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R Prost and L F Czervionke

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How Does an MR Scanner Operate?

Robert Prost and Leo F. Czervionke

Part 1. General Overview of Magnetic Resonance (MR) Scanner Components

Think of an MR scanner as a two-way radio system contained within a powerful magnetic field in which the transmitter sends a signal, not to a distant object, but to an object surrounded by the radio antenna itself. The receiver portion of the radio then listens for a signal returning from the object, and this signal is stored then processed by a computer to form an image of the object.

Magnet System

The purpose of the magnet is to provide a uniform magnetic field at all points in the bore of the magnet to align mobile protons within the patient. The strength of the magnetic field is measured in units of tesla or gauss—1.0 T equals 10 000 G. The magnetic field produced by the magnet is typically 30 000 times stronger than the magnetic field of the earth. Because it is not possible to obtain a perfectly homogeneous magnetic field, adjustments to the magnetic field strength are made by shimming the magnet.

Passive shimming is done by strategically placing small pieces of iron in the bore of the magnet to correct for local field inhomogeneities. Active shimming is performed by positioning shim coils in the magnet and passing current through the windings of these coils. Active shim coils have a separate power supply.

Resistive magnets are electromagnets in which the magnetic field is produced by continuously passing an electric current through the windings. Resistive magnets produce heat, and this heat is dissipated by a cooling system. The windings of superconducting magnets are made of special metal alloys (eg, niobium-titanium alloy) that lose electrical resistance when

cooled to extremely low temperatures. The windings of these magnets are supercooled by liquid helium. Once the electrical current is passed through these supercooled windings, the current will continue almost indefinitely. Because heat eventually will cause the cryogen to boil away, new cryogen must be added occasionally to the system, usually every 4 to 6 weeks. In the case of superconducting magnets, an emergency quenching system is included to quickly dissipate the magnetic field in the event of an emergency.

The magnet and the shims may be resistive, superconducting, or permanent magnets. Resistive magnets require constant direct-current power supplies. Superconducting magnets intermittently require power supplies to maintain the appropriate current in the supercooled windings. There are relatively few clinical systems using permanent magnets. Permanent magnets operate in the lower field-strength range (up to 0.3 T), and they are extremely heavy.

Gradient System

The purpose of the gradient system is to linearly modify the main magnetic field. This modification is the basis of spatial encoding in MR. Along the direction of the gradient, a proton will resonate at a frequency that is a function of its distance from the magnet center along the direction of the gradient. Any of the three gradients located in the magnet bore may be set to function as phase- or frequency-encoding gradients.

Three gradient coils are built into every MR system. These coils produce gradient fields in the three principal axes (x, y, and z). Powerful audio amplifiers drive each of the three gradient coils. The gradient amplifiers send high currents through the coils for brief periods during the

From the Section of Neuroradiology, Department of Radiology, Medical College of Wisconsin, 9200 W Wisconsin Ave, Milwaukee, WI 53226. Address reprint requests to Leo F. Czervionke, MD.

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pulse sequence. These fields modify the frequency and/or phase of the spins in the patient in the scanner.

Spin resonance frequency is changed by switching on a gradient and leaving it on. Spin phase is modified by temporarily switching the gradient on, then off. The frequency of the spin changes during the time the gradients are on. When the gradient is switched off, the frequency of resonance is restored, except that the position of the spinning proton within the cycle is shifted depending on the amount and duration of the frequency shift caused by the gradient pulse.

Because gradients are rapidly switched on and off during the scan, eddy currents, which degrade image quality, are induced in the magnet housing (cryostat). They can be minimized by the use of shielded gradient coils. Shielded gradients operate by using second gradient coils external to the first, which keep the gradient fields from penetrating the magnet housing.

The Radio Frequency System

This is the radio transmitter and receiver portion of the MR scanner. Its purpose is to excite the patient's mobile protons, which have been aligned parallel to the main magnetic field. *Transmitter* components include the exciter, the radio frequency power amplifier, the power monitor (for safety), and the radio frequency coil (similar to a conventional radio antenna). Many radio frequency coils have been designed for special imaging purposes. Most MR systems include body and head coils for general imaging of these parts, as well as surface coils for imaging localized anatomy. Phased-array coils, which combine several surface coils, have become available on some systems that produce images with high signal-to-noise ratios over a larger portion of the patient than a conventional single-surface coil.

Receiver components include the coil, preamplifiers with their associated protection circuits, and the receiver that translates the radio frequency MR signal from the patient into low-frequency digital data.

The transmitted signal used to excite the spins is at very high power (up to 16 000 watts); the signal coming back from the patient is at extremely low power (approximately 10^{-9} watts). The preamplifier is used to amplify the

extremely low-power signal emanating from the patient.

The preamplifier is connected to the radio frequency coil through a circuit called the transmit/receive, which prevents the destruction of the sensitive circuitry in the preamp by the high-power radio frequency transmit pulses.

Computer System

There are four main components of the computer system needed to operate an MR scanner. The *operator console* is the computer interface used to send instructions to the host computer and to access the images once they are reconstructed. The *host computer* is responsible for carrying out scan prescription, filming, archiving, display, and upper-level system management. The *acquisition computer*, the "heart" of the system, operates in real time to activate the gradients at the proper time, coordinates the pulse sequence generator and the exciter, and controls the digitization of the received signal and its storage into memory. Physiologic gating of the pulse sequence is carried out through the acquisition computer. Reconstruction requires a special computer called an *array processor* that performs a vast number of mathematical manipulations of the raw image data.

Part 2. How the MR Image is Made

The Scan Sequence Is Prescribed

The operator at the console selects certain parameters such as repetition time, echo time, field of view, matrix size, and flip angle. The operator uses these parameters to activate the software that was programmed and compiled by the scanner manufacturer. The software program is stored in the host computer and contains information that tells the computer how to generate machine language code. This code tells the acquisition computer how to run the pulse sequence: the strength and duration of the radio frequency pulse and how the gradients should be applied. For a selected pulse sequence, the computer also runs a test to ensure that the parameters chosen do not violate FDA guidelines for radio frequency power deposition. Safety limits of the machine are also checked so that the gradient and the radio frequency power amplifier are not damaged by the scan. An independent check of radio frequency

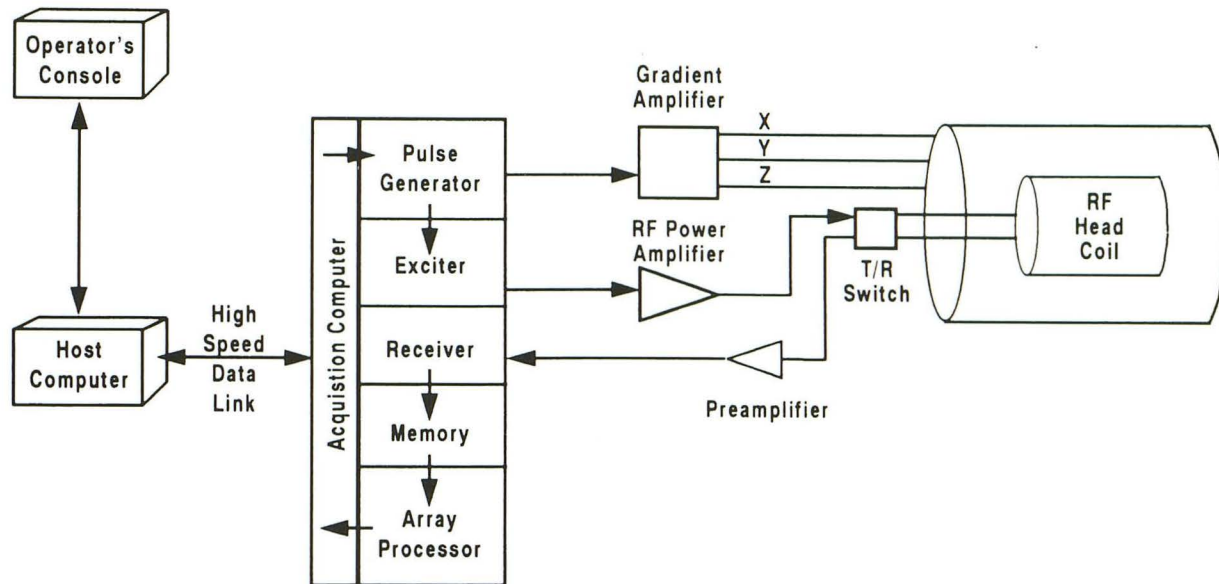


Fig 1. Simplified schematic diagram of information flow for a typical MR scanner system. The acquisition computer serves as the central coordinating system for signal generation, signal reception, and data reconstruction. RF indicates radio frequency.

power deposition is also made with the power monitor within the radio frequency subsystem.

The Autoprescan Sequence Is Initiated

With the patient in the scanner, the operator begins the autoprescan sequence (this may be done manually). A software subroutine is initiated that causes the pulse generator to begin a pulse sequence to: (a) the *resonance (Larmor frequency)*, (b) the *transmit gain*, amplitude of the transmitted radio frequency signal for the prescribed flip angle, and (c) the *receiver gain*, which determines the sensitivity setting for the receiver (how "hard" the receiver should listen for the signal returning from the patient). During autoprescan, three distinctly different patterns of sound are heard from the scanner that are the result of the pulse sequence subroutines being run to determine the above three values.

The Scan Is Performed

The general pathway of data flow for producing an MR image is shown in Figure 1. When the operator initiates the scan, real-time instructions previously generated by the host computer (as a result of the prescription choices made by the operator) are executed by the *pulse generator*, which is governed by the *acquisition computer*. The pulse generator creates wave forms to drive both gradient and radio frequency amplifiers. Wave forms sent to the

exciter are converted into pulses of radio frequency energy that oscillate at the Larmor frequency (as determined during prescan). These pulses are amplified by the *radio frequency power amplifier* and sent to the *radio frequency transmit coil* in the magnet, where a strong transverse field is created to tip the spins in the patient perpendicular to the direction of the magnetic field. Simultaneously, waveforms for the x, y, and z *gradients* are sent to the gradient amplifiers and then to the gradient coils in the magnet.

Physiologic data acquired from the patient (eg, electrocardiogram, respiration, and peripheral pulse) are used by the acquisition computer to modify the gradient waveforms and pulse sequence timing, if gating was selected by the operator at the time the scan was prescribed.

During the pulse sequence, the *preamplifier* is turned on to amplify the small signal received from the nuclei in the body at the time of the echo. This analog signal is amplified and digitized by the receiver. The digitized data are stored in the acquisition computer memory.

The pulse sequence is repeated with different strengths of the phase-encoding gradient. For example, if a 512×256 matrix was selected, the sequence is repeated 256 times for each different step (amplitude) of the phase-encoding gradient. The *receiver* collects each phase-encoding "view" as an analog signal and sequentially sends the signal to an *analog-to-*

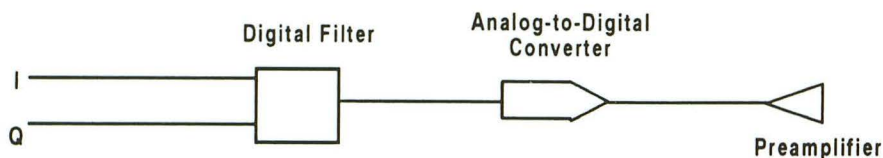


Fig 2. Schematic diagram detail of data flow from the receiver coil. Flow of data is from right to left. The signal is separated into real (Q) and imaginary (I) components.

digital converter for digitization. The digitized data are then filtered by mathematical means to reduce noise. The data are then separated into two data channels, one real (Q channel) and one imaginary (I channel) (Fig 2).

Image Reconstruction

In the *acquisition computer*, filtered and digitized raw data are stored in *memory*. The region in memory where the data samples are stored is referred to as *k-space*, which is a mathematical construct created to conceptualize how spatial frequencies are stored in memory. K-space is represented graphically by a two-dimensional matrix coordinate system, and each "position" in k-space is filled in as the data are collected. The image data are stored in memory in the form of complex numbers. The values of these numbers and their positions in k-space provide all the signal intensity and spatial information necessary to reconstruct the MR image. (A

more complete explanation of k-space will be found in an upcoming MR Technical Moment.)

When all repetitions of the sequence have been completed, and all data are stored in memory, data are transferred to a smaller memory area in the *array processor*, where the data are processed one section at a time. The data are transformed using a complex Fourier along each axis. Two Fourier transformations are needed to reconstruct a two-dimensional acquisition, and three Fourier transforms are necessary to reconstruct data from a three-dimensional acquisition. As a final step, a "stretching" algorithm is used to correct the geometric distortions in the image that result from imperfections (nonlinearities) in the gradient fields.

After the data are processed, the acquisition computer sends the data back to the host computer through a high-speed data link. The host computer stores the image on a hard disk, from which the operator can review the image.