2 Hardware for Magnetic Resonance Imaging

KENNETH W. FISHBEN, JOSEPH C. MCGOWAN, and RICHARD G. SPENCER

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2.1 Introduction

While modern magnetic resonance imaging (MRI) instruments vary considerably in design and specifications, all MRI scanners include several essential components. First, in order to create net nuclear spin magnetization in the subject to be scanned, a polarizing magnetic field is required. This main magnetic field is generally constant in time and space and may be provided by a variety of magnets. Once net nuclear spin magnetization is present, this magnetization may be manipulated by applying a variety of secondary magnetic fields with specific time and/or spatial dependence. These may generally be classified into gradients, which introduce defined spatial variations in the polarizing magnetic field, B0, and radio frequency (RF) irradiation, which provides the B1 magnetic field needed to generate observable, transverse nuclear spin magnetization. B0 gradients are generally created by applying an electric current supplied by gradient amplifiers to a set of electromagnetic coil windings within the main magnetic field. Similarly, RF irradiation is applied to the subject by one or more antennas or transmitter coils connected to a set of synthesizers, attenuators and amplifiers known collectively as a transmitter. Under the influence of the main magnetic field, the field gradients and RF irradiation, the nuclear spins within the subject induce a weak RF signal in one or more receiver coils which is then amplified, filtered and digitized by the receiver. Finally, the digitized signal is displayed and processed by the scanner’s host computer. In this chapter, we will discuss the various technologies currently in use for these components with an emphasis on critical specifications and the impact that these have on the instrument’s performance in specific MRI experiments. While the focus of the current work is imaging, the hardware components described below are also applicable to magnetic resonance spectroscopy (MRS) and this text will include specific information related to spectroscopy where appropriate.
The function of a MRI scanner’s magnet is to generate a strong, stable, spatially uniform polarizing magnetic field within a defined working volume. Accordingly, the most important specifications for an MRI magnet are field strength, field stability, spatial homogeneity and the dimensions and orientation of the working volume. In addition to these, specifications such as weight, stray field dimensions, overall bore length and startup and operating costs play an important role in selecting and installing an MRI magnet. Magnet types used in MRI may be classified into three categories: permanent, resistive and superconducting. As we shall see, the available magnet technologies generally offer a compromise between various specifications so that the optimum choice of magnet design will depend upon the demands of the clinical applications anticipated and the MRI experiments to be performed.

2.2.1 Permanent Magnets

Permanent magnets for MRI are composed of one or more pieces of iron or magnetizable alloy carefully formed into a shape designed to establish a homogeneous magnetic field over the region to be scanned. These magnets may provide open access to the patient or may be constructed in the traditional, “closed” cylindrical geometry. With care, permanent magnets can be constructed with good spatial homogeneity, but they are susceptible to temporal changes in field strength and homogeneity caused by changes in magnet temperature. The maximum field strength possible for a permanent magnet depends upon the ferromagnetic alloy used to build it, but is generally limited to approximately 0.3 T. The weight of a permanent MRI magnet also depends upon the choice of magnetic material but is generally very high. As an example, a 0.2-T whole-body magnet constructed from iron might weigh 25 tons while the weight of a similar magnet built from a neodymium alloy could be 5 tons. While the field strength of permanent magnets is limited and their weight is high, they consume no electric power, dissipate no heat, and are very stable. Consequently, once installed, permanent magnets are inexpensive to maintain.

2.2.2 Resistive Electromagnets

Other than permanent magnets, all MRI magnets are electromagnets, generating their field by the conduction of electricity through loops of wire. Electromagnets, in turn, are classified as resistive or superconducting depending upon whether the wire loops have finite or zero electrical resistance. Unlike permanent magnets, resistive electromagnets are not limited in field strength by any fundamental property of a magnetic material. Indeed, an electromagnet can produce an arbitrarily strong magnetic field provided that sufficient current can flow through the wire loops without excessive heating or power consumption. Specifically, for a simple cylindrical coil known as a solenoid, the magnetic field generated is directly proportional to the coil current. However, the power requirements and heat generation of the electromagnet increase as the square of the current. Because the stability of the field of a resistive magnet depends both upon coil temperature and the stability of the current source used to energize the magnet coil, these magnets require a power source that simultaneously provides very high current (typically hundreds of amperes) and excellent current stability (less than one part per million per hour). These requirements are technically difficult to achieve and further restrict the performance of resistive magnets. While resistive magnets have been built which generate very high fields over a small volume in the re-