Principles of nuclear magnetic resonance and its applications in medication

Yijie Huang*
Beijing Luhe international Academy, Beijing, 100001, China
* Corresponding Author Email: 100536@yzpc.edu.cn

Abstract. There is no doubt that the Nuclear Magnetic Resonance is one of the most fascinating inventions in modern era. Nuclear magnetic resonance is the physical process of nucleus in the body, which align with the direction of magnetic field under the action of external magnetic field, resonant absorb the radio frequency pulse of a certain frequency. NMR spectroscopy is a branch of spectroscopy in which the resonant frequency is in the RF band and the corresponding transition is a transition of the nuclear spin on the magnitude of the nuclear energy. With its large-scale application in various aspects, people's life was facilitated greatly. In the field of medication, as a new imaging technique, it has no negative effect on human health, and high-resolution image could be produced without any radiation. Millions of patients and injuries could get the correct diagnosis and lead a healthy life later on thanks to it.

Keywords: Principle; Application; Nuclear magnetic resonance.

1. Introduction

In recent years, Nuclear Magnetic Resonance has been widely used in medical fields, it is a wonder of modern science, an extraordinary imaging technique. By using detected proton density of different regions with T1 and T2 Relaxation time, it could provide clear image of human organ without any harm, which considerably facilitate people's life. In this article, part 2 discuss about the principle of magnetic resonance. From the spinning of the hydrogen nucleus and its processional motion, to the relaxation after the cease of radio frequency pulse, and to the gradient magnetic field and spatial orientation in the three-dimensional space, followed by the K space and Fourier transform. In the part 3, the medical applications of Nuclear Magnetic Resonance were mentioned, it has been used in diagnose of Alzheimer's disease precaution of foetal abnormalities, and the inspection of the injured such as soft tissue damage [1]. In part 4, the future challenge would be stated. Lastly, this article has provided a relatively broad and basic background for the future development of NMR, and also summarized the applications of NMR in some aspects nowadays.

2. Principle of Nuclear Magnetic Resonance

2.1. Nuclear spin and precession

The human body is about 70 percent water, which indicates that there are a lot of hydrogen nucleus in the body. If the nuclei has at least one odd number out of proton number and neutron number, it will spin to create a magnetic field, which is called nuclear magnetism [2]. The magnetic energy of the nucleus of hydrogen can be divided into two energy levels as shown in figure 1, the low energy level is in the same direction with the magnetic field, and the high energy level is in the opposite direction.

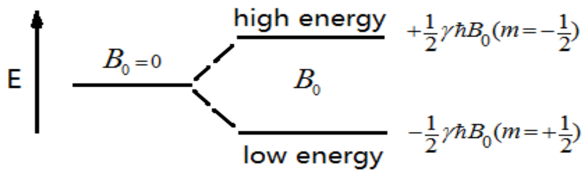

Figure 1. Nucleus in various energy levels.

The magnetic energy metric $E_p = -\mu_2 B_0$ could be used to calculate the energy of hydrogen nucleus in B_0, meanwhile the projection of μ_p on direction of B_0 is μ_2 .So

$$E = \pm \frac{1}{2}\gamma_P \hbar B_0 \tag{1}$$

The magnetic moment vectors of high and low energy levels are illustrate on the figure2, μ_a and B_0 are both pointing upwards, and the energy is low in the equilibrium position , μ_b and B_0 are in the opposite direction, and it can return to the equilibrium position automatically after a little disturbance, as the result, the energy level is higher.

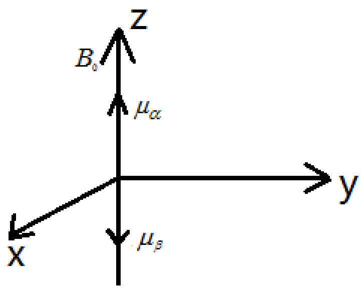

Figure 2. Magnetic field direction.

The numerical difference in energy between the two stages is $\Delta E = \gamma_P \hbar B_0$. If such energy is absorbed, the low-energy nucleus can transition to higher energy level, while the energy could be provided by electromagnetic waves (radio frequency waves), their frequency should meet the radiation requirement

$$v_0 = \gamma_p B_0 / 2\pi \tag{2}$$

However, the rotation of the nucleus in the magnetic field is not exactly align with the direction of the magnetic field. Its spin axis will form an Angle with the natural alignment direction and rotate around the natural alignment direction as shown in figure3.

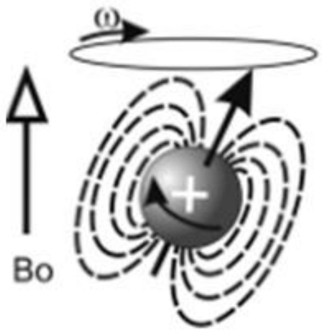

Figure 3. Procession motion.

This motion is called precession [3]. And the precession frequency, the Larmor frequency is equal to the product of the magnetic field strength and the magnetic spin ratio. Magnetic spin ratio is a constant that takes many details of the nucleus into account [4]. Different nuclei have different magnetic spin ratio. The nuclear spin ratio of hydrogen atom is larger than that of other elements in human body, so that its precession frequency is also larger.

2.2. Relaxation

Relaxation happens when the RF pulse is removed. And there are two kinds of relaxation, T2 Relaxation and T1 Relaxation (figure 4 and 5).

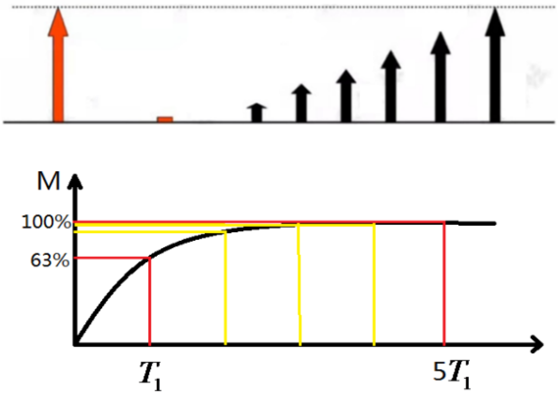

Figure 4. T1 Relaxation.

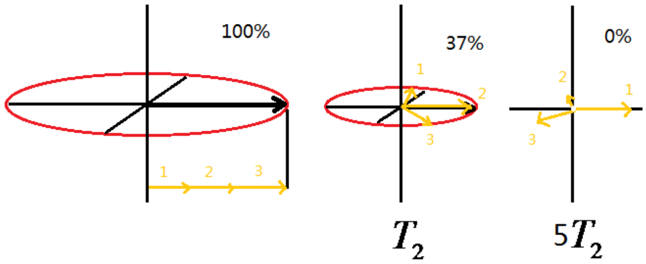

Figure 5. T2 Relaxation.

Former is essentially the diminishing of transverse macroscopic magnetization vector and later is essentially the recovery of longitudinal macroscopic magnetization vector. After pulse is removed, hydrogen nucleus who have been moved to excite state would return ground state, and all the hydrogen nucleus would gradually loss phase with each other since they are being in a magnetic field that is inevitably inhomogeneous [5]. T1 constant is define as the time taken for 63% of total longitudinal vector to recover (5T1 is consider time taken for 100% longitudinal vector to recovered), while T2 constant is define as the time taken for there is only 37% of total transverse vector left (5T2 is consider time taken for there is 0% transverse vector left). And different tissues in the body have different T1 and T2 constant.

2.3. Gradient magnetic field

Gradient magnetic field is widely used in nuclear magnetic resonance, the magnitude of magnetic field usually has a declining or increasing pattern. For example, in a coordinate system consisting of the X, Y, and Z axis (figure 6), a gradient magnetic field in the z direction means magnetic field applied is proportional to the magnitude of the z coordinate.

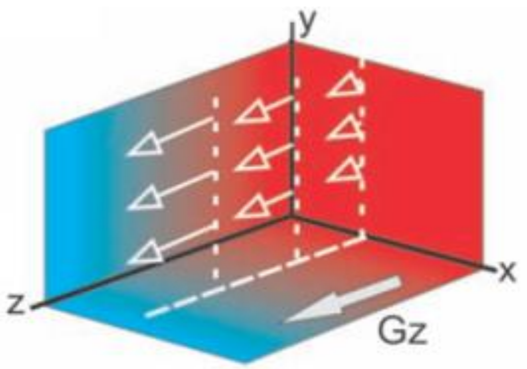

Figure 6. Applying gradient magnetic field.

In this way, the magnetic field only increases with the z coordinate in the ZX and YZ planes, and the magnetic field strength is the same at all points in any XY plane.

2.4. Spatial orientation

In order to get a magnetic resonance image which is 2-dimensional form the 3-dimensional world, a desired slice or plane has to be selected in the first place. While this process is called selective excitation. Take head of human shown in figure 7 as an example, in this situation, an image in shaded area is desired (Image in actual situation would not be this "thick" of course).

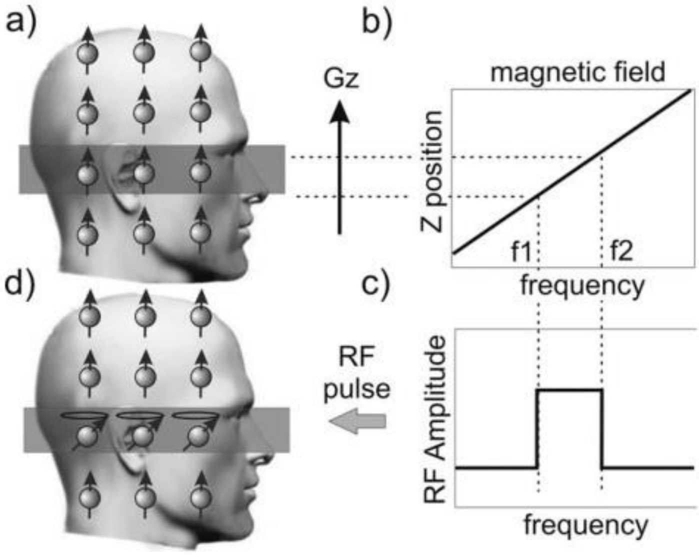

Figure 7. Spacial orientation of MRI of head.

A gradient magnetic field is introduced in the Z direction, and nucleus will have Larmor frequency according to its position. As for the desired slice, it would get a bandwidth form f1 to f2 [6]. If the Rf pulse with corresponding frequency is used, the magnetization of nucleus in shaped area would be selectively excited. Eventually, with suitable receiver coil used, only the signal generated form magnetization in selected area would be detect, and produced the image wanted. Then, finishing locating the slice desired, the task left is to determine the distribution of magnetization in the slice.
Before going to discuss that, it is useful to first consider a line of nucleus in gradient magnetic field (figure8).

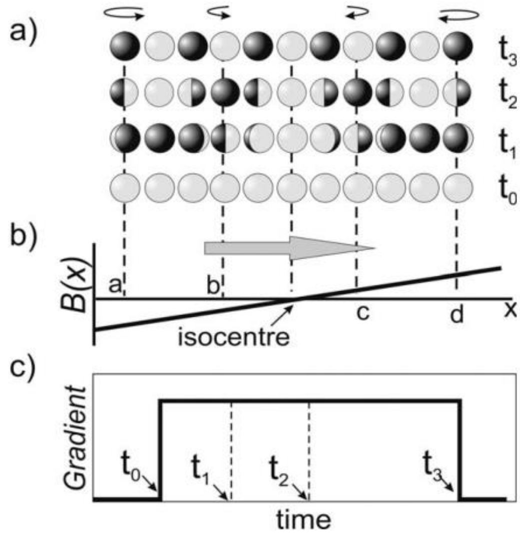

Figure 8. Introducing gradient on a line of nucleus.

Nucleus would experience different magnitude of magnetic field corresponding to their position, and that cause then to spin with various speed. The nucleus on each side spin in different direction (clockwise and anti-clockwise respectively), and nuclei spins slower as approaching the centre, while on the centre, the nuclei experience no field, and would not spin. After a certain period of time (t3), all the neighbouring nuclei are in opposite phases. So, the time of application of the gradient application could be used to determine the phase of the nucleus as a function of time.

Then, considering a two-dimensional pattern of nucleus, which experience a field in X direction (figure 9).

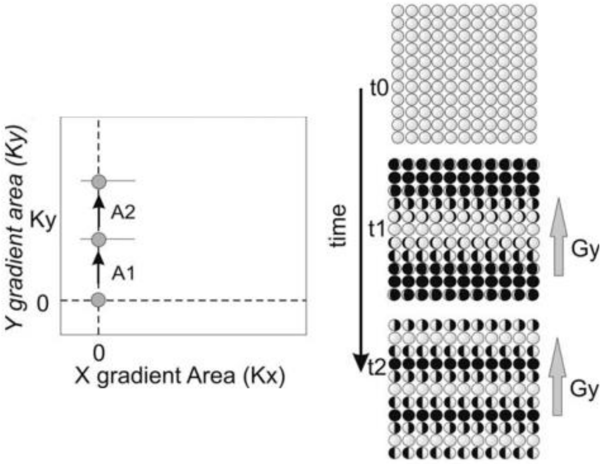

Figure 9. Introducing gradient in X direction on a 2-dimensional pattern of nucleus.

Nucleus would spin and form a vertical stripe pattern; its spatial frequency is depended on the time gradient magnetic field is applied. Information in the stripe pattern would be used in K space which would be discussed later. The k-space representation could be produced by making a plot with area under the X and Y gradients represented on X and Y axes respectively, while the area is proportional to the spatial frequencies. Similarly, when applying a gradient magnetic field in Y direction (figure10), stripe pattern formed could also lead to its specific position on K space.

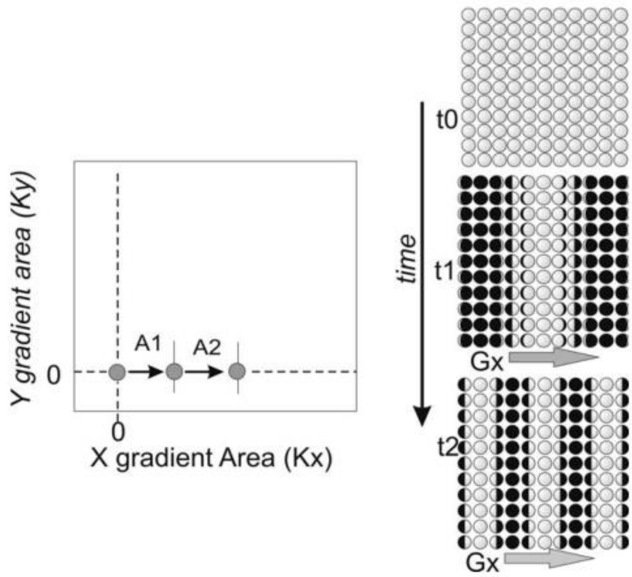

Figure 10. Introducing gradient in Y direction on a 2-dimensional pattern of nucleus.

2.5. K space and Fourier transform

K space(figure11b) is a square with sides of 256 points and it totally contains more than 65536 points, while each point indicates a specific stripe pattern by difference in density, angle, phase and amplitude (figure 12), and these four factors is connected to the features of the point, which is its position and brightness [7].

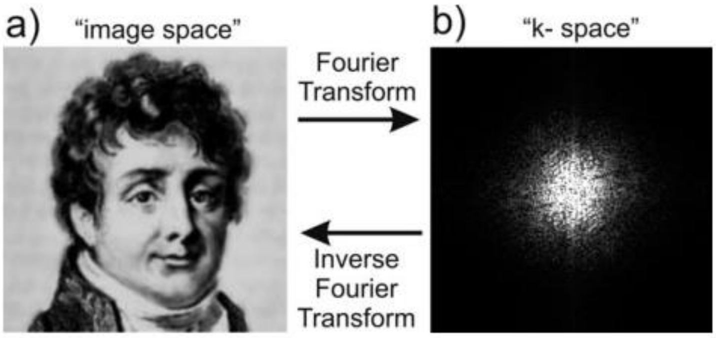

Figure 11. K space and actual image.

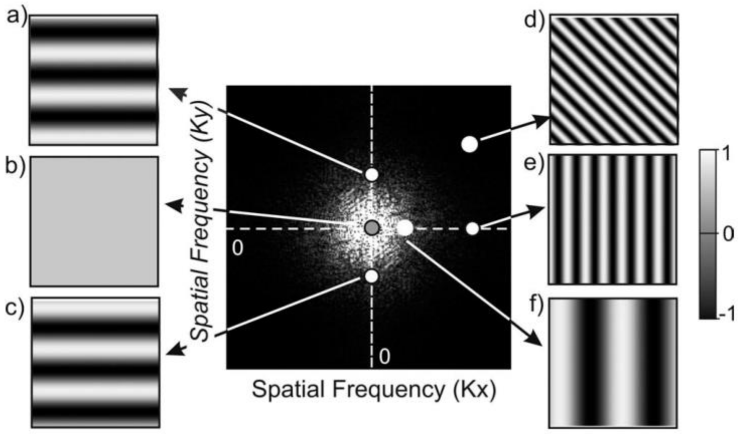

Figure 12. K space and stripe pattern.

As for density, is actually the spatial frequency mentioned above, which can be consider as number of stripes per unit length. On the K space, every point has Kx and Ky coordinate, which is determine by the spatial frequency of corresponding stripe pattern. For example, the vertical stripe is corresponding to the point on the X axis of K space, and vice versa. While the points that is not on the axis is influenced by spatial frequency on both Kx and Ky direction.

Amplitude and phase of stripe pattern is responsible for the brightness of the point as shown in figure13. Depending on the stripe pattern, the signal also changes over time. This variation of the signal is further processed by the receiving coil to obtain the amplitude and phase of each point in k-space, in other words, the brightness of each point.

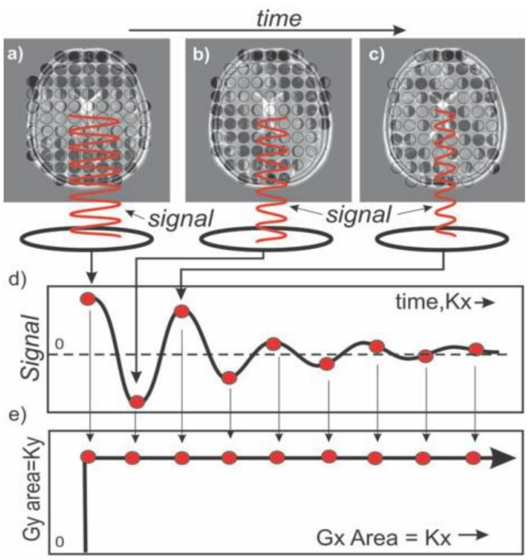

Figure 13. Determining amplitude with evolving stripe pattern.

After the K space the produced, it has to be transformed to real image, which is something Fourier transform is responsible to [8]. Fourier transform is a mathematical way to produce an image and determine those correct stripe patterns. If inverse Fourier transform is used to each stripe pattern and combine them, it will produce the actual image, and if Fourier transform is used to the actual image, it will produce the corresponding K space. So, the K space and actual image can be considered equivalent to each other.

In the figure14, the result of limit area in K space after inverse Fourier transform. If only the central area is selected, a blurred and obscure image would form, it only shows the general shape of the picture (figure14b). As the selected centre area expands, the image becomes clearer, the picture in figure14c is produced, but details are still missing [9]. If the part of K-space outside the central region is taken for Fourier transform, picture in figure14d would be produce. It shows the details besides the main structure, though with lack of colour. The central area of K space shows an overall rough picture, while its surrounding shows details of actual graph.

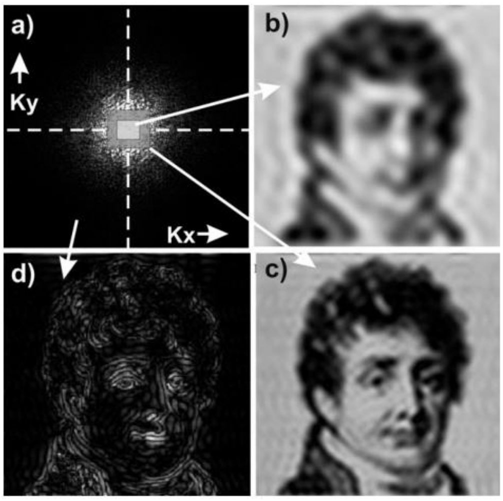

Figure 14. Using Fourier transform to different part of K space.

3. Application of MRI

Nowadays, following the development of MRI, it has been used in various aspects, medication is one of them.

3.1. Medication

Magnetic resonance imaging (MRI) examination has become a common imaging examination, MRI as a new imaging examination technology, will not have an impact on human health, its advantage has made it widely used (figure 15).

Figure 15. MRI used in.

MRI could aid the early diagnosis of Alzheimer's disease, which is an irreversible neurodegenerative disease of the brain. The prevalence of AD increased significantly with the growth of the age, is considered to be the seventh largest cause of death. At present, there is still a lack of clear and effective biomarkers, and only early intervention can delay the development of AD. As an effective tool for imaging brain tissue, MRI can observe functional changes in related brain regions, which are often directly related to the disease. The detection of such changes plays an important role in the early diagnosis and intervention of the disease.

Furthermore, MRI has facilitated the diagnosis of early fetal abnormalities and analysis of brain development. Fetal MRI image quality assessment and brain segmentation are the basis of fetal brain 3D reconstruction and quantitative analysis. The prediction of fetal brain age based on MRI images also plays an important role in the diagnosis of early fetal diseases and the analysis of brain development.

Other than these applications, MRI is also used to observe the morphological changes of soft tissue under the knee tendon lesion in patients with KOA (figure 16) [10].

Figure 16. Magnetic resonance image of soft tissue of knee.

4. Conclusion

In this article, basic physical background has been introduced. Application of gradient magnetic field make the protons that are supposed to be moving randomly to align to the direction of the field. And RF pulse help generate a transverse magnetization vector that is detectable, while the cease of the pulse would cause the relaxation, that vary in different types of tissue. By use of series of pulse with appropriate frequency and interval, fine Magnetic Resonance Image can be produced. Eventually, after K space is produced with characteristic and evolving of stripe pattern generated by gradient magnetic field, Fourier transform is used to get the final image. It article is expected to give a brief and basic introduction of nuclear magnetic resonance, and be helpful to its future advancement in various field.

References

[1] Feng, J., Zhang, S. W., & Chen, L. (2022, May 1). Extracting ROI-Based Contourlet Subband Energy Feature from the sMRI Image for Alzheimer's disease Classification. IEEE/ACM Transactions on Computational Biology and Bioinformatics, 19(3), 1627–1639.

[2] Grodzins, L., & Klepper, O. (1971, March 1). Measurement of the Magnitude and Sign of the Nuclear Quadrupole Interaction via the Spin Precession of an Angular Correlation. Physical Review C, 3(3), 1019–1023.

[3] Bagryanskaya, E., Grishin, Y., Sagdeev, R., & Molin, Y. (1986b, August). Stimulated nuclear polarization under induced coherent spin precession. Chemical Physics Letters, 128(4), 417–419.

[4] Abdurakhimov, L. V., Borich, M. A., Bunkov, Y. M., Gazizulin, R. R., Konstantinov, D., Kurkin, M. I., & Tankeyev, A. P. (2018, January 22). Nonlinear NMR and magnon BEC in antiferromagnetic materials with coupled electron and nuclear spin precession. Physical Review B, 97(2).

[5] Bloembergen, N., Purcell, E. M., & Pound, R. V. (1948, April 1). Relaxation Effects in Nuclear Magnetic Resonance Absorption. Physical Review, 73(7), 679–712.

[6] Hargreaves, B. A., Cunningham, C. H., Nishimura, D. G., & Conolly, S. M. (2004). Variable-rate selective excitation for rapid MRI sequences. Magnetic Resonance in Medicine, 52(3), 590–597.

[7] Markl, M., & Hennig, J. (2001, June). Phase contrast MRI with improved temporal resolution by view sharing: k-space related velocity mapping properties. Magnetic Resonance Imaging, 19(5), 669–676.

[8] Katoh, M., Spuentrup, E., Buecker, A., Schaeffter, T., Stuber, M., Günther, R. W., & Botnar, R. M. (2006, June). MRI of Coronary Vessel Walls Using Radial k-Space Sampling and Steady-State Free Precession Imaging. American Journal of Roentgenology, 186(6_supplement_2), S401–S406.

[9] Wedeen, V. J., Wendt, R. E., & Jerosch-Herold, M. (1989, July). Motional phase artifacts in fourier transforms MRI. Magnetic Resonance in Medicine, 11(1), 114–120.

[10] Tsvetkova, E., Ionichenok, N., Karusinov, P., Smirnov, A., Denisov, L., & Nasonov, E. (2014). The prevalence of different mri structural changes in knee osteoarthritis (koa). Osteoarthritis & Cartilage, 22, S287-S287.