Diploma in Biomedical Engineering

[MEDII Report]

Submitted By

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Class: TE01

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Introduction

MRI, also known as Magnetic Resonance Imaging, is a device which uses strong electromagnetic fields and radio frequencies to manipulate magnetic nuclei in our biological bodies and capture the change of frequencies to allow computer generated images of anatomical structures. MRI is excellent for evaluating soft tissues due to having a good soft tissue contrast. That allows clearer visualisation of soft tissue structure which can be easily distinguished from a diseased tissue for diagnosis and track of progress and treatment of the disease. MRI is primarily used to detect anomalies of the central nervous system, diagnosis of joint abnormalities, display of heart wall structure, imaging of eyes and the sinuses and help diagnose infectious diseases such as those associated with acquired immunodeficiency syndrome (AIDS). The MRI is also a safer method compared to radiographic imaging methods like computed tomography (CT) due to it not using ionizing radiation. It is also a painless process with no known biological side effects.

Physical Properties

For an MRI to work, it depends on the magnetic spin properties of certain atomic nuclei in body tissues and fluids and their behavioural change when strong magnetic fields are applied. An atomic nucleus is a small dense region that consists of protons and electrons. An atomic nucleus with an even number of protons (Helium) have their individual spin and magnetic moments cancelling each other out. However, an atomic nuclei with an odd number of protons (Hydrogen) has a net spin and magnetic moment. That causes the nuclei to act like a small magnet.

Hydrogen, which is present in water is mainly used in an MRI due to the huge abundance of water in our bodies and the hydrogen's properties of having a net spin and magnetic moment. Usually it is aligned randomly in our bodies, but when there is a presence of a strong magnetic field, the hydrogen atoms in a water molecule line either parallel (spin up) or antiparallel (spin down) relative to the direction of the magnetic field.

When the water molecules spin, they can "wobble", in the presence of a strong magnetic field, they wobble in the axis of rotation about the magnetic field and this process is called "Precession". The frequency of precession which is called the "Larmor Frequency" is proportional to the magnetic field strength. The relationship can be expressed in an equation:

$$f = \gamma B_0$$

f = Larmor Frequency

γ = Gyromagnetic ratio in MHz per T (constant for a particular nucleus)

B_0 = External magnetic field strength in T (Tesla)

Firstly, to acquire an MRI, the displacement of the net magnetization vector and a uniform magnetic field is needed. These are acquired using a radiofrequency at the appropriate Larmor Frequency. When the hydrogen molecules in water absorb the radiofrequency energies, it causes some hydrogen molecules to flip from parallel to antiparallel which increases its net magnetization vector. Another radiofrequency pulse called the 90° pulse then rotates the net magnetization vector 90° into a plane perpendicular to the magnetic field.

At the same time, the Larmor Frequency is needed for the low-energy water molecules as they will only absorb radiofrequency energy as the same frequency as their precession. The reason for needing to supply energy to the low-energy water molecules is because as the frequency of the magnetic fields change during an MRI scan, most of the water molecules' precessions inside us will be the same as the magnetic field, causing them to rotate in phase with it. However, there are some that will not rotate along the uniform magnetic field, those are the low-energy water molecules. To capture an image of the body part, the machine focuses on the low-energy molecules by using radiofrequency waves that resonate with the already present magnetic field. This provides the low-energy water molecules the energy they need to rotate in phase with the magnetic field.

Finally, the machine will stop emitting radiofrequency waves which causes the low-energy water molecules to stop rotating in phase with the magnetic field and relax to their original positions and release the energy that was absorbed by the radiofrequency waves. Free induction decay occurs during this stage where the intensity of the signal decays rapidly. The signal decay will be measured in two different time constants. T1 and T2. T1 recovery is the spin-lattice relaxation time constant. It determines how fast the longitudinal magnetization (90° Pulse) takes to grow back to 63% of its final value. T2 decay is the spin-spin or transverse relaxation time, it represents how much time is needed for magnetization to be reduced by 63% due to precessional dephasing. Since the hydrogen atoms relax at different rates in different tissues, T1 and T2 are used to characterize the type and physiological state of the tissue.

Instrument Design

The MRI consists of 5 principal components such as

- Main magnet
- Gradient coils
- Radio Frequency coils
- Control electronics
- Computer console

MRI imaging makes use of an MRI scanner. It is a large tube that contains the main magnet, gradient coils as well as the radiofrequency (RF) coils.

The purpose of the main magnet is to create a strong and ideal homogeneous magnetic field to align the hydrogen nuclei. Homogeneous magnetic field improves T2 decay which coincides well with the image standard as well as the existence of distortions. Therefore, this magnetic field homogeneity needs to be adjusted to reduce blurring, shading and more. [1]. There are typically 3 magnets to generate the magnetic field, the permanent magnet, the resistive magnet, and the superconductor magnet. Permanent and resistive magnets have magnetic fields capped at below 0.35 tesla (T) therefore, these two magnets are not able to generate high resolution images. This results in the superconductor magnet being used as its magnetic field is more than 0.35T. [2].

The permanent magnets use permanently magnetized iron which is bent to form a ‘C’ and the magnetic field between the two poles is sufficient for imaging. The magnet is not suitable for higher magnetic fields as the magnet would be too massive in terms of size and weight. However, a drawback for this magnet is its magnetic field homogeneity. This is because it is sensitive to the environment’s temperature. Therefore, complex temperature regulations are needed to maintain the magnet’s field homogeneity. [3]

The resistive magnets are made copper either in the shape of a solenoid or Helmholtz pair coil. The magnetic field is more constant in the coil and mainly in the centre. The cost of production for this magnetic is rather cheap but due to the large currents needed to magnetize the coil, it might be more expensive to use it. Other than that, due to the large currents needed, special cooling systems are needed which will only increase the cost of usage. [3].

The superconductor magnets make use of a solenoid-shaped coil made of alloys such as niobium/titanium or niobium/tin and they are encompassed by copper. When the coil is cooled down to around 10kelvin, the resistance to electrical current is almost zero. This can be achieved by either cooling the coil with liquid helium or nitrogen. [3]. Since the coil is cooled, this allows the use of bigger currents to increase the magnetic field strength to about 8 T. However, for certain alloys like that as stated above (niobium/titanium), when it is cooled at 10kelvin, it can generate a 10 T magnetic field once the standard current is given into the coil. The use of the superconductor magnets can attain better temporal stability and homogeneity as compared to the two other magnets.

Underneath the layer of the main magnet, there are gradient coils used to generate intentional variations to the main magnetic field to produce three different axes. [4]. These gradients are either coils of wire or thin conductive sheets on a cylindrical shell underneath the main magnet. [5].

The purpose of the gradient coils is to create another magnetic field to distort the main magnetic field in an expectable manner, causing resonance frequency of protons to change thus knowing the position. [4]. There are usually three types of gradient coils, each used for a different axis known as the X, Y and Z coils. [5]. The x-axis creates the localisation from left to right, the y-axis creates the localisation from the back of the patient to the stomach and lastly, the z-axis creates localisation in the horizontal direction which is in line with B_0. These gradients then split the body into smaller sections known as a voxel. Each voxel would have a unique frequency due to the gradient fields applied thus resulting in different Larmor frequency for each voxel. Consequently, after the MRI signal is sent and received, it can detect the position. Therefore, the gradient coils are used to allow spatial encoding (location of the voxels. [6].) of the MR signal. [4].

Since we are talking about the sending and receiving of the MRI signal, the innermost coil which is the RF coil is used for that function. RF coils act as the “antennae” of the MRI machine, where they can send and collect the signal sent out. However, the RF coils can also act as a receive-only design where another body coil is used to send the signal. [7]. An important design consideration for the RF coils is that it needs to have a good electrical isolation between the transmit and receive coils. This is because, if this is not done, the patient will not be protected from electrical hazards. [8].

For different body parts, there are different coil geometry available. For example, for shoulders, and other small body parts, the surface coils are used. [7]. These coils are usually used to image objects at the surface and it has the simplest design of all where it is just a loop of wire either circular or rectangular placed at the area of interest. [7]

For imaging of the cervical spine or pelvis, the Helmholtz pair coils are used. [7], as typically, large structures are portrayed by a phased array coil which is made up of a series of surface coils placed in an array.

Lastly, to image the brain or abdominal, a birdcage coil is used. The name of the coil is as such due to its birdcage like structure thus its unique name. This coil, however, provides the best RF homogeneity as compared to all the coils mentioned above. [7].

Lastly would be the control electronics and Computer console. The electronics are as shown in Figure ().

In the G block, it consists of the gradient amplifier, waveform generator and time control as well as the pulse programmer S/W. The general purpose of this block is to control the gradient field operation like the fast switching of three different fields and amplifying the field strength by controlling current flow.

In the R block, it consists of the frequency synthesizer, power amplifier, transmitter/receiver switch, preamplifier, receiver blanking and RF amplifier. The general purpose of this block is to control the RF coil operation.

There are also the demodulator, Quadrature mixer, ADC and host PC/FFT. The ADC converts digital format and performs fourier transformation to generate frequency domain displays which are passed to the computer to be reconstructed into an image.

The PC controls all the action, process data and reconstructs the image.

Data Acquisition Techniques

3 main types of pulse sequences:

1. Free induction Decay

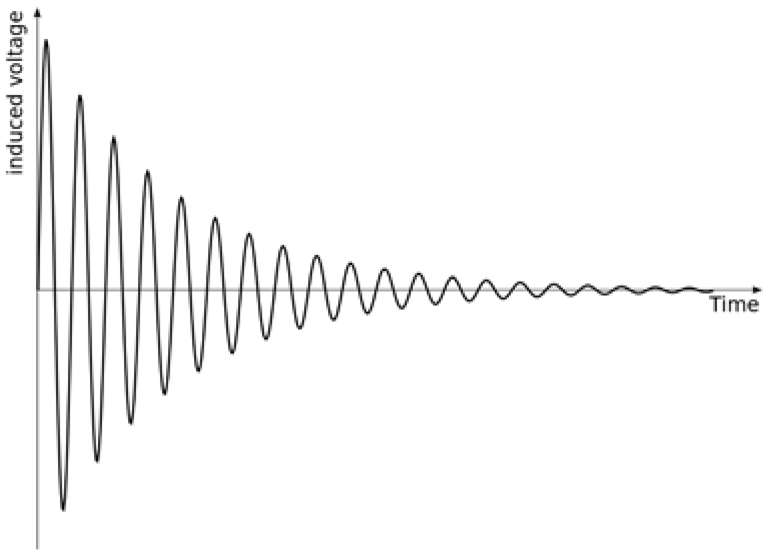
2. Spin Echo

3. Inversion Recovery

Free Induction Decay (FID)

It is a short-lived sinusoidal electromagnetic signal which appears after a 90° RF pulse is applied. When the RF pulse is switched off, the protons will undergo precession and a small electrical current induced-MR signal is released. This MR signal is known as FID.

The signal will decay as time increases due to the inhomogeneities in the main magnetic field. As the T2 value is greater than T2*, the transverse magnetization disappears before T2 contrast can be formed. Thus, a process known as spin echo can be used to recover this lost transverse magnetization.



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Spin-echo pulse sequence

This sequence helps to recover dephasing in the free induction decay signal. A spin echo (SE) is produced by 2 successive RF-pulses that are 90° and 180°. The 180° RF pulse will only be applied after some time from the initial RF pulse.

When the initial 90^0 pulse is applied, the protons will undergo FID. In order to recover the loss of magnetisation, a 180^0 inversion pulse is applied that inverts the magnetic vectors. This makes the protons ‘turn around’ and carry out precession in the opposite direction. This is known as re-phasing. During re-phasing, the faster moment will catch up with the main moment and the slower moments will drift back to the main moment. This creates an ‘echo’ which peaks at time = 2T. This sequence is repeated for at least 10 times to allow T2 to be measured using this sequence.

<u>Inversion recovery pulse sequence</u>

This pulse sequence is used to obtain the T1 measurement and is useful in suppressing unwanted signals in the MR images such as fats and fluids. An initial 180^0 RF pulse is emitted prior to the normal spin-echo pulse sequence. This causes an initial inversion of the longitudinal magnetization causing the signal to align to the -z direction. Over time, the magnetization will increase in the direction of the main magnetic field (+z). Note: Different tissues magnetize at different rates. As the signal crosses the zero axis, a 90^0 RF pulse is applied which causes all the signals to rotate into the transverse plane.

<u>Image Reconstruction</u>

Image reconstruction is a crucial step for MRI to work.This is because the raw data acquired from above is not in image space and thus image reconstruction is needed to convert this raw data into images for viewing. Image reconstruction has many steps such as Fourier transform, interpolation, raw data filtering and phased array coil combination.

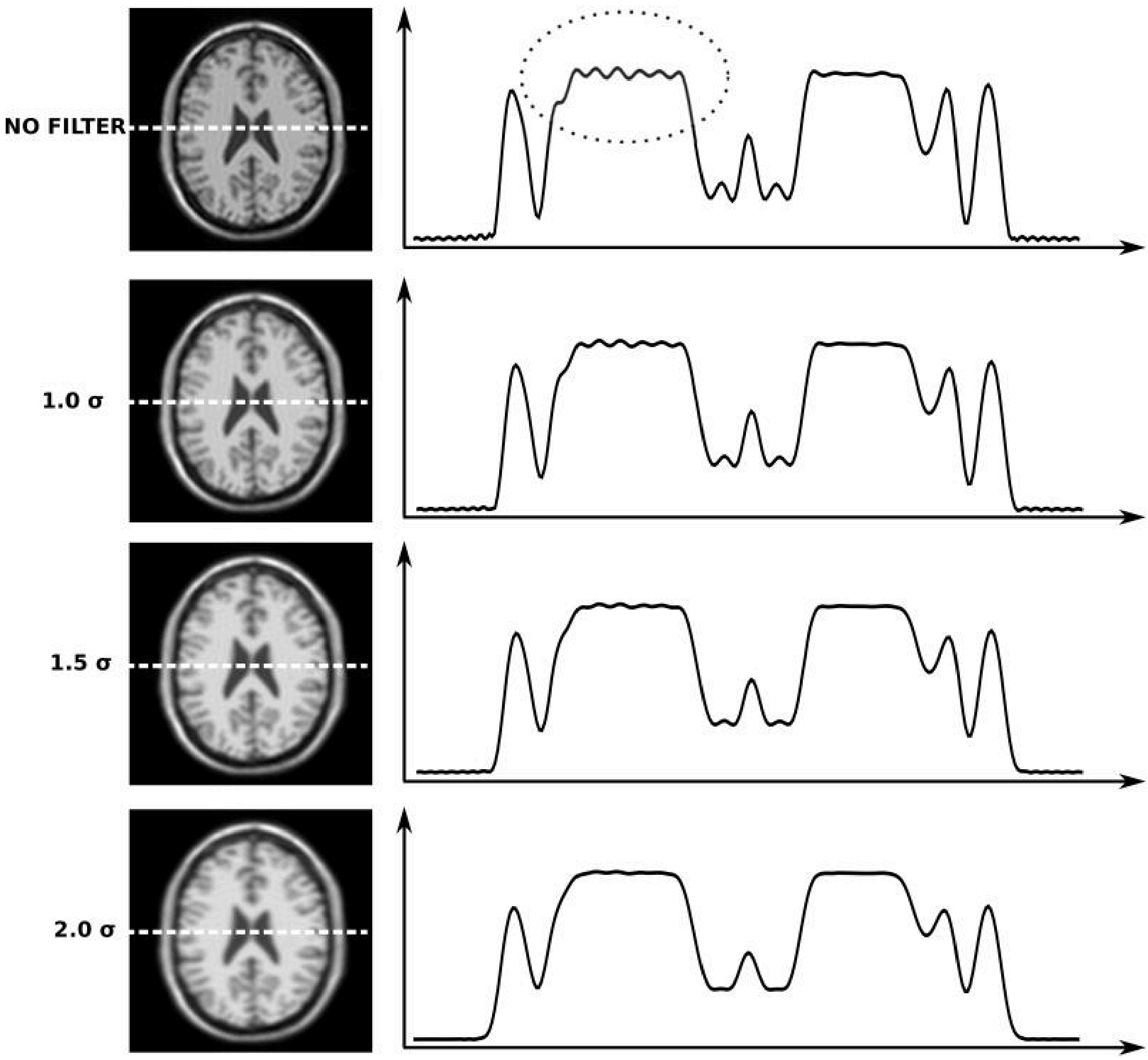
<u>Point Spread Function</u>

Compared to a single pixel, the central peak of the point spread function is broader. This means information or signals from neighbouring pixels bleed from one pixel to another during interpretation, leading to images having blurry images. The edges are blurry as the edge is spread across multiple pixels by the point spread function. Truncations of the k-space cause the point spread functions to have multiple side lobes in addition to the broadened main lobe. The point spread function will always have ringing artifacts in the reconstructed images as we are always sampling a limited region of k-space. Gibbs ringing is the name of this occurrence. In situations where very bright signal regions border low signal regions, Gibbs ringing artifacts can misleadingly create artifacts with bright signal rings in the lower signal areas.

<u>Raw data filtering</u>

Raw data filters are used to address issues like Gibbs ringing artifacts. The filters create a more smooth transition between the edge of k-space and the sampled part of k-space by attenuating the signal at the outer part of k-space. However this causes an increase in SNR and a loss in spatial resolution as the attenuation of the outer regions of k-space cause a broadening of the point spread function.

The image below shows the effect of raw filtering. In the first row you can see an image that has significant Gibbs ringing artifacts as it is unfiltered which is circled. As you move down the rows, the outer parts of k-space get attenuated more and more and you can see how the ringing artifacts start to get more and more dampened with the downside of loos of some spatial resolution. You can also see how as the point spread function broadens,the central peak of the image is attenuated and broadened.



Fourier transform

The data acquired from the MRI is in the spatial frequency domain which is also known as the k-space. This k-space is related to the image domain through a fourier transform. Each k-space point contains phase information and spatial frequency about every pixel in the image and each pixel in the image points to every point in k-space.

Interpolation

Magnetic resonance images are reconstructed with square pixel where a given pixel in the image represents the same distance in both *x* and *y* directions. Among the spatial dimensions, the spatial resolution varies. As the patient has to stay as still as possible during the entire process, the time taken to obtain the image is kept as short as possible. As it takes longer to acquire data in the phase encoding direction dimension, to shorten the time taken data in the phase encoding direction normally has a lower spatial resolution. Phased array coils which help improve sound noise ratio in reconstructed images as well as enable parallel imaging acceleration of the acquisition process are used in modern clinical MRI systems. Acquiring k-space data for each receive channel occurs during image reconstruction. An image for each of the receive channels is produced from the data using Fourier transform to image space. Due to the fact that the coils are situated at different locations relative to the patient, the image produced for each receive channel will be shaded differently and some will have more signal in different parts of the image as the receive coils have spatially varying sensitivities.

Noise Pre-Whitening

Data from the MRI is often acquired from phased array coils. Each coil from the phased array coil provides part of the data required for the reconstruction of the image. As there are multiple coil elements, there is a possibility of noise level in one coil being significantly higher than others. This can affect the image quality if the noise between the different coils are correlated. A noise covariance matrix can be used to inspect the noise distribution in a given measurement system. By turning on sampling in the receive channels, the noise distribution can be easily measured. Following that, the sampled noise can be analysed to produce a noise covariance matrix. Once the covariance is known, the noise will be decorrelated such that the distribution is white. This is also known as noise pre-whitening. The left side of the figure below shows the results before the process is carried out. The right is the final result.

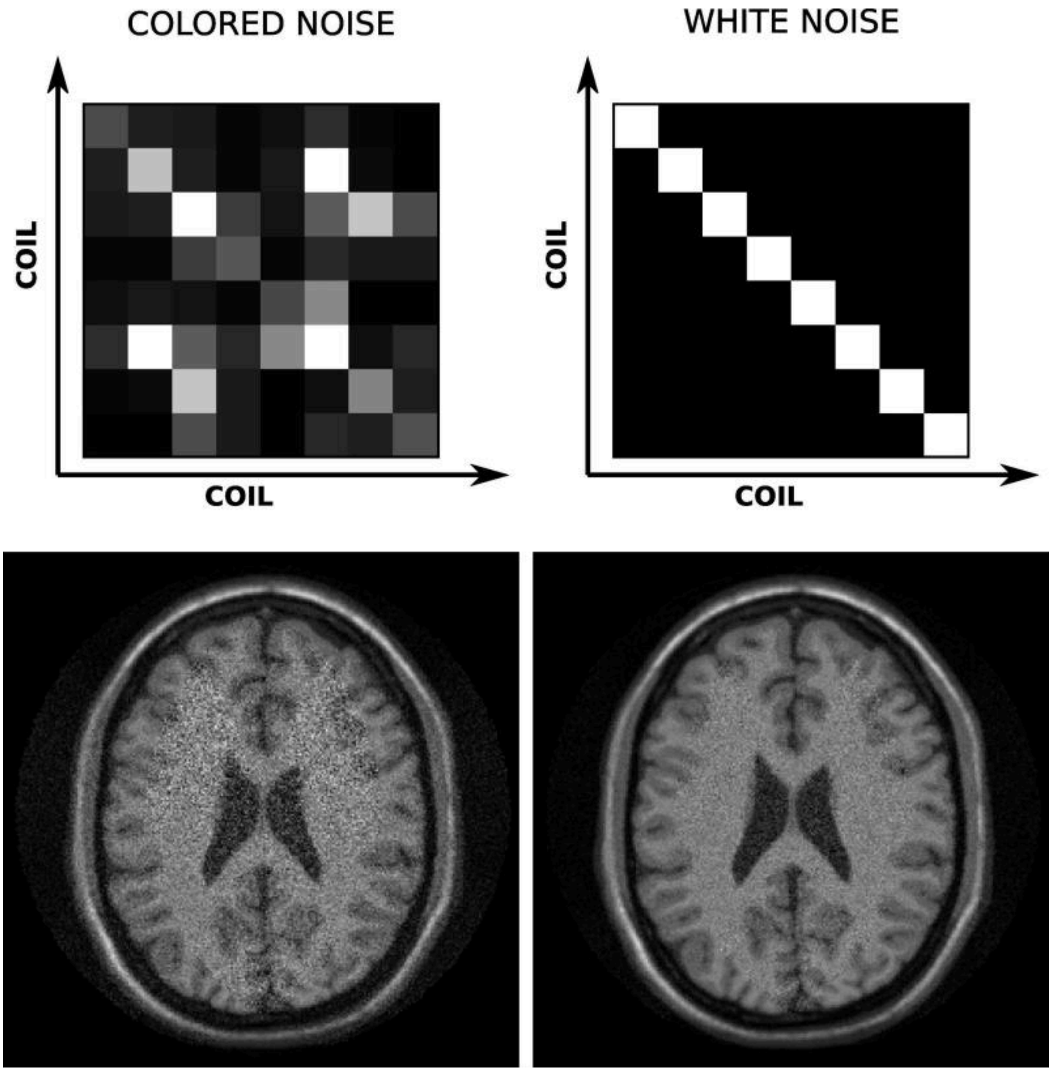
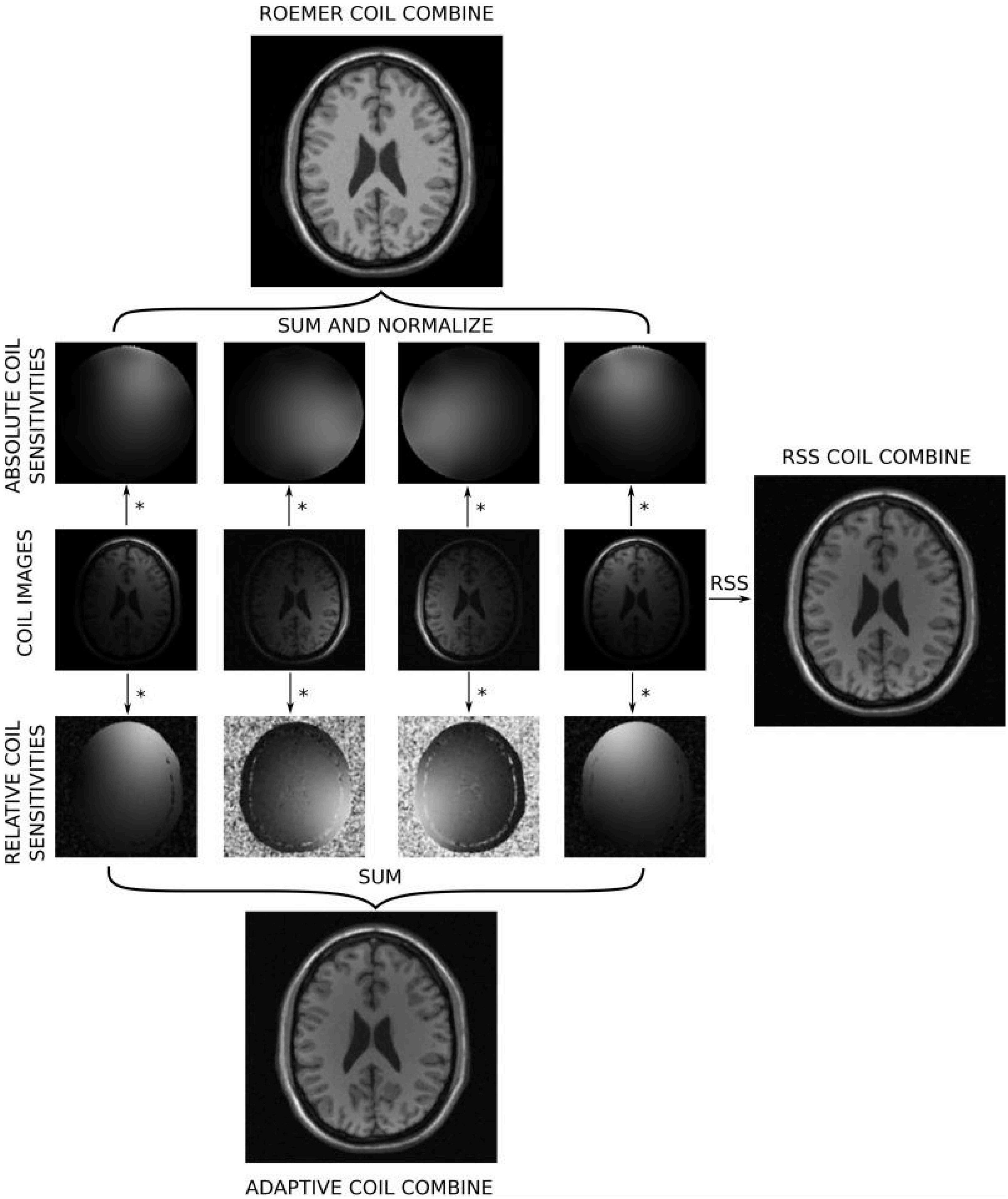


Figure showing the outcome of noise pre-whitening.

Coil Combination Methods
Root-Sum-Squares(RSS) coil combination is one of the simples to use to combine the different images from the various coils into one image. For this technique, the square root of the sum of the shared magnitudes of each coil image forms the magnitude of the combined image. This method is well suited to cases with high sound to noise ratio. However, for applications like phase sensitive inversion recovery construction and phase contrast flow, this method is less than optimal and is problematic as phase information is lost in the process. B1- weighted coil combination is the optimal coil combination if the coil sensitivities are known. The principle behind B1- weighted coil combination is the multiplying of the pixel value of each coil with the complex conjugate of the coil sensitivity of that channel, summing this value across all channels, dividing the sum produced with the sum of the

squared coil sensitivity of all channels. This essentially means that any phase added by the coil itself is removed and the signal is summed up. In the image below, the Roemer coil combine is an example of a B1-weighted coil combination and the middle row is the RSS coil combine.

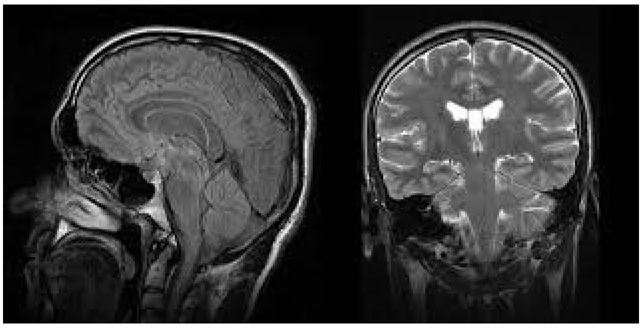


Clinical Applications:

The MRI is used in radiology to form anatomical images for diagnostics. The MRI has a wide range of applications for various medical diagnoses. Compared to CT scans, MRI does not use ionizing radiation and thus the patient will have a risk of getting cancer due to radiation. On top of that, MRI excels in viewing certain diseases that a normal CT scan might not be able to capture. Diseases such as prostate cancer and uterine cancer are almost invisible to CT scans. However, MRI scans take a longer time (around 20 to 40 minutes) compared to CT scans and require the patient to lie still in a noisy chamber.

Neuro Imaging:

The MRI is the best choice for most conditions in the nervous system as there is a good contrast between the white and grey matter.The MRI is the preferred choice for neurological cancers over CT as it provides a better image of the posterior cranial fossa which accommodates the brainstem and the cerebellum.

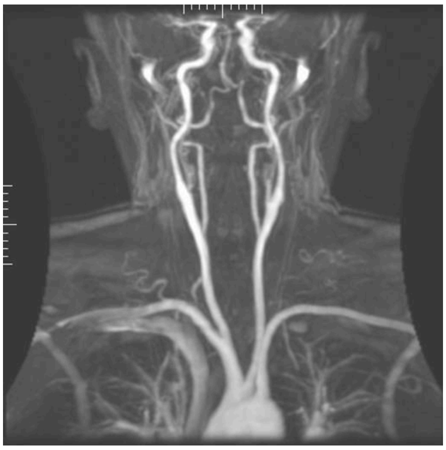


Cardiac Imaging:

MRI can be used to complement other imaging techniques to assess the structure and function of the heart.

Angiography:

Apart from viewing the nervous system, MRI is also able to provide images of arteries for diagnosis of aneurysms which is the dilation of a vessel wall. A paramagnetic contrast agent (normally gadolinium) can be administered to the patient in order to enhance the images produced for a clearer picture.



where does it belong in clinical workflow, the standards applicable and measures taken to ensure privacy and security of data

Clinical Workflow:

MRI belongs in the recording of patient's vital and patient's assessment and reviewing of results. MRI scans are used to detect abnormalities in the body such as tumours, infections or brain injury so it's essentially recording of the patient's vitals. The image produced from an MRI scan is used for diagnosis for diseases and injuries so in the clinical workflow obtaining the results is the patient's assessment. The results obtained from the scan will be reviewed before communicating with the patient.

Privacy and security of data:

Anonymization: protection of data

It is a removal of a patient's private data from the record. This process ensures the patient's privacy is removed or/and modified so that it can no longer be linked or associated with the patient. The anonymized data can no longer be processed and used for identification through normal means by third party.

Pseudonymization: protection of data

It is the replacement of a patient's private data with artificially generated data with a look-up table as reference. Both the pseudonymized data and its look-up table are kept separately for further security. This ensures that the patient's private data are secured as this process requires both the changed data and its look-up table for identification and not only that, it also requires data manipulation,

Secure multi-party computation: protection of algorithm

Secure multi-party computation (SMPC) whereby processing is performed on encrypted data shares, split among them in a way that no single party can retrieve the entire data on their own. In the domain of medical imaging, SMPC can be employed to perform analyses on datasets completely in the encrypted domain and without otherwise perturbing the data. It can thus help to increase the effective amount of available data without revealing individual identities or risking information leakage.

Homomorphic encryption:

Homomorphic encryption is essentially cryptography which is considered the strongest form of data protection as the data is protected by a mathematical equation. The encryption is constantly updating over the neural network so the algorithm is always changing.

Algorithm software:

Some algorithm software are able to mask the individual's identity and their data associating with it by changing some of its values. However for neuroimaging of the faces can be hard for data masking as data and its quality will be diminished.

Data from MRI are protected through various means but for neuroimaging data from the MRI can be difficult to protect as there are facial reconstruction of an individual. To protect such data would mean removing part of the head in the image but this would cost diminishing results and inaccurate results. However to get accurate results would mean a tighter security of data as the neuroimage of an individual can be manipulated by a third-party.

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