequency is the same as the Larmor frequency. RF pulses of other frequencies are not transferred to the nucleus, just as a radio cannot receive music from a given radio station unless the radio is tuned to the proper frequency.

6. The correct Larmor frequency depends on both the strength of the applied magnetic field and the number of neutrons and protons in the nucleus.

7. The strength of an applied magnetic field is measured in tesla (1 T = 10,000 gauss).

   - The Earth's magnetic field is about 0.5 to 1.0 gauss, and the field of a refrigerator magnet is a few hundred gauss.

   - The magnetic field strength of MRI units ranges from 0.3 T for some permanent or smaller units up to 3.0 T for newer clinical units.

   - The most common field strengths of MRI units are 0.5, 1.0, and 1.5 T.

8. All the nuclear magnetic moments in a sample together give rise to a net magnetization along the applied magnetic field. The duration and the amplitude of the RF pulse of the correct Larmor frequency determine how much the **net** nuclear magnetization is tipped relative to the applied magnetic field lines.

RF pulse @ Larmor freq.

Rotation of nuclear magnetic moment

90 degree RF pulse

180 degree RF pulse
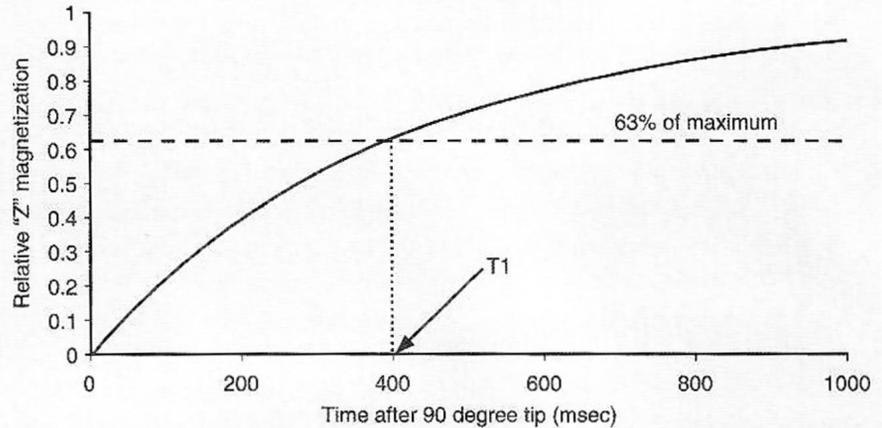
Applied magnetic field (B_0)
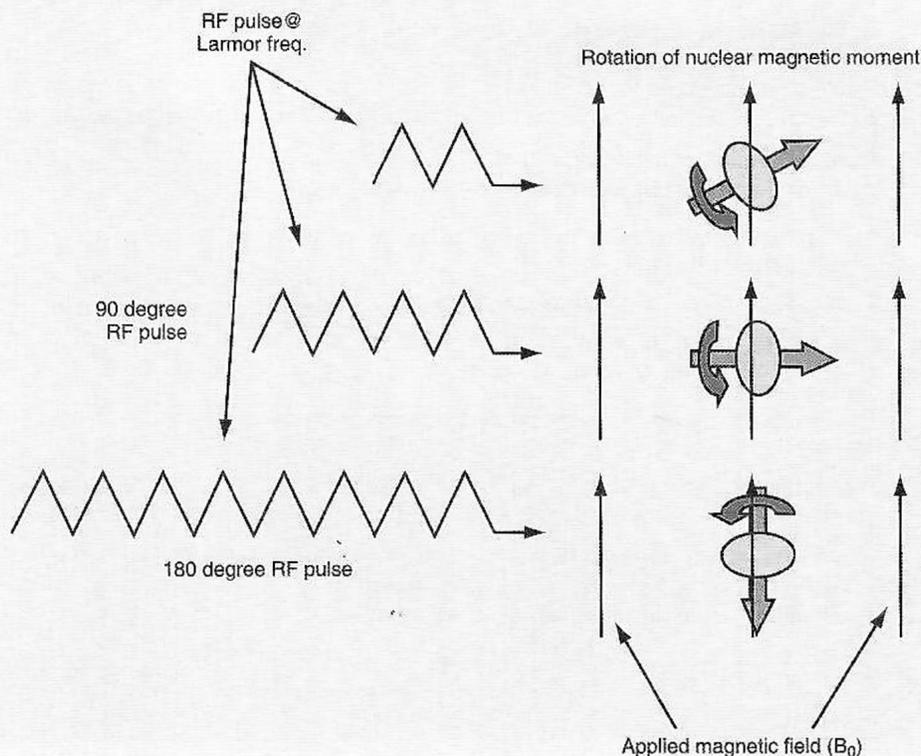
9. After the net magnetization is tipped by the RF pulse, it will recover by realigning itself with the applied magnetic field. The recovery of the magnetization is characterized by a time constant, T1.

   - **T1 (or the longitudinal or spin-lattice) relaxation time** is the time required after a 90-degree tip for 63% of the magnetic moments to realign with the applied magnetic field (B_0).

   - The time depends on the molecule to which the hydrogen atom is attached.

   - It is different for various type of tissues and fluids.

Regrowth of longitudinal magnetic moment

- T1 increases with applied magnetic field strength roughly as $(B_0)^{0.3}$.

- For an increase in magnetic field from 0.5 to 1.5 T, the T1 relaxation time would increase about 40%.

- The T1 of liquids is shorter than the T1 of solids such as bone and plastics.

  $_{liquid}T1 <\ _{solids}T1$

- Typical T1 times of tissue for a 1.5-T MRI are 300 to 4000 milliseconds.

10. **Faraday's law** states that a coil of wire that is located in a changing magnetic field has a current induced in it by the changing magnetic field.

   - The strength of the current is proportional to the strength of the magnetic field.

   - The frequency is proportional to the rate of the changing magnetic field.
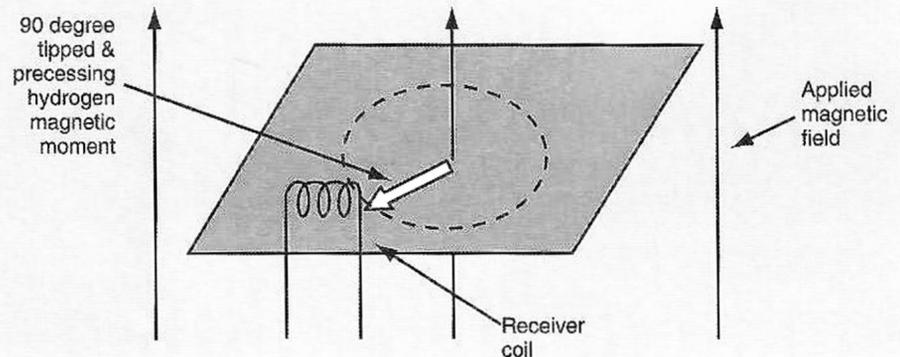
- Hence, a 90-degree RF pulse will tip the net magnetization vector such that there is a component in the transverse plane. The magnetization vector in the transverse plane will rotate, passing a receiver coil that senses the changing magnetic field from the precessing hydrogen nuclei.

- This magnetic moment increases and decreases in strength as it points toward and away from the coil, respectively, creating a sinusoidal current in the wire.

- The strength of the receiver current depends on the strength of the net hydrogen magnetic moment in the 90-degree (X, Y) plane.

- The frequency of the current oscillation in the receiver coils is at the Larmor frequency.

11. **Free induction decay (FID)** represents the rapid loss in signal after a 90-degree tip of the hydrogen magnetic moments with an RF pulse.

Free induction decay (FID) signal
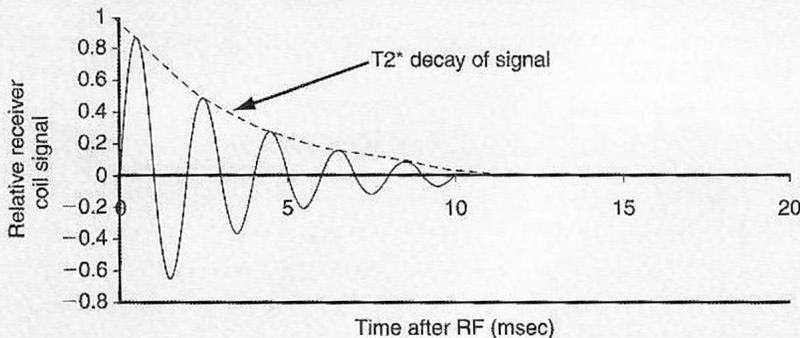
- **T2* decay rate** of the FID signal is due to two different processes.

  (1) Nonrecoverable dephasing caused by random spin-spin exchanges with adjacent atoms and molecules.

  (2) Recoverable dephasing caused by local nonuniformities in the main magnetic field.

- The **T2 relaxation rate** is the decay rate of just the nonrecoverable portion (spin-spin interactions), which has a different and longer decay rate.

- **Dephasing** means that some of the hydrogen nuclei spin faster and some slower because of local magnet field nonuniformities until the magnetic moments cancel each other. At the point of total dephasing, there is no net magnetic moment in the x-ray plane.
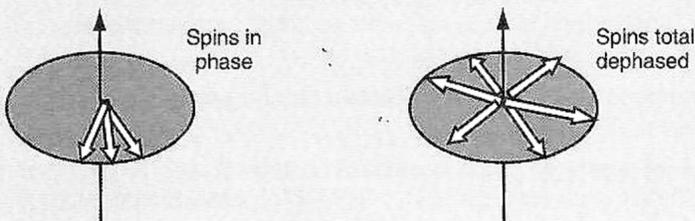
12. The *echo* can be formed by following a 90-degree Larmor RF pulse with a 180-degree RF pulse. (Smaller tip angles than 90 degrees can be used.)

    - After the 90-degree RF pulse, the hydrogen atoms dephase rapidly by T2 decay (FID), and the MRI signal disappears.

    - However, the magnetic moments of the hydrogen nuclei are still in the X,Y (transverse) plane, but they are randomly oriented.

    - ***The 180-degree RF pulse changes the direction of precession*** of the hydrogen nuclei. The fastest nuclei are in the rear and the slowest in the front.

    - Eventually, the ***fast spinning nuclei close the gap with the slower spinning nuclei*** and the MRI signal reappears, which is called the echo.

    - An example is runners going around a track. The faster runners gain the lead, but then the coach blows a whistle to reverse direction (180-degree reversal). The fastest runners are then in the back, but they eventual regroup with the slowest runners, who are now in the front of the pack.

    - However, the nonrecoverable signal (T2) will be lost, and the echo will be lower in amplitude because of random spin-spin losses.

    - T2 relaxation is a measure of the rate at which the echo amplitude decays.

    - T2 is the time for the amplitude of the echo to decay to 37% of the initial FID amplitude.

Amplitude of echo
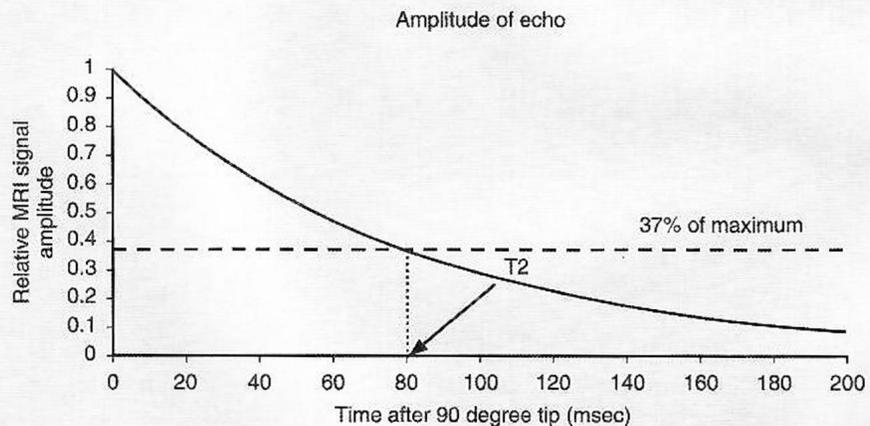
13. $T2^* \ll T2 < T1$.

14. Typical T2 times for 1.5-T MRI are 50 to 250 milliseconds. In general, T2 relaxation times do not vary much with main magnetic field strength. They are primarily dependent on the molecules to which the hydrogen nuclei are attached and the surrounding molecules.

15. Vector components of the hydrogen magnetic moments are composed of a longitudinal (z-axis) and a transverse (x,y-axis) component.

    - Only the transverse (x,y-axis) magnetic moment produces a signal, and only if the magnetic moments are in phase.

    - As the longitudinal (z-axis) magnetic vector increases with time constant (T1), the transverse (x,y-axis) decreases.

    - The combination of the transverse and longitudinal components is constant.

    - After a 90-degree RF pulse, the magnetic moments of the hydrogen nuclei are all in the transverse plane (x,y-axis). With time, the magnetic moments realign so that the net magnetic moment is entirely along the longitudinal plane (z-axis).
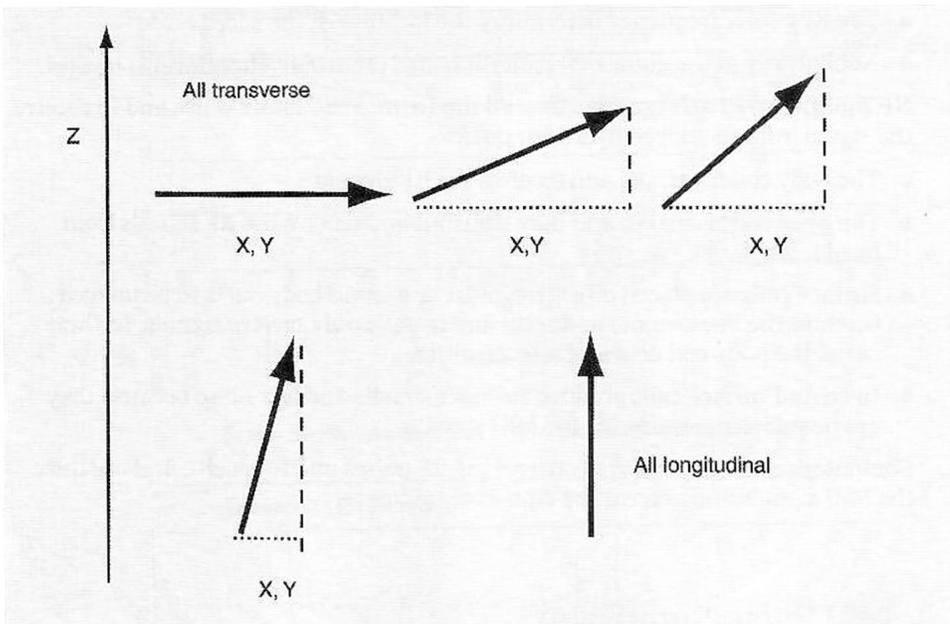
B. MRI Equipment

1. The main magnetic field consists of a series of Helmholtz coils used to produce a strong and nearly uniform magnetic field at the center of the solenoid coils.

   - **Superconducting magnets** use liquid helium, which has a temperature near absolute zero ($-272°$ C), to cool the wires so that they have **virtually no resistance**.

   - Superconducting magnets are continuously activated once the power is applied.

   - **Quenching** can occur if the liquid helium is heated and rapidly "boils off." A big pipe is required to vent the quench gas, which is thousands of times larger in volume than the liquid.

   - Typical field strengths are 0.3 to 3.0 T.

2. There are other types of magnets, as follows:

   - These magnets are often in the open or vertical configuration.

   - **Resistive magnets**, which consume considerable power, require cooling and produce magnetic fields of less than 0.3 T.

   - **Permanent magnets**, which are very heavy (>100,000 lb), have very small fringe fields and have main field strengths that are usually less than 0.3 T.

3. **Shim coils** are used to correct for minor nonuniformities in the main magnetic field. Typical uniformity is better than a few parts per million (ppm) over a 30-cm-diameter sphere in the center of the magnet.

4. **Gradient coils** are used to create a small difference in the magnetic field in a linear fashion in the x-, y-, and z-axes.

   - Because of the differences in the magnetic fields, only the hydrogen nuclei at the correct magnetic field strength would be affected by the RF field.

   - The gradients are used to select the MRI slice and to encode the x and y positions within the slice.

   - Higher gradients produce thinner slices, and lower gradient strength produces thicker slices.

- The RF center frequency determines the location of the slice.
- Nonlinearity in the gradients results in spatial distortion (curvature) in images.

5. **RF quadrature coils** are used to send the Larmor excitation pulse and to receive the signal from the tipped hydrogen nuclei.

- The body coil transmits and receives the RF signals.
- The head coil is smaller and may transmit and receive the RF signals from head images.
- Surface coils are placed directly against or around body parts to be imaged (such as the knee, spine, or finger) and usually only receive signals. In these cases, the body coil acts as the transmitter.
- Head and surface coils produce stronger signals and less noise because they are nearer to the source of the MRI signal.

6. Computer systems are used to control the RF pulses and to receive and organize the MRI signals and process the data from an image.

C. MRI Pulse Sequences

1. A **spin echo (SE) sequence** is a 90-degree RF pulse followed by a 180-degree RF pulse. Then the entire sequence is repeated with a different phase encoding.

- **Echo time (TE)** is equal to double the time between the 90- and 180-degree RF pulses.
- TE is selectable by the MRI operator. Longer TE times enhance T2 relaxation time differences in the body tissues.
- **Repetition time (TR)** is the delay before the 90- and 180-degree RF pulses are repeated.
- TR is the other parameter that is selected by the MRI operator. Shorter TR times enhance T1 relaxation time differences in the body tissues.
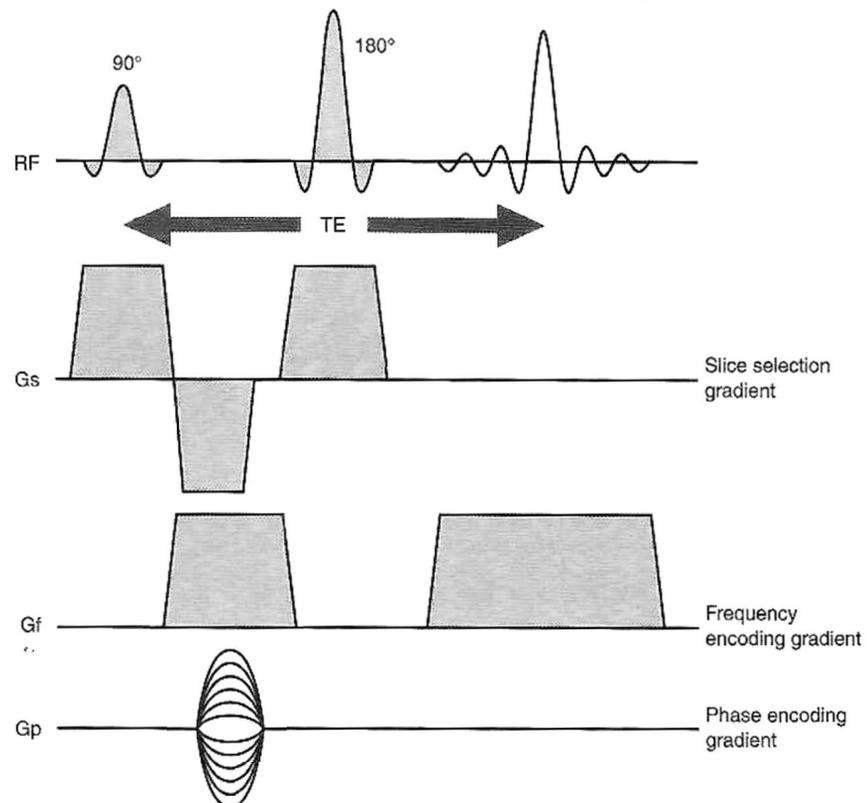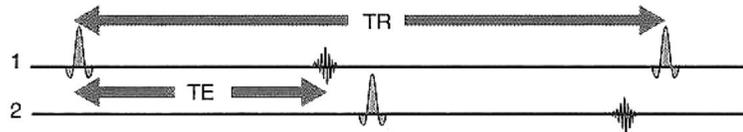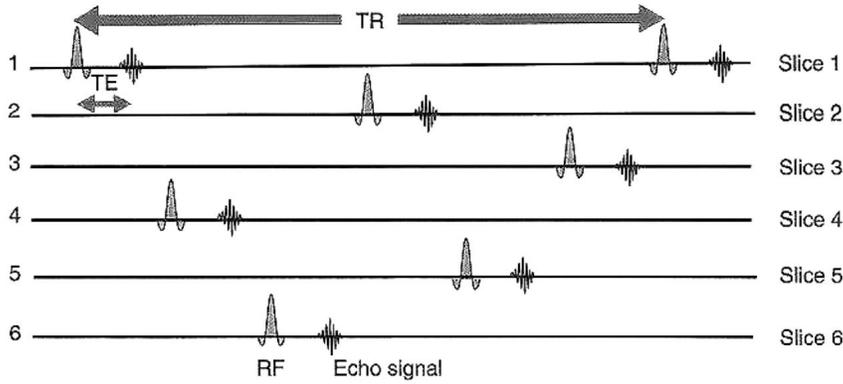
TYPE SE SCAN	TE SELECTION	TR SELECTION
T1 weighted	Short	Short
T2 weighted	Long	Long
Proton density	Short	Long
Not used	Long	Short

2. **Gradient echo (GRASS = gradient recalled acquisition steady state)** typically uses an RF pulse less than 90 degrees (usually with a 20- to 45-degree tip angle). The gradient fields are used to dephase the net magnetization of the hydrogen nuclei. The gradients are then reversed to produce an echo without a 180-degree RF pulse.

- GRE (gradient refocused echo) is usually faster than SE.

- The signal is a mixture of T1 and T2 parameter effects.

- The signal is usually less, and the image has more image noise and artifacts.

- Because the tilt angle for the magnetic moments of the hydrogen atom is less than 90 degrees, the hydrogen magnetic moments realign more quickly with the applied magnetic field and demonstrate less of a T1 effect, unless the transverse magnetization is removed by spoiling (see figures below and at top of next page).
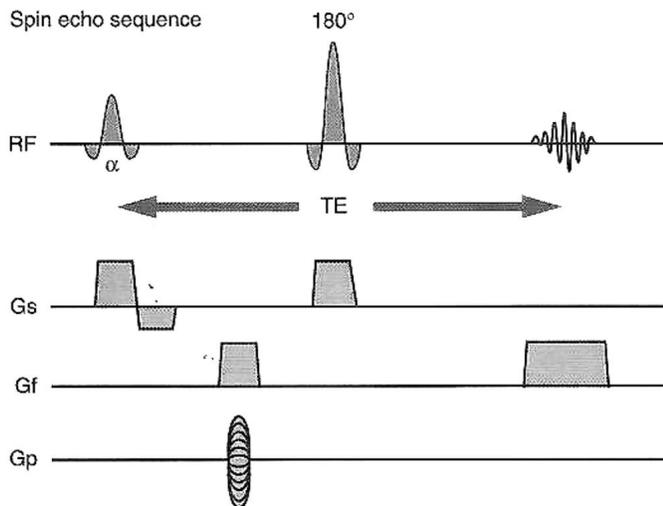
Gradient refocused echo
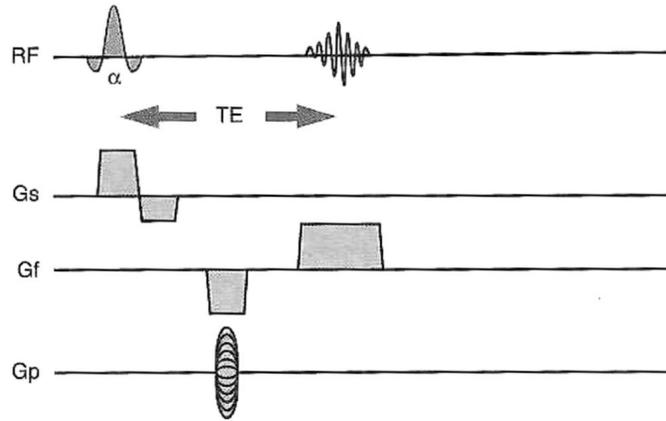
3. **Inversion recovery** uses a 180-degree RF pulse followed by a 90-degree and 180-degree RF pulse to produce an echo.

- **Inversion time (TI)** is the time between the first 180-degree RF pulse and the following 90-degree RF pulse.

- **STIR** = short T1 inversion recovery

- In STIR imaging, TI can be adjusted so that adipose tissue (fat) has been realigned to the 90-degree position just as the 90-degree RF pulse is applied. This flips the magnetic moment of fat to 180 degrees (90 degrees + 90 degrees) so that the fat in the image has no net signal (see figure below).

- **FLAIR** = fluid-attenuated inversion recovery. As with the technique to nullify fat with STIR, fluid (cerebrospinal fluid) can be nullified by using an appropriate T1 (about 2100 ms).

Inversion Recovery
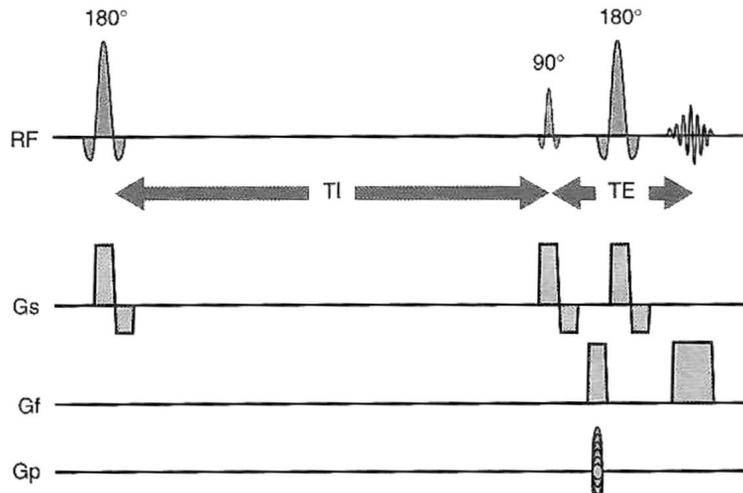
4. **Fast spin echo (FSE)** is a 90-degree pulse followed by a series of 180-degree pulses. Thus, in one sequence, a series of echoes is obtained, one for each phase encode of the image. The image acquisition time is shortened by a factor equal to the number of echoes formed per TR (echo train length or turbo factor).
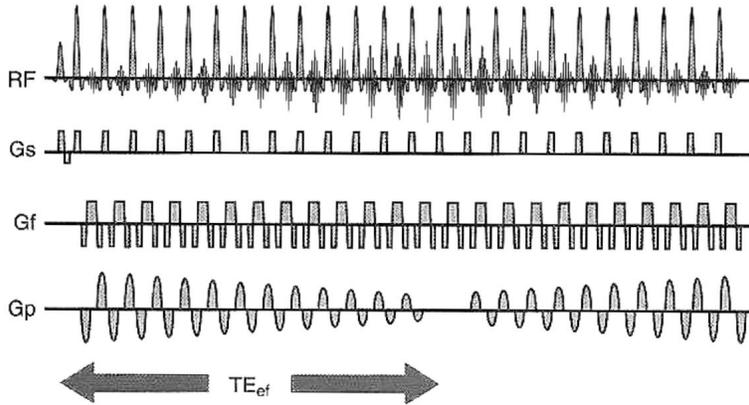
5. **Echo planar imaging (EPI) sequence** employs a continuously oscillating gradient field to gather a significant amount of the total image in a very short period of time.

 • EPI pulse sequences provide one of the very shortest image times.
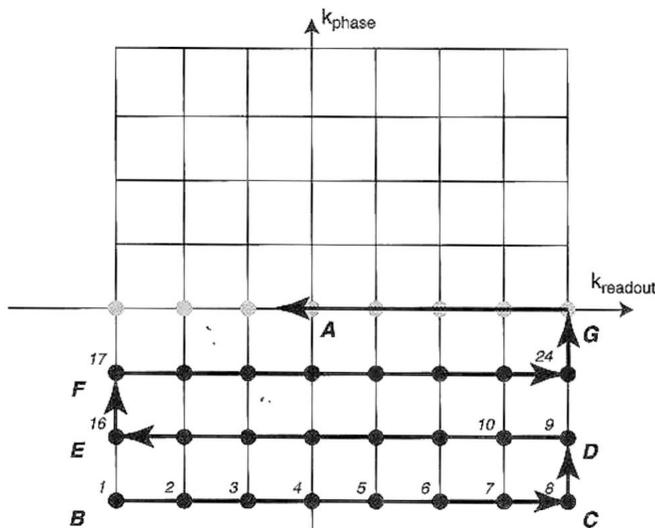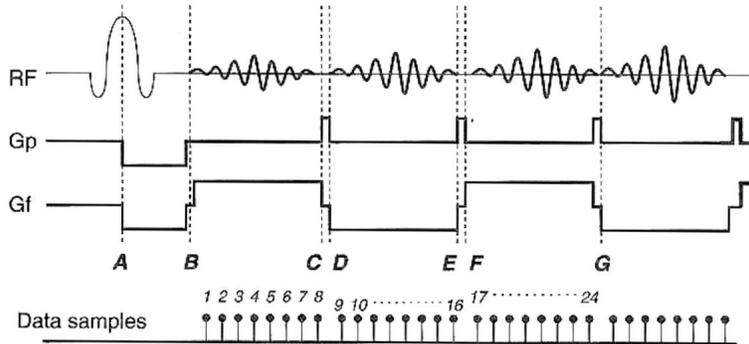
D.   MRI Image Quality

1.   *Spatial resolution* totally depends on *pixel size*, which is field of view (FoV) divided by the matrix size. A 512×512 matrix has better spatial resolution than a 128×128 matrix.

2.   *Signal-to-noise (SNR) ratio* is the key to low-contrast visibility. A strong signal increases the SNR, which improves low-contrast visibility.

   - A larger strength magnet (higher tesla number) produces a better SNR.

   - Large voxels contain more hydrogen atoms, which improves the MRI signal. Therefore, large FoVs improve the SNR.

   - A thicker slice provides more signal.

   - A smaller matrix size provides more signal.

   - Most tissue has a similar (but not the same) number of hydrogen atoms per cubic centimeter.

   - Short TE times and long TR times provide larger amplitude MRI signals.

   - 90-Degree tips for hydrogen nuclei produce a stronger signal than partial angle tips, as used in gradient echo images.

   - Receiver coils close to the body, such as surface coils, have stronger signals.

   - Summation of multiple images (larger NEX [number of excitations]) improves the SNR.

   - Narrow bandwidth improves SNR at the expense of greater chemical shift artifact.

3.   *Volume averaging* becomes worse with larger voxels.

4.   *Scan times for spin echo* sequences depend on the following factors:

   Scan time = NEX $\times$ (# phase encodings) $\times$ TR

5.   The number of spin echo slices that can be simultaneously acquired during a single sequence is given by the following formula:

   # slices per sequence = [TR − load time]/[TE + pulse time]

   where load time is 20 to 100 msec and pulse time is 2 to10 msec.

E.   MRI Artifacts

1.   *Chemical shift artifact* is due to the Larmor frequency of hydrogen nuclei, which depends on the molecule in which the hydrogen atom is located.

   - The frequency of hydrogen in lipids is about 3 ppm different from that of hydrogen in water, which represents about a 200-Hz difference for 1.5 T.

   - The fats are displaced in the frequency direction, producing a void on one side and a bright area of superimposition on the other side.

   - Chemical shift artifact always occurs in the frequency direction.

2.   *Motion ghosts* occur in the phase-encoding direction from fluid flow, respiration, or the patient's movement.

   - There are multiple low-intensity ghosts in the phase-encoding direction due to motion.

   - The direction of ghosting can be changed by reversing phase- and frequency-encoding directions, which may limit ghosting artifacts.

   - Flow effects can produce either dark blood or bright blood, depending on flow and pulse sequence parameters.

3. ***Aliasing appears as wraparound***, in which a portion of the body is wrapped around onto the other side of the body and overlaps other tissue.

   - This is due to undersampling the data.

   - It can be reduced by using either more pixels or a larger FoV.

4. ***Susceptibility artifact*** is due to differences in the susceptibility coefficients of adjacent structures, such as metal and tissue or air and tissue.

   - Voids appear around metal in the body, and the adjacent area is distorted.

5. ***Volume averaging*** is similar to that seen in computed tomography (CT) when different materials are averaged in large voxels.

6. ***Zipper artifact*** is a light and dark series of short lines (resembling a zipper) along the zero axis due to RF feedback.

7. ***Truncation artifacts*** are alternate light and dark rings at the edges of the body that follow the body contours. They are due to inadequate sampling and have been called ***Gibbs ringing***.

8. ***Cross-talk*** ghosts are faint images of bright structures outside the slice. Because they are close to the edge of the slice, the ghost of the image appears.

9. ***Zebra stripes*** can be due to eddy currents in the MRI or the body.

10. ***Distortion or bending*** of contours can be due to nonlinearity of gradient fields.

F. MRI Safety

1. Static magnetic fields greater than 2 to 10 T can cause the sensation of light flashes in the eyes and can interfere with conduction loops of the central nervous system.

2. Large, rapidly changing magnetic fields (>20 T/sec) can cause currents in the body that affect electrocardiograms and can produce muscular tetanus and respiratory difficulties. The Food and Drug Administration (FDA) limits allowed changes in magnetic fields to <20 T/sec.

3. High-power RF (as in fast spin echo) can cause tissue heating, which should be kept below an increase of 1° C. The FDA specifies the limitation in the specific absorption rate (SAR) from RF of less than 4 watts/kg averaged over the whole body for a 15-minute period and less than 3 watts/kg averaged over the head in a 10-minute period. The peak value in any gram of tissue must be less than 8.0 watts/kg for the head and less than 12 watts/kg for the body in a 15-minute time period.

4. Pacemakers, biostimulators, hearing aids, and similar electronic devices should never be scanned and should be excluded from fringe magnetic fields greater than 5.0 gauss. (Some newer pacemakers have been scanned with no malfunctions.)

5. Credit cards and magnetic storage devices can be erased at fringe magnetic fields greater than 10 gauss.

6. X-ray tubes, computer display screens, and patients' monitors can be affected in 1- to 5-gauss magnetic fields.

7. Ferromagnetic materials (iron, nickel, cobalt, and steel) should be excluded from MRI rooms because they can become flying objects in strong magnetic fields.

8. Patients with shrapnel, metal fragments, metallic prosthetic devices, heart valves, and surgical clips should be screened because the metal could move in a strong magnetic field and cause critical injuries to the patient.

9. The noise of the pulsing MRI gradients can injure hearing, and ear plugs are recommended for patients being scanned. The FDA specifies that the acoustic

noise levels must be less than 140 dB where patients or staff members are located.

10. Contrast reaction to the gadolinium contrast agent in MRI is a concern.

11. Burns from RF heating of wire leads, jewelry, zippers, dental implants, tattoos, intrauterine devices, and similar devices are a concern.

12. Instruments such as pagers, cell phones, magnetic identification cards, and analog watches can be destroyed if these devices are taken inside MRI rooms.

13. In an emergency (such as a cryogen quench or a heart attack), the patient should be removed from the MRI scanning room.

14. The areas around an MRI room should be zoned, and patients should be surveyed for potential problems.

15. There are no known long-term adverse effects from routine MRI scanning of standard patients.

G. Questions

20-1. Nuclei that have the strongest magnetic moments are those with _____.

(a) High Z (b) Low N (c) Odd number [Z and Z + N]
(d) Even number [Z and A] (e) Only hydrogen

20-2. The Larmor frequency of nuclei depends on _____.

(a) Number of protons and neutrons in the nucleus
(b) Gyromagnetic ratio (c) Molecule in which nuclei are located
(d) Main magnetic field strength (e) All of the above

20-3. The shortest relaxation time in MRI is the _____.

(a) T1 (b) T2 (c) T2* (d) TE (e) TR

20-4. The spin-lattice relaxation time is also called the _____ relaxation time.

(a) Transverse (b) T2 (c) T2* (d) Longitudinal (e) Gradient

20-5. The coil that provides the best signal-to-noise ratio (SNR) is _____.

(a) Body (b) Head (c) Surface (d) Shim (e) Gradient

20-6. The relaxation time that controls the free induction decay (FID) signal is the _____ relaxation time.

(a) T1 (b) T2 (c) T2* (d) TE (e) TR

20-7. Cryogenic superconductive magnets have their electrical windings cooled by _____.

(a) Liquid oxygen (b) Liquid fluorine (c) Liquid hydrogen
(d) Liquid helium (e) Liquid krypton

20-8. The Larmor frequency of hydrogen nuclei at 1.5 T is about _____ MHz.

(a) 13.7 (b) 23.5 (c) 42.6 (d) 63.9 (e) 89.6

20-9. The brightest signal from a T2-weighted spin-echo MRI image would be from _____.

(a) Pure water (b) Bone (c) Fat (d) Cerebrospinal fluid
(e) Cartilage

20-10. The brightest signal from a T1-weighted spin-echo MRI image of the brain would be from the _____.

(a) Adipose tissue (b) Gray matter (c) White matter
(d) Cerebrospinal fluid (e) Pure water

20-11. A T1-weighted spin-echo image is produced by using a pulse sequence with a _____ TE time and a _____ TR time.

(a) Long, long   (b) Long, short   (c) Short, long   (d) Short, short
(e) Medium, long

20-12. A T2-weighted spin-echo image is produced by using a pulse sequence with a relatively _____ TE time and a relatively _____ TR time.

(a) Long, long   (b) Long, short   (c) Short, long   (d) Short, short
(e) Medium, long

20-13. A proton density–weighted spin-echo image is produced by using a pulse sequence with a _____ TE time and a _____ TR time.

(a) Long, long   (b) Long, short   (c) Short, long   (d) Short, short
(e) Medium, long

20-14. The pulse sequence most often used to nullify the signal from adipose tissue is _____.

(a) Spin echo   (b) Gradient echo   (c) STIR   (d) Echo planar
(e) Fast spin echo

20-15. The fastest MRI pulse sequence is _____.

(a) Spin echo   (b) Gradient echo   (c) STIR   (d) Echo planar
(e) Fast spin echo

20-16. All of the following improve the SNR for a spin echo image, *except* _____.

(a) Thick slice   (b) Large z-gradient   (c) Larger pixel sizes
(d) More NEX   (e) Greater magnet strength

20-17. The "180 degree–90 degree–180 degree" RF pulse sequence is employed in _____.

(a) Spin echo   (b) Partial saturation   (c) Inversion recovery
(d) Magnetization transfer   (e) MRS

20-18. The reconstruction technique used for most MRI images is _____.

(a) Back-projection   (b) 2DFT   (c) Iterative series
(d) Taylor expansion   (e) Matrix inversion

20-19. As the magnetic field strength (B_0) increases, the _____ parameter also increases.

(a) T1   (b) T2   (c) T2*   (d) TI (inversion time)
(e) γ (gyromagnetic ratio)

20-20. The scan time for a spin echo pulse sequence depends on all of the following factors, *except* _____.

(a) NEX   (b) TR   (c) Number of frequency encodings
(d) Number of phase encodings   (e) Use of Fourier symmetry

20-21. The spatial resolution in body MRI images is about _____ LP/mm.

(a) 0.7   (b) 2.2   (c) 4.3   (d) 8.5   (e) 12.1

20-22. The MRI coils that often lead to spatial distortion problems are _____.

(a) Shim   (b) Gradient   (c) Body   (d) Active fringe shield
(e) Eddy shields

20-23. _____ MRI artifacts are repeated low-intensity images in the phase-encoding direction.

(a) Chemical shift   (b) Susceptibility   (c) Motion ghost   (d) Aliasing
(e) Truncation

20-24. _____ MRI artifacts cause images to wrap around to the opposite side and overlap other parts of the anatomy.

(a) Chemical shift   (b) Susceptibility   (c) Motion ghost   (d) Aliasing
(e) Truncation

20-25. _____ MRI artifacts displace fat and tissue to create voids and bright areas of overlap in the frequency-encoding direction of units with large field strength.

(a) Chemical shift   (b) Susceptibility   (c) Motion ghost   (d) Aliasing
(e) Truncation

20-26. _____ MRI artifacts cause voids and distortions near air-tissue interfaces.

(a) Chemical shift   (b) Susceptibility   (c) Motion ghost   (d) Aliasing
(e) Truncation

20-27. Fringe fields from MRI units must be less than _____ gauss in areas where individuals with pacemakers, biostimulators, insulin infusers, and other, similar biologic electronic devices have unrestricted access.

(a) 1.0   (b) 5.0   (c) 10.0   (d) 20.0   (e) 50.0

20-28. Tissue heating from MRI RF signals should be such that the SAR does not deposit more than _____ watts/kg averaged over the body of the patient.

(a) 0.4   (b) 4.0   (c) 8.0   (d) 10.0   (e) 25.0

20-29. Potentially detrimental bioeffects from MRI include all the following, _except_ _____.

(a) Acoustic noise   (b) Induced current in central nervous system
(c) Enzyme disassociation   (d) Tattoo heating
(e) Dislodging surgical clips and metal fragments

20-30. The MRI pulse sequence that is most likely to cause the most RF heating in the patient's tissue is _____.

(a) Spin echo   (b) Fast spin echo   (c) Gradient echo
(d) Inversion recovery   (e) Echo planar

H. Answers

20-1. Answer = (c). Both protons and neutrons have magnetic moments. Both protons and neutrons pair up with particles with the opposite spin so that the net magnetic moment is zero for a pair. Hence, the strongest magnetic moments would be for an odd number of protons and an odd total number of neutrons plus protons. Hydrogen, which has just one proton in the nucleus, is the best example of a strong magnetic moment.

20-2. Answer = (e). The Larmor relationship states that the precessional frequency is a product of the gyromagnetic ratio and the magnetic field strength. However, the gyromagnetic ratio depends on the number of neutrons and protons in the nucleus. From the chemical shift, it is apparent that the precessional frequency for hydrogen depends on the molecules in which the hydrogen atom is located; the frequency is different for hydrogen located in water as compared with hydrogen in lipids. The Larmor frequency is directly related to magnetic field strength.

20-3. Answer = (c). T2* is less than T2, which in turn is less than T1 for most substances. TE and TR are imaging parameters; they do not represent relaxation times, which would be related to the molecule in which the hydrogen is located.

20-4. Answer = (d). See note in this chapter (**A9**). T1 is longitudinal relaxation time, and T2 and T2* are transverse relaxation times.

20-5. Answer = (c). Coils that are closest to the hydrogen nuclei being imaged (which are the source of the MRI signal) have the highest signal intensity and SNR.

20-6. Answer = (c). See note and the graph on FID (**A11**).

20-7. Answer = (d). Early cryogenically cooled MRI units used liquid helium in contact with the magnet windings; the liquid helium was surrounded with liquid nitrogen. Modern MRI units only use liquid helium. Liquid nitrogen has a higher temperature and is not conducive to superconduction (zero resistance) in the magnet winding wires. Liquid oxygen is dangerous because it can lead to explosions. Liquid hydrogen could generate extraneous MRI signals and is not used. Fluorine is caustic and usually not in liquid form.

20-8. Answer = (d). See the notes in this chapter, which state that the gyromagnetic ratio for hydrogen is 42.6 MHz/T. Multiplying by 1.5 T equals 63.9 MHz for the Larmor frequency.

20-9. Answer = (a). Pure water has both long T1 and long T2 relaxation times. In a T2-weighted image, water would be one of the last substances to dephase. Therefore, water has the brightest signal, closely followed in brightness by cerebrospinal fluid. Cartilage and bone are solids, which have very little MRI intensity. Adipose (fat) tissue has relatively short T1 and T2 times, resulting in a weak T2-weighted signal.

20-10. Answer = (a). With a very short T1 relaxation time, adipose tissue would have the brightest T1-weighted signal because it realigns rapidly in the z-axis. It would be followed in brightness by white matter and then gray matter. The weakest signal would be from cerebrospinal fluid and water, both of which have very long T1 relaxation times.

20-11. Answer = (d). See table in this chapter (**C1**) for the different combinations of TR and TE.

20-12. Answer = (a). See table in this chapter (**C1**) for the different combinations of TR and TE.

20-13. Answer = (c). See table in this chapter (**C1**) for the different combinations of TR and TE.

20-14. Answer = (c). The IR in the term STIR stands for inversion recovery. The time between the 180-degree and 90-degree pulses (time after inversion, TI) is such that the magnetic moment for fat is zero in the z-direction when the 90-degree pulse is applied. Thus, fat does not produce a signal, and it is nullified from the image.

20-15. Answer = (d). Because of sinusoidally oscillating high-strength gradients, EPI can complete the image in a single shot, which can be on the order of 1 second. However, the images have considerable noise associated with them.

20-16. Answer = (b). Large voxel elements contain more hydrogen atoms, which result in a stronger signal. Therefore, thick slices, smaller matrix, and larger pixel sizes produce a larger voxel. A large z-gradient produces a thin MRI slice, which contains fewer hydrogen atoms. More NEX means that several images are added together, which produces a better SNR. A larger applied main magnetic field produces a stronger signal approximately related to the size of the field, B_0.

20-17. Answer = (c). A spin echo sequence is a 90-degree RF pulse followed by a 180-degree RF pulse. Partial saturation uses a series of 90-degree RF pulses. Magnetization transfer uses a presaturation pulse of a broad, nonresonance frequency to affect the bound versus free proton pools. MRS stands for magnetic resonance spectroscopy. MRS attempts to measure the slightly different resonance frequencies of hydrogen atoms depending on where the nuclei are located in assorted molecules.

20-18. Answer = (b). Because the data in an MRI slice are in the form of phase and frequency encoding, 2DFT is the most direct method of reconstructing MRI images from the measurements. 3DFT can also be used to image volumes,