Chapter

Hardware of MRI System

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Abstract

Magnetic resonance imaging (MRI) is comprehensively applied in modern medical diagnosis and scientific research for its superb soft-tissue imaging quality and non-radiating characteristics. Main magnet, gradient assembly, and radio-frequency (RF) assembly are main hardware in an MRI system. The hardware performance has direct relationship with the ultimate system overall performance. The development of MRI system toward high magnetic field strength will acquire high signal-to-noise ratio (SNR) and resolution, and meanwhile the manufacture difficulty of main magnet, gradient assembly, and RF assembly will also be significantly elevated. This will make challenges on the design, materials, primitive device, and also the whole machine assembly. This chapter introduces the main hardware of the MRI system and corresponding functions and developments.

Keywords: MRI, superconducting magnet, gradient coil, RF coil

1. Introduction

In the 1950s, it was discovered in the biomedicine field that hydrogen atoms in water molecules can produce nuclear magnetic resonance phenomena [1]. Nuclear magnetic resonance was used to obtain information from the distribution of water molecules in the human body, by which the internal anatomy of the human body could be mapped accurately [2]. After decades of development, MRI has become indispensable medical imaging devices [3]. The influence of MRI on the clinical and life science comes from its unrivaled imaging capabilities, and it can obtain not only clear structural images of the anatomic structure and the organic lesion completely without trauma [4], but also the other physiological information.

In recent years, MRI techniques have developed rapidly, especially toward high-field imaging, such as 7 T, 9.4 T or even higher field strengths [5]. MRI technique development requires an associated performance improvement in the system hardware, which mainly includes the main magnet [6], gradient coil [7], and radio-frequency (RF) coil [8].

2. Main magnet

Early MRI magnet system mainly used ferromagnetic shield structure [9]. The use of large amounts of ferromagnetic shield [10] makes the weight and size of the system relatively large and installation costs of the system high. With the rapid development of magnet technologies, the active shield structure has been successfully developed for the high-field magnet system [11], which greatly reduces the scope of 5 Gauss line. Generally, the superconducting magnet consists of multiple solenoidal coils and shielded coils [12]. The inner solenoid coil is called the primary coil, generally through forward current. The outer solenoid coil is called shield coils, through the reverse current. Open MRI system helps improve patient comfort and expands the scope for the patient [13]. It is easy to achieve a high magnetic field by using combination of iron core and superconducting coil. The cryogenic system is used to keep superconducting wire in a cryogenic environment and ensure safe operation of the superconducting magnet.

In the Institute of Electrical Engineering, Chinese Academy of Sciences, (IEE, CAS), several sets of MRI magnets have been designed or fabricated, including 0.7 T planar whole-body MRI system, 1.5 T cylindrical whole-body MRI system, 7.0 T animal MRI system, and 9.4 T cylindrical whole-body MRI system [14].

Due to structural advantages of the open MRI system, it can be applied to interventional therapy. The shape of magnetic field depends mainly on yoke and pole, and coils provide magnetic source. The magnet system has less superconducting wire, and only 120 L of liquid helium with zero boiling off liquid helium by one GM cryocooler. Magnetic field strength of superconducting open MRI is generally higher than 0.7 T due to a higher uniform magnetic field produced by superconducting coils [15]. **Figure 1** shows a 0.7 T open MRI system designed by IEE, CAS.

A 9.4 T whole body imaging system is developed in IEE, CAS, shown in **Figure 2**. The magnet has a horizontal length of 3.5 m and large warm bore with a diameter of 0.8 m. The magnet system is designed with the minimum cost of wire consumption. By means of the optimal algorithm, the coil sizes and positions are optimized to reduce the coil volume and constrain the magnetic field inhomogeneity. In the optimization, the coil stress and current margins are also constrained to satisfy the coil safety requirements. Fully stable NbTi superconducting wire type WIC (Wire-In-Channel) is employed to wind the coils. Both active and passive quench protection system are employed to protect the magnet from damage during a quench event. The magnet system will reach the final field homogeneity as low as 0.1 ppm (peak to peak) in the central 30 cm DSV and the stability of 0.05 ppm/h.

Figure 1.
A 0.7 T whole-body open MRI system.

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Figure 2.
A 9.4 T superconducting magnet for whole-body MRI system.

The magnet is cooled by liquid helium bath, and the evaporated helium is condensed by two re-condensing cryocoolers.

3. Gradient coil

A gradient coil set is an important component in a standard MRI scanner which produces linear gradient magnetic fields that are superimposed over a strong uniform magnetic field. The uniform magnetic field is produced by a main magnet, which aligns with the proton precession direction. The superimposed gradient magnetic field slightly changes the proton precession frequency or phase, thus encoding the spatial information of an imaged object in the frequency associated with a position in space [16]. In general, the magnetic field gradient produced by the gradient coils is required to be as linear as possible, and a well-designed gradient coil should also have low inductance, low resistance, high efficiency, etc. [17]. This is especially pertinent in high-field imaging and fast imaging when all the coils' parameters must be highly optimized.

In a gradient assembly, there are three gradient coils, called the x, y, and z coils [18]. **Figure 3** shows a set of actively shielded gradient coils (here the actively shielding gradient coil is a coil pattern containing both the primary coil and shielding coil [19]). The red and blue colors of the gradient coils indicate where the current flows in clockwise and anticlockwise [20]. The three-axis gradient coils are fixed by epoxy resin in an encapsulated gradient assembly [21], as is shown in **Figure 4**. In an integrated gradient assembly, there are also cooling devices and a shim tray installed [22]. The hard epoxy resin largely impedes the vibration of the gradient coils [23], which avoids torsion and deformation of the gradient coils under strong Lorentz force.

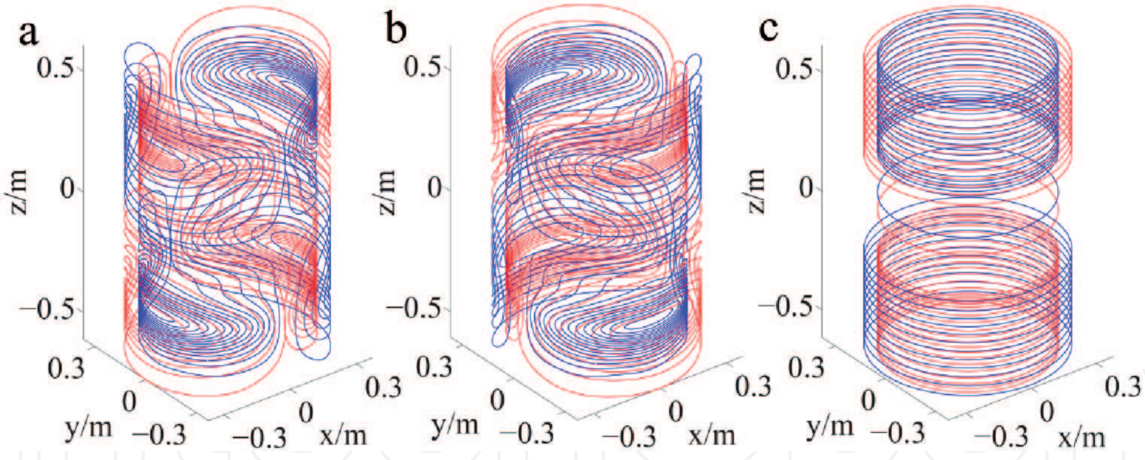

Figure 3.
Actively shielded gradient coils used in an MRI scanner: (a) x gradient coil, (b) y gradient coil, and (c) z gradient coil. The red and blue colors indicate the direction in which the current flows.

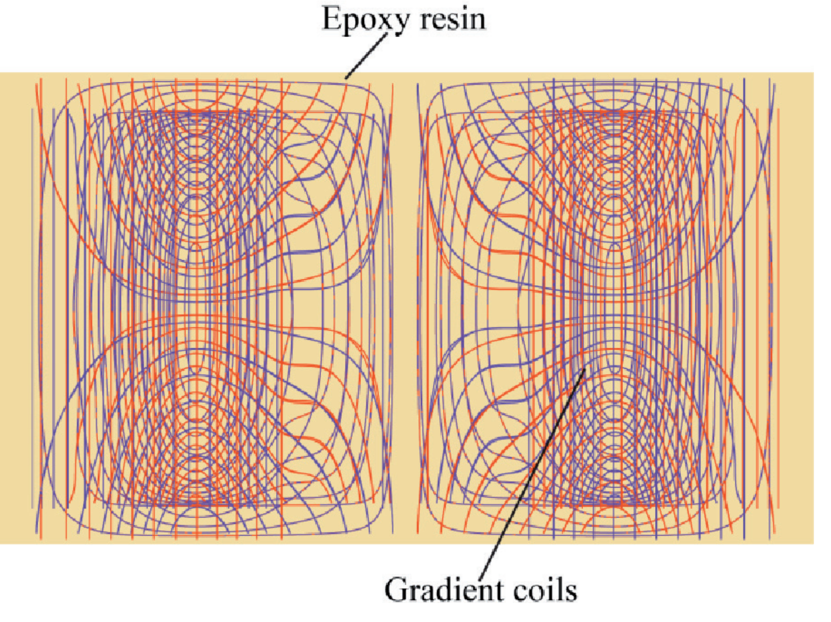

Figure 4.
Illustration of the three-axis gradient coils fixed in the epoxy resin.

4. RF coil

RF coil is the key component of the MRI system, which serves as the transmitter as well as receiver in the formation of the final images [8]. There are various kinds of RF coils. The difference between coils lies in different parts of human body and different field strengths.

According to imaging part of the human body, it can be classified into head coils, body coils, knee coils or foot coils, etc. No matter how many kinds of coils there may be, all the coils can be basically treated as two kinds of coils, namely surface coil and volume coil. For the surface coils [24], the shape of which is usually a circle, which will facilitate the fabrication of coil. Surface coils are often used as receivers, the reason is that the field it produces is inhomogeneous, which is detrimental to the imaging process. But the signal-to-noise ratio (SNR) of the surface coils is higher than volume coils, partly because it can be located closely to the imaging area. Nowadays, surface coils are not used alone to achieve the receiving purpose. A bunch of surface coils [25], which we call loop array, are used for its good performance in receiving as well as transmitting. An illustration of surface coil is shown in **Figure 5**.

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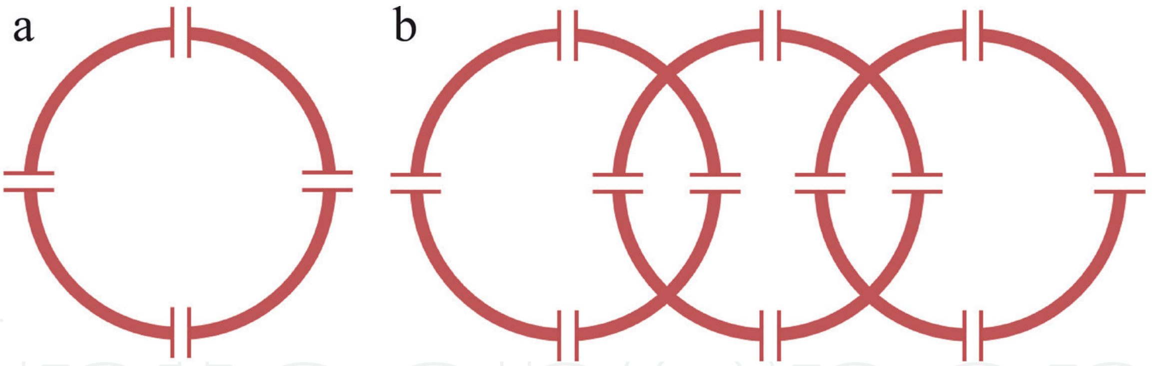

Figure 5.
Diagram of surface coils: (a) single coil and (b) array coil.

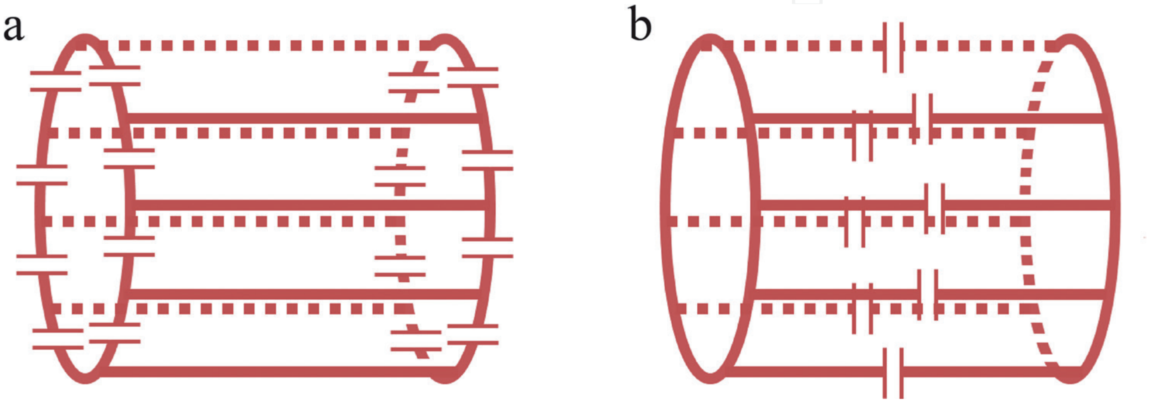

Figure 6.
Diagram of volume coils: (a) high-pass birdcage volume coil and (b) low-pass birdcage volume coil.

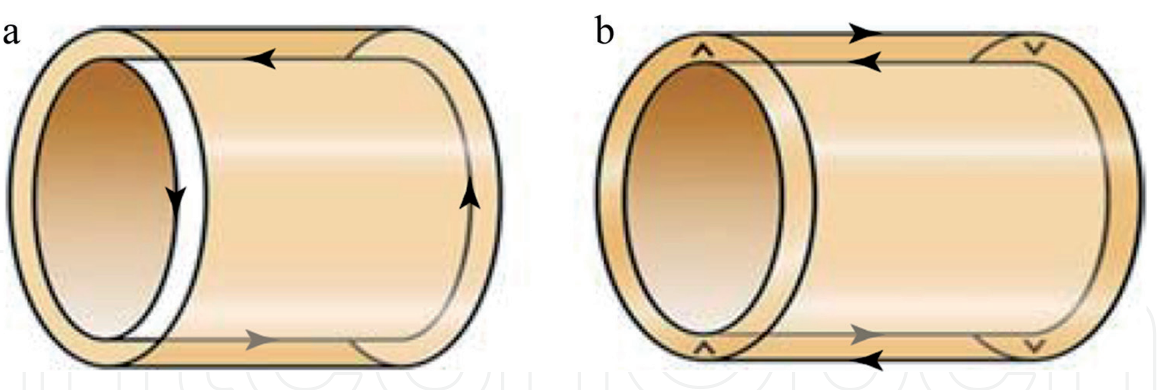

Figure 7.
Sketch map of volume coils: (a) birdcage coil and (b) TEM coil.

Another kind of RF coil is the volume coil, and the most popular volume coil is the birdcage coil [26–29], which is shown in **Figure 6**. A prominent character of birdcage coil is its quadrature excitation strategies both spatially and temporally. The distinctive excitation technology generates a circularly polarized field, which can result in a highly uniform B1 field.

An alternative volume coil named TEM coil [30] maybe used in ultra-high field MRI as illustrated in **Figure 7**. TEM is the most general term for "transmission line," and it can be realized through many kinds of circuit, such as coaxial lines, strip lines, microstrips or waveguides. In birdcage coils, the end rings form the "return path" of the current on the rungs. But in high frequencies, the end rings can be problematic. The inductance and resonant frequency of birdcage coils are limited by the size of the end rings. And the end rings are related to the diameter of the coil. The magnetic field generated by end rings is along with the B0 field, which is nonproductive for the excitation of nucleus. So, in TEM coils, the end rings are replaced by shield to serve as the return path. The inductance and resonant frequency of TEM coil are independent of the diameters of the coil. A length determined TEM coil can be built to arbitrary diameter, without influence on the frequency. So, its use in the ultra-high field imaging is flexible. The TEM coil can be regarded as a toroidal array of many transmission line elements. The impedance of each element can be modified individually. The reactance between each element can be controlled to achieve parallel imaging applications.

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