REDVET - Revista electrónica de Veterinaria - ISSN 1695-7504
Vol 25, No. 1 (2024)
http://www.veterinaria.org
Article Received: November 2023 Revised: December 2023; Accepted: January 2024

Spatial Encoding (Localization of signal) in Magnetic Resonance Imaging (MRI)- A Review

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Abstract:
Magnetic Resonance Imaging (MRI) is a vital diagnostic tool in medicine, providing clear images of the body's internal structures. A key component of MRI is signal localization or the spatial encoding of data. Signal localization refers to the ability to map the MRI signals to precise anatomical locations, which is essential for accurate image reconstruction. Unlike in CT and plain films in which localisation of the signal is simple (an x-ray beam travels through the patient and then detected by the detectors) MRI is much more complicated. With MRI the signal is localised in the 3D space by manipulating the magnetic properties of the nuclei in a predictable way. The signals are then returned with a particular frequency and phase and these are slotted into their respective locations. The MRI system locates signal, so that it can position each signal at the correct point of the image.

Introduction:
Magnetic Resonance Imaging (MRI) is a non-invasive imaging technology that has revolutionized medical diagnostics since its development in the 1970s. MRI produces powerful magnetic field and radiofrequency (RF) waves to produce detailed images of internal structures within the human body, providing essential information for the diagnosis and monitoring of various medical condition. MRI works on the principle of Nuclear Magnetic Resonance. (1)
MRI technology relies heavily on spatial encoding, to accurately locate images of the anatomy being examined, spatial encoding or signal localization process involves translating signals from tissue into precise spatial coordinates using encoding techniques. Encoding techniques alter and encode the signals into spatial coordinates, by mapping the radiofrequency (RF) signals—which are released by tissue in reaction to applied magnetic fields—to particular spatial positions within the body, this method enables MRI scanners to produce precise images.(2) Understanding how these signals are localized and are encoded is crucial for enhancing resolution, accuracy and speed, ultimately this all improves the clinical diagnosis.

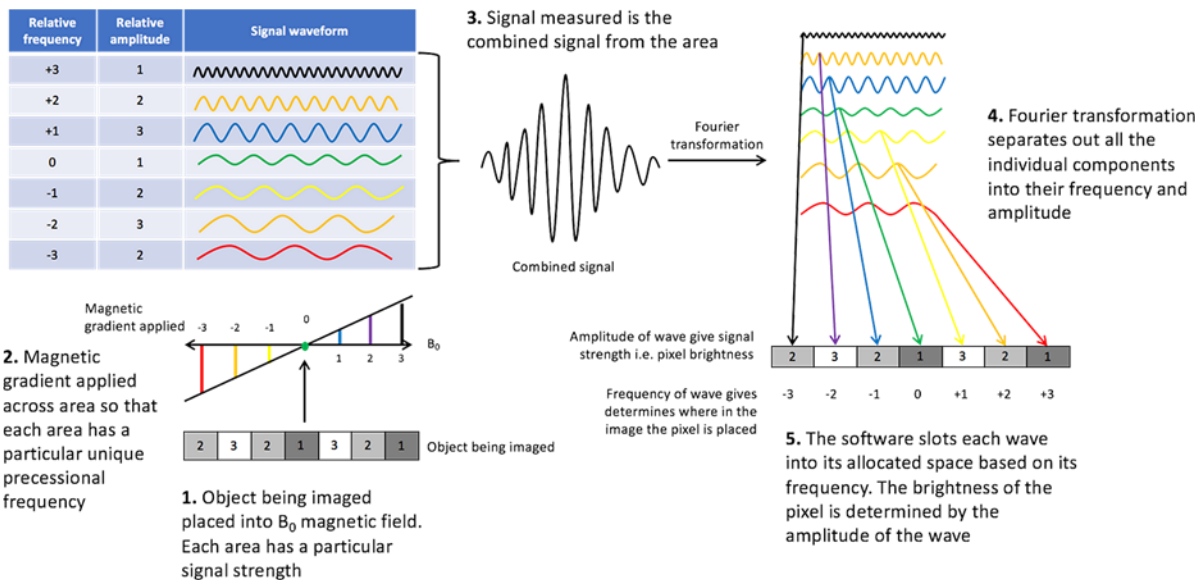

Fig: Spatial Encoding

To accurately place each signal at the appropriate location on the image, the MRI system must be able to find signals spatially in three dimensions. The all process of signal encoding includes three steps, the first one begins with the selecting

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a specific slice. After selecting a slice, the signal is encoded along the image's two axes. To achieve this localization, gradients field is produced by gradient coils, that alter or modifies the main magnetic field. Gradients play important role in the signal localization, making it impossible to locate the signals without them(3).

Gradients

Gradient or gradient coils are used to alter the magnetic field strength over the magnetic field. Gradient coils are situated inside the magnet's bore that allow current to flow through them and the gradient field is produced. This field either increases or decreases the primary static magnetic field B0. The gradient coils change the magnitude of B0 in a linear fashion, allowing for the prediction of the magnetic field strength and, consequently, the precessional frequency experienced by nuclei located along the gradient's axis as the gradient field increases the precessional frequency of all those nuclei increases i that area and where the gradient field is low the precessional frequency of all nuclei decreases. These magnetic fields have different strength in varying location hence these fields are called gradient fields or gradient.(4)

Three gradient coils are situated inside the magnet's bore and are named after the axis that they act along. To pinpoint the location of the body signal, these magnetic fields are superimposed on the main magnetic field along the X, Y, and Z direction. The middle of the axis of all three gradients remain at the field strength that is equal to main magnetic field ad is known as the magnetic isocentre.

Gradients perform the following three main tasks in spatial encoding.

- Slice selection- locates slice within the region of interest selected.
- Frequency encoding- spatially locating signal along the long axis of the anatomy of the slice that is selected.
- Phase encoding- spatially locating signal along the short axis of the anatomy of the slice that is selected.(5)

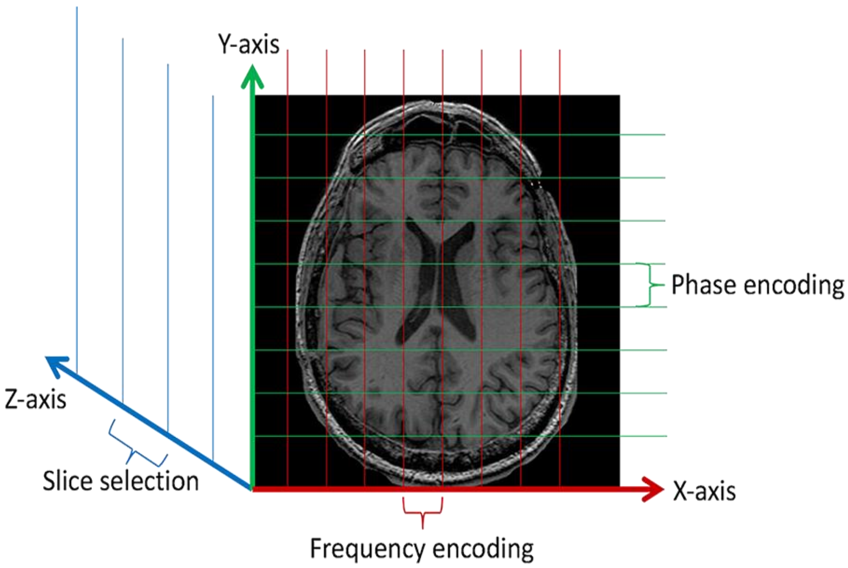

Fig: frequency and phase encoding gradients

Slice Selection:

The slice selection is the process of separating a particular slice or selecting a single slice in the region of interest, it is done by turning ON the gradients once the gradients are turned ON a specific point along the axis of the gradient has specific precessional frequency. Focused imaging is made possible by applying a selective radiofrequency (RF) pulse at this frequency, which only excites the spins inside the targeted slice all other slices remain unaffected and that is how the particular slice is selected. Also the gradient's slope indicates the slice thickness in the image, a steep slice slope is used to create thin slices, and a shallow slope is used to create thick slices.(6)

Frequency Encoding:

The signal now coming from a chosen slice needs to be located along both of the image's axes. The signal is usually located along the long axis of the anatomy by process called frequency encoding, once the frequency encoding is turned ON, the magnetic field strength, and therefore the precessional frequency of signal along the axis of the gradient, is altered in a linear fashion. The gradient therefore produces a frequency difference or shift of signal along its axis and the signal can now be located along the axis of the gradient according to its frequency. The Frequency Encoding is also called the Readout Gradient.(7)

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• The long axis of the anatomy in coronal and sagittal images lies along the Z axis of the magnet and therefore the Z gradient performs the frequency encoding.
• The long axis of the anatomy in the axial images usually lies on the horizontal axis of magnet and therefore X gradient performs frequency encoding, also while imaging the head the long anatomical axis lies along the anterior posterior axis of magnet so in this case frequency encoding is performed by Y gradient.

Phase Encoding:
The signal must now be located along the image's remaining axis that is short axis of the slice and this localization of signal is known as phase encoding. Once the phase encoding gradient is turned ON the magnetic field strength is altered along the short axis of slice and therefore the precessional frequency of nuclei gets altered. The speed of the precession of nuclei changes, so does the accumulated phase of the magnetic moment along their precessional path. Phase encoding gradient is turned ON after the application of excitation pulse. The degree of the phase shift between the two points along the gradient is determined by the steepness of the slope.(8)
• The short axis of the anatomy in coronal images lies along horizontal axis of magnet therfore X gradient performs phase encoding.
• The short axis of the anatomy in sagittal images lies along vertical axis of the magnet therefore Y gradient performs phase encoding.
• The short axis of the anatomy in axial images usually lies along the vertical axis of the magnet, therefore phase encoding is performed by Y gradient, also while imaging the head the short axis of the anatomy lies along the horizontal axis of magnet and the X gradient here performs phase encoding.

Conclusion:
Magnetic Resonance Imaging (MRI) is a sophisticated and non-invasive diagnostic tool that relies on the principles of spatial encoding to generate accurate and detailed images of internal structures. The process of signal localization is crucial for MRI, as it enables the system to assign signals to their respective anatomical locations in a three-dimensional space. This localization is achieved through the use of gradient coils, which modify the magnetic field in a predictable manner, allowing for precise control over the frequency and phase of the signals emitted by the body's nuclei. The three main tasks of the gradient coils—slice selection, frequency encoding, and phase encoding—are fundamental to spatial encoding. Slice selection isolates the desired slice from the body, while frequency and phase encoding allow for the spatial localization of the signal along the long and short axes of the selected slice, respectively. These techniques work together to produce high-quality images with accurate spatial representation, improving diagnostic accuracy. Understanding the role of gradients and how they contribute to spatial encoding is essential for optimizing MRI resolution, accuracy, and imaging speed. As MRI technology continues to evolve, ongoing advancements in gradient design and spatial encoding methods promise even better imaging capabilities, further enhancing the clinical value of this indispensable diagnostic tool.

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