Medical Image Analysis
First hand-in

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Question 4.1

The main difference between the two modalities comes from that anatomical imaging can discriminate between different constituents of the body(water, bone, soft tissue, fluids) while functional imaging can discriminate different levels of metabolism caused by biochemical activity that may be generated by the uptake of a radiopharmaceutical substance. Another difference comes from that the functional imaging needs a stimulation of the organ (internal or external) to trigger the biochemical activity

As for the anatomical imaging examples of modalities are: X-ray imaging, ultrasound and magnetic resonance imaging (MRI).

Examples of functional imaging modalities: functional MRI, single photon emission computed tomography (SPECT) and fluorescence imaging.

Question 4.3

X-rays are generated by the interaction of high-speed electrons with heavy target atoms such as tungsten or molybdenum. It is used the principle that an accelerated electron losses energy in interaction with an atom and the loss of energy emits X-ray photons in a scattered direction.

For medical imaging applications, it is used an X-ray imaging tube as an external ionized radiation source to generate an X-ray radiation beam that is transmitted through the human body in scanning mode. As radiation beam passes through a specific location, X-rays undergo absorption and scattering.

For diagnostic imaging, lower energy X-rays are used(and higher energy photons are used in radiation therapeutic applications). Usually, X-rays between 0.1nm and 0.01nm (corresponding to energy range 12.3 keV to 123keV) are used for diagnostic purposes. The reason for using this range is that the attenuation is reasonable to discriminate bones, soft tissues and air. The wavelength is also short enough for providing excellent resolution of images. If the photon energy is higher, then the human body becomes transparent and there is loss in contrast of the image because the photons have less attenuation.

Question 4.5

X-ray tubes for mammography operate on low operating voltage, usually less than 30kV. X-ray tubes with X-ray energies between 17 and 25keV are usually used. Typically, molybdenum or rhodium are used as a target material in X-ray mammography tubes to provide the characteristic X-ray radiation in the desired range.

The main challenge in mammography comes from the fact that breast tissue is quite vascular and soft with low X-ray attenuation coefficients in comparison to other structures in the body. The detection of architectural distortions, small lesions or microcalcifications requires high spatial resolution (50-100 microns).

For early detection of breast cancer, the mammographic images are required to have high sensitivity and specificity, but at the same time, mammographic imaging techniques must minimize scattering radiation to provide accurate imaging for breast tissue with relatively low radiation dose. Recent advanced X-ray film-screen imaging methods use specialized X-ray tubes, breast compression devices, antiscatter grids and optimized detector system to optimize diagnostic capabilities for the early detection of breast cancer.

Question 4.9

Fourth-generation scanners normally use a ring of 720 or more detectors that are equally spaced around the circumference of a circle. The detectors used in X-ray CT scanners are ionization chambers filled with xenon gas or scintillators with photomultiplier tubes.

Spiral X-ray is used for applications that require high resolution imaging that is produced by collecting data for consecutive axial slices (such as brain imaging). Applications like these require a longer scanning time. In full resolution CT imaging the patient bed is kept stationary while the source detector ring gantry is translated to select axial slices while in spiral CT, the patient bed is moved at constant speed into the gantry space during imaging while the gantry is rotated within the circular opening. The forward movement of patient bed enables the sampling points to provide the data along a spiral or helical path. Due to the motion of the patient bed, total scanning time for collecting data for multiple sections is significantly reduced.

Question 4.10

By considering that the slice thickness is determined by the pitch which is defined the movement of bed one complete rotation (360 degrees) gantry, by changing the pitch value from 1 to 2 I would say that the slice thickness is half if the patient movement speed is kept constant. So if the patient bed is moved 2mm per second, then the slice thickness becomes 1mm.

Question 4.11

From the photon energy, we know that the energy of a photon is:

$$E(eV) = \frac{1.24}{\lambda}$$

where λ is the wavelength (425nm). By calculating this, the energy of a X-ray photon is $E = 2.917eV$.

Since we receive 25keV, then the number of light photons generated by a X-ray photon is

$$N = \frac{25000}{2.917} = 8570$$

Since we have also have an intensifying screen, then the number of light photons generated by a X-ray photon is:

$$N = 8570 * 0.80 = 6850$$

Question 5.1

The basic objective of MR imaging is to map the spatial location and associated properties of specific nuclei or protons present in the object being imaged. The hydrogen proton is the most common form of nuclei used in MRI.

The principle of NMR is based on the quantum properties of nuclei and protons. A fundamental property of nuclei with odd atomic weight and/or odd atomic numbers is the possession of angular moment, generally called spin. These protons carry an electric charge and spin around their axes. Because of spinning, the charged protons create magnetic field around them and possess both angular moment and magnetic moment.

For soft tissue imaging, nuclear magnetic resonance (NMR) property of the selected nuclei of the matter of the object and provides high-resolution images with excellent soft-tissue contrast that is superior to X-ray CT because of the underlying physics of the imaging process. It is difficult to produce images with good soft-tissue through X-ray CT because X rays do not provide measurable differentiation for them. MRI uses selected nuclei available in the body for MRI, which produces an electromagnetic signal for imaging. the contrast in the MRI signal is based on the difference of hydrogen protons in the tissue and physiological structures.

Question 5.2

(i)For the Hydrogen atom, the gyromagnetic ratio is $\gamma = 42.58MHz/T$ so the Larmor frequency is:

$$\omega_0 = 42.58 * 1.5 = 63.87MHz$$

(ii)For the Na atom, the gyromagnetic ratio is $\gamma = 11.26MHz/T$ so the Larmor frequency is:

$$\omega_0 = 11.26 * 1.5 = 11.89MHz$$

(iii)For the P atom, the gyromagnetic ratio is $\gamma = 17.23MHz/T$ so the Larmor frequency is:

$$\omega_0 = 17.23 * 1.5 = 25.845MHz$$

(I looked on table of Wikipedia for the gyromagnetic ratios)

Question 5.3

A significant advantage of MRI is that it can create any directional cross-sectional images along with multidimensional image sequences without making any physical changes in the instrumentation during imaging.

Another advantage of MRI is fast signal acquisition with a very high spatial resolution in the range of a millimeter to one – hundredth of a millimeter. In practice, these parameters are realized with a lower range to maintain a reasonable signal – to – noise ratio for acceptable image quality.

Another important advantage of MRI is the ability to track flow during image acquisition leading to diffusion perfusion imaging.

Another major advantage or MRI is its sensitivity to soft tissue contrast. The actual contrast – to –noise ratio depends on the data collection method, imaging parameters and any flow as applicable.

Question 5.4

Under the NMR phenomenon, the RF energy received by a nuclei at the Larmor frequency causes characteristic excitation of nuclei. The nuclear excitation forces the net longitudinal and transverse magnetization vectors to move. The movement of longitudinal and transverse vectors can be explained through Bloch's equation. Assuming N to be the total number of spinning nuclei in the object being imaged, a stationary magnetization vector, $\underset{M}{\rightarrow}$ can be defined from the available magnetic moments as:

$$\underset{M}{\rightarrow} = \sum_{n=1}^{N} \underset{\mu_n}{\rightarrow}$$

We now define a stationary magnetization vector $\underset{M}{\rightarrow}$ with its components in the unit direction vectors, $\underset{i}{\rightarrow}$ $\underset{j}{\rightarrow}$ and $\underset{k}{\rightarrow}$, in the direction of the actual coordinate system, x, y and z. For a rotating frame we define the rotation magnetization vector $\underset{M_r}{\rightarrow}$ with the unit vectors $\underset{i'}{\rightarrow}$ $\underset{j'}{\rightarrow}$ and $\underset{k'}{\rightarrow}$, also in the coordinate system x,y and z as:

$$\underset{M}{\rightarrow} = M_x \underset{i}{\rightarrow} + M_y \underset{j}{\rightarrow} + M_z \underset{k}{\rightarrow}$$

and

$$\underset{M_r}{\rightarrow} = M_{x'} \underset{i'}{\rightarrow} + M_{y'} \underset{j'}{\rightarrow} + M_{z'} \underset{k'}{\rightarrow}$$

Question 5.5

The deterioration of an NMR signal is analyzed in terms of two separate processes, each with their own time constants. One process, associated with T_1 , is responsible for the loss of signal intensity while the other process, associated with T_2, is responsible for the broadening of the signal. In other words, T_1 is the time constant for the physical processes responsible for the relaxation of the components of the nuclear spin magnetization vector M parallel to the external magnetic field. T_2, relaxation affects the components of M perpendicular to magnetic field. In conventional NMR spectroscopy, T_1 determines the recycle rate, the rate at which an NMR spectrum can be acquired.

Question 5.6

The free induction decay of the electromagnetic signal in the RF coil is the basic signal that is used to create MR images. The RF pulse, transmitted through an RF coil with electronic circuitry, causes nuclear excitation, changing the longitudinal and transverse magnetization vectors.

The RF coil contains computerized programming and switching control that is used to receive the RF emissions during the nuclear relaxation phase.

The computerized control of electronic circuitry allows he programming of the RF coil to transmit and receive specific RF pulses as required by the pulse sequences for image reconstruction. The RF receiver section uses the coupler to switch the signal from the RF coil to an ansemply of pre-amplifiers and demodulators. The signal received is sent to an analog-to-digital converter to record the data in digital format.

During the nuclear excitation phase, an RF coil with electronic circuitry is used to transmit time - varying RF pulses. The same RF coil with computerized programming and switching control is used to receive the RF emissions during the nuclear relaxation phase. The NMR signal, as described above, is recorded through FID in the RF coil at a selected RF. The computerized control of electronic circuitry allows the programming of the RF coil to transmit and receive specifi c RF pulses as required by the pulse sequences for image reconstruction. The RF transmitter section includes a wave synthesizer, RF modulator, RF amplifi er, and a coupler that couples the RF signal to the RF coil. The RF receiver section uses the coupler to switch the signal from the RF coil to an assembly of pre - amplifi ers and demodulators. The FID signal thus received is then sent to an analog - to - digital converter to record the data in digital format.

Question 5.7

The strength of MRI signal depends primarily on the three parameters: density of protons in tissue (the greater the density of protons. the larger the signal will be), T1 and T2 and also depends on the coil sensitivity.

For most soft tissues in the body, the proton density is very homogeneous and does not contribute in major way to signal differences seen in an image. T1 and T2 can be dramatically different for different soft tissues and these parameters are the most responsible for the major contrast between soft tissues. T1 and T2 are strongly influenced by viscosity or rigidity of a tissue.

Question 5.8

The transverse magnetization equation solution is obtained through a clockwise procession-based spin-spin relaxation process with a decay rate of $1/T_2$ until $\xrightarrow[M_{x,y}(t)]{} \rightarrow 0$. The longitudinal magnetization vector $M_z(t)$ decays with a rate of $1/T_1$ through the spin-lattice relation process until it returns to the net magnetization vector in the thermal equilibrium, $\underset{M_z^0}{\rightarrow}$. The longitudinal and transverse magnetization vectors with respect to the relaxation times in the actual stationary coordinate system can be given by:

$$M_z(t) = \underset{M_z^0}{\rightarrow}\left(1 - e^{-\frac{t}{T_1}}\right) + \underset{M_z}{\rightarrow}(0)\ e^{-\frac{t}{T_1}}$$

$$\xrightarrow[M_{x,y}(t)]{} = \xrightarrow[M_{x,y}(0)]{} e^{-\frac{t}{T_1}} e^{-i\omega_0 t}$$

$$\text{with } \xrightarrow[M_{x,y}(0)]{} = \xrightarrow[M_{x,'y'}(0)]{} e^{-i\omega_0 \tau_p}$$

Where $\xrightarrow[M_{x,y}(0)]{}$ represents the initial transverse magnetization vector with the same time set to zero at the end of the RF pulse. of duration τ_p. The equation describes the nature of the change in the transverse and longitudinal magnetization vectors with respect to time after RF pulse.

Question 5.9

I use the first equation from Question 5.8 and since initial net magnetization vector is considered to be zero, we then have:

$$M_z(t) = \underset{M_z^0}{\rightarrow}\left(1 - e^{-\frac{t}{T_1}}\right)$$

Since we want to recover by 90%, and T1=100ms we then have:

$$\left(1 - e^{-\frac{t}{T_1}}\right) = 90\%$$

$$e^{-\frac{t}{T_1}} = 0.1$$

$$-\frac{t}{100ms} = \ln 0.1$$

$$t = (-2.3) * (-100ms) = 2300ms = 2.3s$$

Question 5.10

In the same manner as for Question 5.9 I use the second equations from 5.8 and I will have:

$$\overrightarrow{M_{x,y}(t)} = \overrightarrow{M_{x,y}(0)} e^{-\frac{t}{T_1}}$$

By using the parameters from the problem, I obtain:

$$e^{-\frac{t}{100ms}} = 0.3$$

$$-\frac{t}{100ms} = \ln 0.3$$

$$t = 1200ms = 1.2s$$