Principle, the State-of-art Facility and Application of MRI

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Abstract. With the continuous development of science and technology, human beings have higher and higher medical needs, but in the past, people did not have a deep understanding of MRI. This article intends to use the survey method to explore MRI, hoping to promote people's understanding of MRI. The main direction of this research article is the principle and application of MRI. This article is divided into 6 main parts. The first part introduces the development history of MRI and the research progress in recent years. The second part explains the components and the types of MRI. The third part analyzes the principle of MRI. The fourth part introduces the latest MRI with the instrument equipment and parameters. The fifth part analyzes the main application range of MRI, and the sixth part explains the current limitations of MRI. Through the research on MRI, we found that the current MRI has limitations, and the high cost also makes some patients daunted by MRI. These results offer a comprehensive discussion for MRI, shedding light on guiding further exploration of MRI.

Keywords: MRI, medical facility, Surgery.

1. Introduction

The predecessor of the MRI was called the NMR (nuclear magnetic resonance), which was first developed by a physics professor from Columbia University. The NMR was invented to measure the movement of atomic nuclei. In the 1971 a doctor who names Raymond Damadian concluded that by scanning a part of the human body in radio waves might detected out the cancerous tissue from the healthy tissue because that they contain different amount of water. At the same time Peter Mansfield who was a physicist in England was working hard to shorten the time that a complete scan needs. By using a new technique called line scan imaging, in 1974 he achieved to capture pictures of a finger in only 15-23 minutes rather than in hours. This was the first time a person can successfully using NMR to can a human body part. In 1977 the first whole-body human scanner was created by Damadian [1]. Nowadays, the MRI is used widely in the medical field. It can provide high detailed internal human body, including cancers, tumors, anomalies of the brain and spinal cord, injuries of the joints etc. [2].

The MRI techniques have been improved in recent years, including data acquisition, image reconstruction, and hardware systems. New technologies that have been developed are also being introduced into the MRI technology. With the help from computer science, it now provides a large data set of functional anatomical images. Just after the first MRI was launched in 1977. In 1980s the 1.5T clinical MRI was introduced as a commercial clinical system. After 20 years of researching, clinical MRI 3T systems received regulatory approval and was launched in the early 2000s. At the time, the expected clinical applications of 3T were higher spatial resolution imaging and faster imaging. The 3T whole body system (for humans) was subsequently developed and commercialized. The 3T system became popular in the late 2000s. Major MRI manufacturers started developing 7T system for the human body since the early 2000s when the 3T system was introduced, the 7T system was being put to operation in the mid 2000s. At the end of 2020, several MRI manufacturers have been regulatory approved for their 7T systems. The 7T system is advantaged in higher SNR ratio related to field strength and high spatial resolution imaging is one of the potential applications [3].

This study will investigate the current development and limitations of the MRI and the future trends of he MRI system. In the next part we are going to talk about the the principle facility as well as the classification of the MRI. We will also discuss the application of the MRI, one is about the application in the medical field, and another two applications applied in the chemical analysis. In application part we will look into the limitations and future outlooks of the two areas that the MRI is applied in.

2. Basic Description of MRI

Magnetic Resonance Imaging (MRI) is a medical imaging technique which can be used in radiology to create images of the human body's soft tissue and hard tissue. MRI employs a linear gradient field and a radio-frequency pulse of a certain frequency to conduct spatial placement of biological tissues. In an excited state, biological tissues absorb the energy of the RF pulses. When the RF pulses are removed, coils receive magnetic signals from biological tissues for imaging purposes [4]. The brain, chest, belly, bones, joints, and other organs in the human body, as well as other tissues, can all be clearly seen in high-resolution images obtained from an MRI scan. In addition, MRI has the characteristics of no ionizing radiation, high safety, and good resolution of soft tissue. Due to its widespread usage in medical diagnosis, research, and surgical planning, MRI enables medical professionals to identify and assess a wide range of illnesses, birth defects, and wounds.

The main magnet, gradient coils, radio-frequency coils, computer and image processing equipment make up the majority of an MRI system. The main magnet, which generates a strong constant magnetic field is what makes up the MRI system. For MRI scans, the main magnet generates a powerful magnetic field that is commonly 1.5 Tesla or 3.0 Tesla. The magnetic field's intensity affects image quality and the ability to see tiny details in structures. In the main magnet are gradient coils which provide auxiliary magnetic fields that can modify the strength of the magnetic field in space. To obtain images of particular regions, gradient coils are employed for positioning and spatial coding. The signal's encoding into a spatial position in the image can be altered by adjusting the gradient coil's current. A tool for transmitting and receiving radio frequency pulses is a radio-frequency coil. Radio-frequency pulses are produced by the sending coil and utilized to activate atomic nuclei in the target object, in this case, human tissue. The resonant signal from the item being watched is picked up by the receiving coil, which then transforms it into an electrical signal for computer processing. MRI systems also include computer systems and image processing equipment that control the scanning process, process imaging data, and generate images. This system performs complex image reconstruction algorithms that turn the collected signals into images of the inside of the human body.

MRI can be typically categorized into three types which are based on the various characteristics of the magnets utilized: permanent magnet MRI, resistive magnet MRI, and superconducting magnet MRI. In general, the magnetic pole of the permanent magnet is spliced with oriented magnetic blocks, and the magnetic flux circuit is composed of ferromagnetic materials with high permeability to improve the field strength [5]. Permanent magnet MRI has lower maintenance cost and smaller size. However, the magnetic field strength of permanent magnet MRI is relatively low, generally between 0.2 and 0.4 Tesla (T). The resistive magnet MRI system uses a resistance coil as the main magnet. These coils are made of resistive materials that generate a magnetic field through an electric current. The main magnets in superconducting MRI systems are superconducting coils. These coils are constructed from superconductors, which can enter a superconducting state at low temperatures and flow current with no resistance.

The main magnet is a very important part of the MRI system. Its main role is to provide a stable, uniform space magnetic field environment. On the other hand, according to the magnitude of the magnetic field strength, MRI equipment can also be classified as low field MRI with less than 0.5 Tesla magnetic field strength, middle field MRI with a magnetic field strength between 0.5 and 1.0 Tesla, high field MRI with a 1.0 to 2.0 Tesla magnetic field strength and ultra-high field MRI with a larger magnetic strength.

3. Principle of MRI

MRI is a kind of nuclear physical phenomenon. It is a processing technology that makes use of the nucleus and the signal it emits when the magnetic field resonates, reconstructs the signal, and then uses computer space coding to create an image. In other words, the spinning hydrogen nucleus (H+) in human tissue is vibrated by a magnetic field and a radio frequency pulse to produce radio-frequency signals, which are subsequently photographed by computer processing [6].

There are a lot of water that contains hydrogen atoms with proton in human tissue. These protons bring positive charges and spin irregularly at high speed. By using right hand, one can know that the spin of a charged proton like a charging coil creates a magnetic field. Normally the orientation of these protons is random which forms an irregular magnetic field. These magnetic fields with all directions cancel each other out resulting in a close to negligible total field strength. However, when a person enters an MRI scanning machine, these protons are in the strong magnetic field generated by the scanner. In an applied magnetic field, most protons produce magnetic fields in the same direction as the applied magnetic field, and these protons are called low-energy protons. However, there are also a small number of protons that produce magnetic fields in the direction opposite to the applied magnetic field, and these protons are called high-energy protons. These two types of protons cancel out, but because of a larger number of low-energy protons, the resulting magnetic field is still in the same direction as the external magnetic field. At this time, the proton still spins and does the motion along or against the direction of the magnetic field in the meantime [7]. The motion in which the two movements are performed simultaneously is called precession. The spin of the hydrogen proton can be viewed as the Earth's rotation, while the precession is similar as the revolution of the Earth (a sketch is shown in Fig. 1).

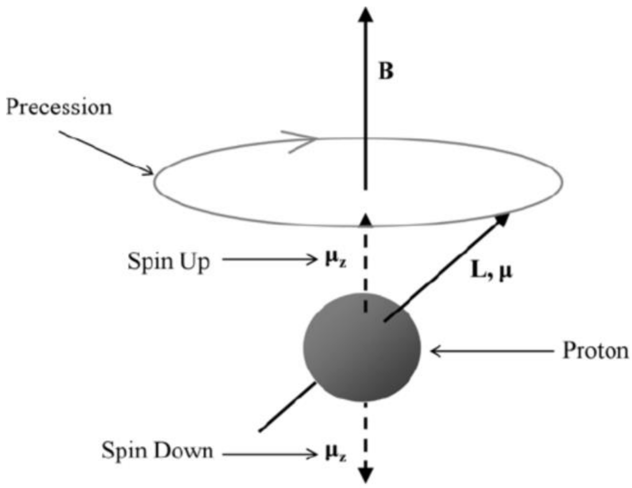

Figure 1. A sketch of the precession

In the equilibrium state, most of the proton direction and the direction of the applied magnetic field are the same (longitudinal magnetization). Because of the different phase, only longitudinal magnetization is generated on the macro, and no transverse magnetization is generated. The RF system then emits RF pulses that excite the imaging area. The frequency of the radio frequency pulse emitted by the radio frequency system needs to be consistent with the precession frequency of the proton, and resonance (nuclear magnetic resonance) will occur. There is a transfer of energy, the proton that gains energy transitions from a lower energy level to a higher energy state which causes the longitudinal magnetic field strength to decrease continuously. At the same time, all the protons with the same frequency that absorb energy become attractive with each other and share the same phase. This time, transverse magnetic field strength continues to grow.

Afterwards, the RF pulses disappear, and these resonant H atoms slowly return to their original direction and amplitude, which is called relaxation. The relaxation process consists of the recovery of longitudinal and transverse magnetization vectors (seen from Fig 2). The time called T1 is the period required for longitudinal magnetization to come back to 63% of the equilibrium state strength, and transverse magnetization from the maximum is reduced by 63% in the time taken to T2 [8]. The relaxation time is related to the proton density, and the T1 and T2 values of different tissues vary greatly. During the recovery process, the energy released by the excited proton forms a magnetic resonance signal. Then the computer system will receive these signals. For T1 and T2 images, the longer it takes, the stronger the signal. Finally, according to the intensity of the conversion to black and white gray scale, so as to draw the image. A stronger signal will be presented by a brighter the image, and a weaker signal will be presented by a darker the image [9].

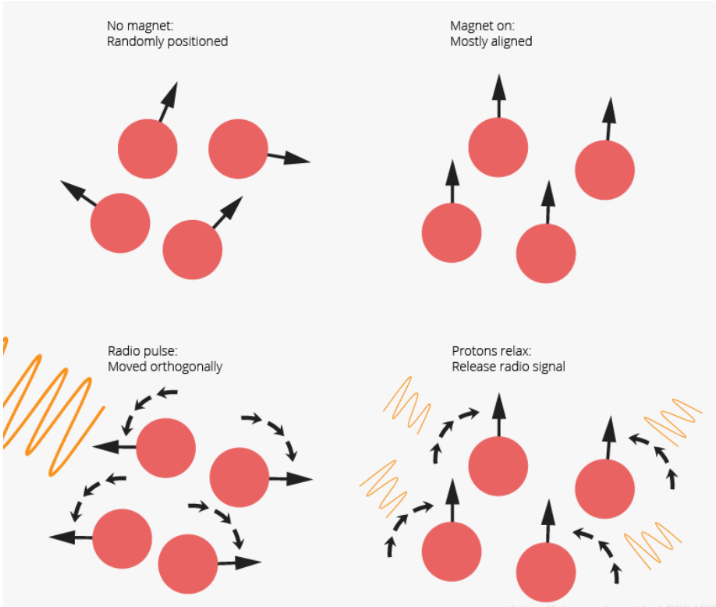

Figure 2. Principle of proton relaxation

4. Facility

Nuclear Magnetic Resonance (NMR) was discovered in 1946 by American theoretical physicists Felix Bloch and Edward Purcell, but NMR was not of interest to chemists until 1949 and 1950, when it was discovered that the precise frequency of NMR relied on the chemical environment in which the nucleus was placed [10]. Prior to 1972, NMR was mainly used as an analytical tool, but in 1967, Jasper Johns and others successfully detected the distribution of hydrogen, phosphorus and nitrogen signals in animals, ushering in a new era of NMR chemical analysis of biological tissues [10]. Medical imaging became possible because to experimental investigations on local imaging of living tissues conducted by physicists and medical scientists between 1973 and 1978 [10]. After 1978, the stage of comprehensive development of magnetic resonance imaging technology and in about 1980, thanks to the investment costs of many countries and companies, the medical application of MRI was promoted and the cost was greatly reduced [10]. These are the history and development of MRI. These years, MRI technology is also constantly evolving and advancing, and in this part, we will introduce Deep Learning MRI technology and facility which is better than traditional MRI construction methods.

With the development of MRI technology, its application in clinical disease diagnosis is more and more extensive, but MRI based on traditional reconstruction methods is faced with difficulties and challenges that imaging time, image resolution and signal-to-noise ratio are restricted each other [11]. In recent years, the proposed Deep Learning MRI (DL-MRI) reconstruction algorithm has greatly solved the shortcomings of traditional reconstruction algorithms [11]. In May 2020, the US FDA for GE Healthcare gave permission to a DL-based convolutional neural network for reconstructing MR images on 3.0T systems called AIR™ Recon DL [12]. The FDA subsequently approved AIR™ Recon DL for 1.5T in September 2020 [12]. AIR™ Recon DL is a DL-based data reconstruction algorithm used to accelerate and improve image reconstruction during MRI. Traditional techniques for reconstructing MRI images frequently rely on intricate mathematical models and repeated calculations, which to some part restrict the speed and effectiveness of MRI scanning. However, AIR™ Recon DL can train neural networks to learn from and comprehend enormous volumes of MRI data by utilizing cutting-edge deep learning techniques. This enables quicker and higher-quality image reconstruction. AIR™ Recon DL creates high-quality MRI pictures based on neural network architecture by learning and reconstructing input low-resolution or partial data (seen from Fig. 3 and Fig. 4). While maintaining picture quality, our technique can drastically cut scanning time and increase clinical work efficiency. It can shorten scan times and increase patient comfort by reconstructing high-quality images from less raw data. In order to produce more precise and clearer rebuilt images, AIR™ Recon DL uses deep learning to learn patterns and characteristics from big data sets and then applies that information to fresh, previously unexplored data sets. This method can enhance image quality, lower noise and artifacts, increase visibility of small structures and damage, and aid in more precise diagnosis.

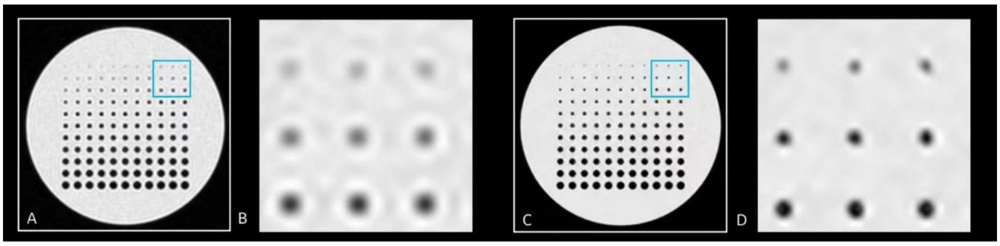

Figure 3. AIR™ Recon DL image compared to traditional algorithm image. (A, B) The image displayed by the traditional algorithm is fuzzy. (C, D) AIR™ Recon DL image is quite sharp

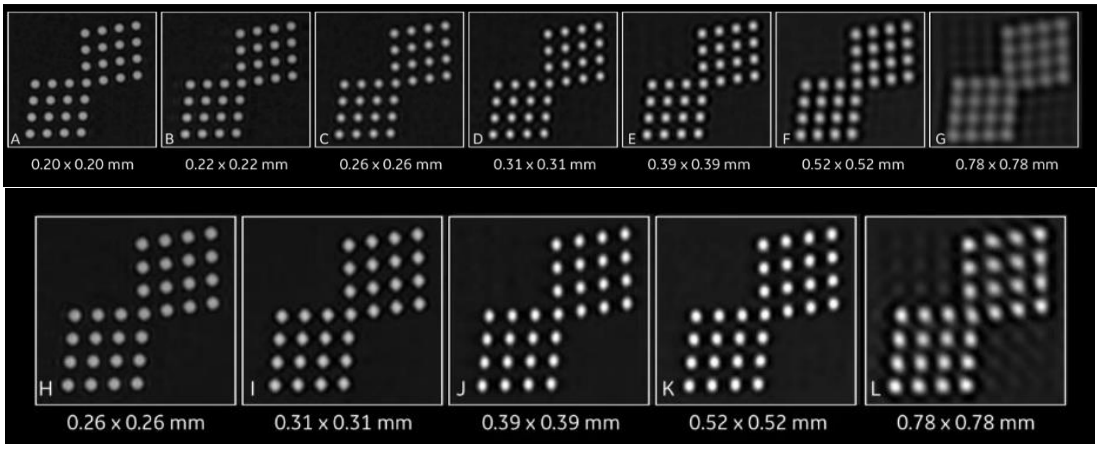

Figure 4. AIR™ Recon DL maintains image sharpness at a larger in-plane voxel size. (A-G) Traditional Algorithm Image (H-L) AIR™ Recon DL image

5. Applications

MRI can detect many types of ions, including sodium ion. This type of ion shows a significant role during the cellular physiological process. Since the Na ion exhibits a relatively low concentration in biological tissues, this results in the MR imaging often only obtaining low signal-to-noise and spatial resolution for relatively long imaging times. However, these drawbacks can be improved by using stronger magnetic fields as well as high-performance probes. The concentration of sodium ions in the tissues is rather sensible, with the extracellular concentration being ten times greater than the intracellular concentration. Magnetic resonance imaging of sodium ions could help doctors identify malignant tumors easily. To be more specific, it provides a non-invasive method of tumor classification. The doctors can use the imaging of sodium ion to study the differences between different grades of tumor and to find that the contrast-enhancing sodium signal in the tumor part, which favors the differentiation of most glioma types. Moreover, the imaging of sodium ion can also be a way for people to detect and prevent getting malignant tumor. The imaging of the sodium ions also provides a good way for doctors to better cope with these malignancies [13].

The abundant moisture of fresh fruits as well as the vegetables ensure a higher signals in the magnetic resonance imaging. This technology helps people know the ripeness of vegetables and fruits, which is much more accurate than observing by our own eyes. This thorny problem can be easily solved with MRI technology. Another feature of MRI technology applied to food is that there is no need to destroy the sample. The complete sample can be scanned, and the sample can still be eaten after scanning. To be more specific, let's use the tomato as an example (the Fig. 5 shows the imaging of the tomato). The change during the period of its ripeness is the color from green to red. Because the MRI can detect the moisture in the tomatoes, we easily found the main change of the tomato depends on season. It is evident that the moisture in tomato in summer is much more than in winter, which means the tomatoes are more likely to ripe in the summer. This discovery brings huge economic value, which also shows the importance of MRI technology [14].

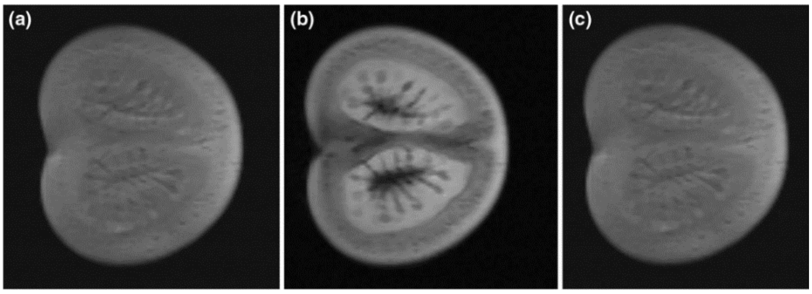

Figure 5. The MRI of a tomato

The nuclear magnetic resonance spectrum is sensitive to any disturbance in the chemical environment surrounding the atomic nucleus. It uses carbon-13 and fluorine to study the combination of the non-covalent pollutants to soil. These studies provide insight into the molecular circumstances of the pollutants, which can help in analyzing the soil composition of the pollutants. For example, measuring binding coefficients runs without any molecular-level information about the binding mechanism [15].

6. Limitations and Prospects

The cell structure in the whole body isn't perfectly the symmetrical permutation, which means the diffusion of the water molecule will be directional dependent. This effect requires a much more precise device to detect different direction so that we can gain a more accurate numeric value [16]. Besides, it is quite difficult to apply the MRI technology to the public due to its high operating cost. Additionally, the cost of MRI changes as the body parts change. If a full body examination is required, multiple payments are needed and the amount spent will bring huge medical burden to average families. As it known to all, prolonged delay in treatment deteriorates the disease badly. So, if there is an acute disease, it is necessary to know the situation immediately. Hence, doing the time-consuming MRI will increase the danger of the disease and prevent the patient from timely treatment. Moreover, before the MRI, the doctor will ask the metal objects to be removed from the body. Since the metal material will be absorbed by the instrument during the magnetic field scan, it'll cause damage to the instrument. Especially for patients who have metal braces and heart stents, these examiners will be injured and prone to have metal displacement.

As for the aspects of the future trend, as the cost as well as the practicality has access to a huge process, so the future trend of the cost will be much lower in the coming years, which means the accessibility would increase dramatically. Moreover, the better resolution and organize contrast will help doctor to detect the disease conveniently, thus increasing the significance of the MRI detection [17]. In addition, a newly advanced MRI scanner allows POC manipulation, which causes low power consumption and works with low noise, which promote the mobility. These properties also show the potential of the clinical application of the POC. This benefit can enlarge the access scope which can solve the lack of the underserved patient populations. With the combination of the MRI as well as the clinical application, this technology may provide valuable information for a patient's overall survival time in the future. This approach may help to select patients who are most likely to benefit from intensive diagnosis and treatment [18].

7. Conclusion

In conclusion, this article illustrates that the MRI's principle, facility, application, drawbacks as well as the future outlooks in various kinds of aspects. The facility as well as applications of the magnetic resonance imaging are mainly for the medical as well as the biological field. This article will help people have a deeper understanding of MRI and further popularize this technology. It also shows the disadvantages that the MRI exists today, but more benefits will be revealed in the future with the development of technology.

Author Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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