

Principle and optimization analysis of electromagnetic devices for MRI

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Abstract. Currently, with the significant increase in global health awareness, people are paying more attention to various aspects of their health, thereby driving the demand for various types of medical devices. As an important medical diagnostic tool, Magnetic Resonance Imaging (MRI) has become more widely used in disease diagnosis. This paper primarily explores the basic working principles of MRI, its optimized design, and the challenges and prospects for its future development. First, the paper introduces the basic working principles of MRI's electromagnetic apparatus, explaining the structure and functions of its five main components: the main magnet, gradient coils, radio frequency system, computer system, and magnet room, as well as how electromagnetic signals are used for imaging. Secondly, the article discusses the optimization of MRI in terms of structure, materials, and algorithms, aiming to improve the uniformity of magnetic field distribution, the accuracy of signal processing, and overall image quality. Finally, the paper analyzes the challenges facing the future development of MRI, such as high costs, complex equipment structures, and limited algorithmic technologies, and it looks ahead to the potential for achieving more efficient and broader applications through technological advancements.

Keywords: Magnetic resonance imaging; principle; optimization; challenge and prospect.

1. Introduction

Currently, there has been a significant increase in health awareness. People are paying more attention to all aspects of their bodies, so the demand for various medical instruments is increasing. As a type of medical instrument, MRI is more widely used in scanning human bodies to diagnose diseases like cancers [1].

This essay mainly explains 3 aspects. The first aspect, basic working principles of electromagnetic devices for MRI, the various electromagnetic principles are introduced based on the structure of the 5 main component and respective functions to form images. Basic principles are introduced from the general operating principles to the principles of each part individually, for example, from the processes of formation of magnetic field, magnetic field gradient to the method of shielding from external magnetic fields and the way how to process the electromagnetic signals and form images. The second aspect, the optimization in design of MRI, including the optimization of the structure and material of the instrument and the optimization of algorithm. The optimization of structure and material is mainly to optimize the magnetic field distribution. The optimization of the algorithm is mainly to optimize the algorithms used in the computer system in processing signals and forming images. The last part, challenges and prospects in the development of MRI, shows the complex situations that will meet in the future development of MRI such as current constraints affecting development and the solutions.

2. Basic working principles of electromagnetic devices for MRI

2.1. General operating principle

MRI is a cylindrical medical instrument and it can create a strong magnetic field around the subject. MRI is also a medical imaging technology based on the principle of nuclear magnetic resonance and mainly used in imaging diagnostics. The human body contains lots of water and hydrocarbons, so hydrogen nucleus is chosen as the element for imaging. A radio frequency (RF) pulse of a specific

frequency is applied to the human body in a static magnetic field, so that the hydrogen nuclei in the water in the human body are stimulated by it to undergo nuclear magnetic resonance and release radio waves that can be received by MRI. Since this signal has different attenuation in different structural environments in the body, it can be detected by an external gradient magnetic field, which can be reconstructed and mapped into an image of the internal structure and function of the human body.

The MRI instrument mainly includes 5 parts, the main magnet around the table that patients lie, the gradient coil, the RF system, the computer system and the magnet room. The structures except the computer system and the magnet room are shown in Fig.1.

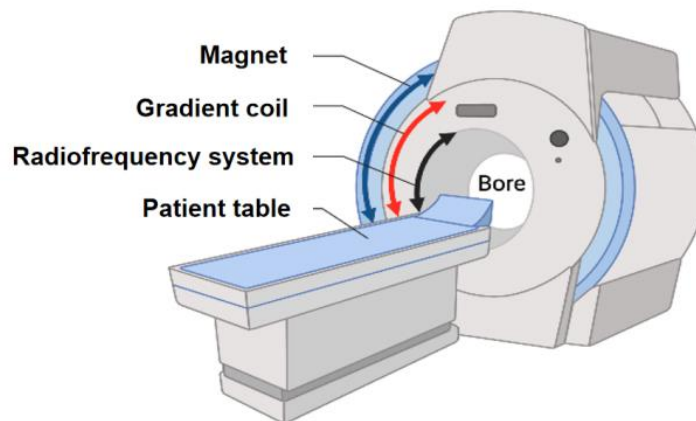


Fig.1 Overall structure of MRI instrument

The main magnet around the patient table is used to form a strong magnetic field around the patient. The gradient coil spatially localizes the nuclear magnetic resonance (MR) signal. The RF system in MRI plays a crucial role in exciting the nucleus and detecting the resulting signals. And it consists of 2 types of coils, the transmitting and receiving coils. The computer system plays the role of both controlling the MRI instrument and processing signals to form images. The magnet room isolates the MRI instrument from the external environment to protect the external from the strong magnetic field.

During the whole process of MRI, some basic physical principles are used, such as Faraday's Law of electromagnetic induction, basic principle that causes resonance, magnetic dipole interaction and signal amplification and filtering. For example, in the process that the oscillating magnetic field produced by the RF pulse induces an EMF in the surrounding conductive tissues to excite the hydrogen nucleus, Faraday's law is used.

2.2. The main magnet

The magnet is the central component of MRI, which is critical in imaging. At the heart of the MRI machine is a strong superconducting magnet, which generates a strong and stable magnetic field, typically ranging from 1.5 to 3 Tesla, though the advanced systems can reach up to 7 Tesla or higher. Compared with the Earth's magnetic field that is about 5×10^{-7} Tesla, the magnetic field formed around the table by the magnet of MRI is much stronger.

The primary role of this magnet is to adjust the magnetic moment of hydrogen nuclei within the body. Hydrogen nuclei are abundant in the human body due to the high content of water and hydrocarbons like fat. When there is not an external magnetic field, these protons are oriented randomly. But when placed in a strong magnetic field, the protons align with the field, either parallel or anti-parallel to the direction of the magnetic field. This alignment creates a net magnetization vector in the same direction as the magnetic field.

2.3. The gradient coil

In MRI, gradient coils are essential components which enable spatial encoding of the magnetic resonance signal, thus allowing for the formation of detailed images of the structures of tissues in human body. The spatial encoding is crucial in forming the 2-D and 3-D images and multidimensional

nuclear magnetic resonance spectra [2]. The structure and function of the gradient coils are integral to the MRI's ability to produce enough accurate and high-resolution images.

For forming a 3-D image, the gradient coils are composed of 3 sets of coils, including X-axis gradient coil, Y-axis gradient coil and Z-axis gradient coil. They are separately responsible for generating 3 different directions of gradient, left-right, front-back and head-foot directions. Each set of coils is embedded within the bore of the main magnet. The design of these coils involves complicated winding patterns of wire, usually copper, which are optimized to produce the desired gradient fields while distortions and power consumption are minimized.

The main function of gradient coils is to superimpose a linearly varying magnetic field onto the uniform magnetic field generated by the main magnet. And this linear variation in the magnetic field is exploited in the spatial encoding of the MRI signal.

2.4. The RF system

In MRI, the RF system serves two critical functions: the excitation of hydrogen protons and the detection of emitted MR signals. It is composed of RF transmitter that sends the RF pulses to excite hydrogen nucleus in the body and RF receiver that detects the signals emitted by the excited protons as they return to their equilibrium state.

Once the protons are aligned caused by the presence of the main magnet, the MRI machine uses RF pulses to disturb this alignment. The RF pulses are delivered at the Larmor frequency, which is specific to the strength of the magnetic field formed by the magnet and the type of nucleus being targeted. For hydrogen nucleus in a 1.5 Tesla magnetic field, the Larmor frequency is about 60 MHz. So, the RF pulses excite the protons, causing them to absorb energy and turn into a higher energy state. When the RF pulse is turned off, the protons begin to relax back to their original alignment, a process during which they emit RF signals.

These emitted signals are detected by the RF receiver and then processed by the computer system into digital signals and data to form images. The relaxation of protons occurs in two mechanisms including T1(longitudinal) relaxation and T2(transverse) relaxation. T1 relaxation is the recovery of longitudinal magnetization, while T2 relaxation is the loss of coherence among spinning protons in the transverse plane. The rate at which these processes occur varies when different tissue types, allowing MRI to differentiate between different structures of the body. Relaxation means the process of returning to the magnetic moment state from the stable high-energy state due to the magnetic resonance of the hydrogen nucleus.

2.5. The computer system

The computer system has two important functions in MRI. One is to control the movement and switching of the hardware of MRI, and the other is to process the collected data and form images.

The computer system precisely controls the MRI scanner's hardware components, including the main magnet, the patient table gradient coils and RF coils. This part involves managing the timing and strength of the gradient fields and the transmitting of the RF pulses to make sure that the spatial encoding and signal acquisition are accurate to ensure the accuracy of the images.

The computer system is also responsible for digitizing and processing the RF signals detected by the RF coil. It will use a series of complicated algorithms to change digitized signals into pixel data to form images and further refine the data to enhance clarity and resolution.

2.6. The magnet room

The magnet room is a space that is specially designed to house the MRI. Its main functions include ensuring patient safety, optimizing image quality, and protecting both the equipment and the external environment from the strong magnetic fields generated by the MRI system that is much stronger than the earth.

The magnet room is composed of different magnetic shielding materials, such as steel or mu-metal, to contain the strong magnetic fields produced by the MRI magnet. This prevents interference with

electronic devices that people outside carry with and ensures that the magnetic field remains stable and focused within the imaging area and MRI cannot be interfered by other electromagnetic signals. Moreover, the walls, floor and ceiling of the magnet room are also lined with conductive materials, mostly copper or aluminum, creating a Faraday cage. This RF shielding that also exists between the gradient coils and RF coils prevents external RF signals from interfering with the MRI and ensures that the RF pulses generated by the MRI scanner will not propagate out of the room to keep the integrity of the imaging process [3].

3. Optimization in design of MRI

3.1. The optimization of structure and material

When optimizing MRI, different components of MRI can be optimized such as the main magnet, the gradient coil, the RF system and cooling system. And the main method of optimization is topology optimization to optimize the structure and the material used.

The main magnet is important in imaging. Using topology optimization techniques, the optimal material distribution and structural layout can be found when designing the main magnet to make the uniformity and stability of the magnetic field maximized. This optimization helps to reduce the non-uniformity of the magnetic field, improving the overall quality and accuracy of the image.

The RF coils are used to transmit and receive RF signals, so their design is critical to imaging quality. Topology optimization can help design a more uniform electromagnetic field distribution, which can improve signal reception sensitivity and imaging uniformity. For example, by optimizing the structure of the RF coil, it is possible to reduce the dead zone of signals and improve their signal-to-noise ratio, which in turn enhances the contrast and clarity of the image. To optimize RF coil geometry, a simulation method that employs a genetic algorithm is applied to maximize signal intensity [4].

The operating of the gradient system is the most critical aspect in the process of MRI. The geometry of the gradient coil can be optimized by topology optimization to make it more efficient in volume and material usage. This optimization not only improves the performance of the gradient coil, but also reduces unnecessary current loss and heat generation, improving the overall system efficiency and stability. Because the pulse currents in the gradient coils in the MRI device will introduce the effect of eddy currents in ferromagnetic material and the quality of imaging will be worsen, the density method is adopted for topology optimization [5].

Wu, a PhD in China, proposes a method of optimization of the solenoid and coils. In his thesis, a type of optimization of current core using integration is proposed to achieve the requirements of high-precision magnetic field calculation. A semicircle and double center electromagnetic integral strategy is devised to effectively solve the turn-to-turn transition deviation of calculation for magnetic field. He proposes the MRI winding. The MRI winding mainly consists of the layer winding solenoid structure with the compensation coil and the separate multiple coils and the mixture of the two structures. On the one hand, it decreases the mechanical stress and strength requirements of structure. On the other hand, it simplifies the difficulty of winding to balance and the economic risks. The uniformity and accuracy of magnetic field formed by coils are improved when the multi-layer coils form base magnetic field, compensate for the inhomogeneity of the base magnetic field and reduce the influence of the stray magnetic field [6].

At last, the high-power operation of MRI systems will produce a lot of thermal energy, so an effective heat dissipation system is the key to ensure stable MRI operation. Topology optimization can help design more efficient heat dissipation structures by optimizing the layout of heat sinks and cooling channels to improve heat dissipation efficiency. This not only improves the operational stability of the system, but also extends the service life of the equipment.

3.2. The optimization of algorithm

In MRI, various algorithms and other AI technologies are used to improve the quality, speed and diagnostic capabilities of MRI. The algorithms are used and are important in each link, mainly in the process of imaging.

Firstly, in noise reduction, various filtering algorithms, such as Gaussian, weighted mean and bilateral filters, are used to remove noise that is mainly the static noise in the radio signals produced by hydrogen nucleus from the images to reduce the signal-noise ratio [7]. The filter algorithms after optimized can help clear the noise up more thorough so that the images will be sharper and more accurate.

Then during forming images, there are several steps, including image reconstruction, artifact correction, segmentation and classification [8, 9]. In image reconstruction, there are two fundamental algorithms, Fourier Transform and compressed sensing. Optimized Fourier Transform converts raw data from the frequency domain into spatial domain images, allowing the doctors to see more detailed structures of the body [10]. Compressed sensing allows for the reconstruction of images from fewer data points, so after optimizing, the scan times can be reduced while maintaining image quality. In artifact correction, motion correction algorithm is used and it can detect and correct blurring and artifacts caused by patient movement on the patient table. The same as before, being optimized can enhance the accuracy and stability of images. What's more, in segmentation and classification, better algorithms can help the computer system better segment and classify different tissues and abnormalities in the images to help doctors make more accurate diagnoses. Of course, the algorithm is optimized to improve the diagnostic accuracy, and initially the algorithm is generated to optimize MRI.

4. Challenges and prospects in the development of MRI

4.1. Challenges

With the present state of technology and the level of medical care in some areas, the MRI instruments are not easy to mass produce and spread to some poorly developed areas, such as the rural areas. MRI instrument is large and complex equipment, so MRI requires a very large amount of money to develop, optimize and produce. So, MRI instrument costs a lot. Moreover, MRI instrument requires specially designed rooms to house, known as magnet rooms, to operate safely and effectively. Due to the working principles in the whole process, the need for magnetic and RF shielding, as well as precise environmental control, adds to the complexity and expense of setting up an MRI facility. However, in the rural areas, they are lack of funds to buy MRI and have little space in the hospital to keep MRI instrument.

Besides the challenge above, it is also a challenge that the immaturity of algorithms and other technologies is not yet able to make a diagnosis with sufficient accuracy through MRI. Images formed by MRI still suffer from artifacts caused by the movement of patients, hardware limitations and external magnetic interference. Also, there are a few reasons that are rare to meet. For example, the process is uncomfortable for some patients who are claustrophobic or have difficulty remaining calm.

4.2. Prospects

Corresponding to the challenges, many aspects can develop mature. With the high rate of development in medical technology, the structure of the MRI instrument in the future will be less complex, and at the same time, it will become smaller and easier to move. This may revolutionize how and where MRI is operated, making it available in more remote or resource-limited settings.

The improvement of MRI can improve patients' comfort by reducing the scanning time and the noise produced. And more advanced algorithms will enhance the accuracy of images and diagnosis. Because the development of artificial intelligence and machine learning technology still have a lot of development space, more advanced machine learning technology can be used in MRI by collecting

all kinds of case and analysis of various images to analyses the image formed by big data. Through similar cases and the corresponding treatment plan, the computer system can find out the problem within the human body and put forward reasonable treatment plans. This can help doctors to make a deeper and more accurate diagnosis [11].

5. Conclusion

MRI is an important medical instrument in medical diagnosis. In reality, MRI is a very complex and delicate instrument and an advanced technology. However, the working principles and basic structure can be described and explained in a relatively simplified way. Moreover, in the process of optimization, various ways are effective to be used not only in optimizing structure and material but also in optimizing algorithms to process information. Besides, in the future development of MRI, the researchers will face different types of challenges due to the insufficiently mature technology but as the development progresses, various obstacles will be overcome. This paper is mainly based on reading a lot of literature and consulting a lot of sources. After having access to more in-depth research experiments, all the content will become professional and detailed enough and be more well demonstrated.

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