FROM MODERN ATOMIC AND NUCLEAR PHYSICS

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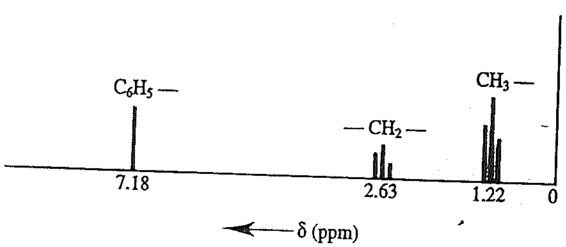

FIGURE 4B.4
NMR spectrum of ethylbenzene.

4B.4 MAGNETIC RESONANCE IMAGING IN MEDICINE

Nuclear magnetic resonance techniques now are being applied to open up remarkable new views of the interior parts and the actual dynamical working of these parts in the human body. Originally, the technique was called Nuclear Magnetic Resonance Imaging, but now simply Magnetic Resonance Imaging, MRI. It provides a powerful noninvasive technique to study the interior of the body in ways that would not have been conceived as possible even a short time ago without surgery or without using ionizing radiation such as x-rays or a radioactive dye injected into the patient. The information can often be as precise from MRI as if the doctor were directly looking at the tissue via surgery. A schematic view of a system for MRI studies is shown in Fig. 4B.6. The basic principles and operation are as follows. MRI makes use of atoms whose nuclei have a magnetic moment. As we shall see in Chapter 9, to have such a magnetic moment a nucleus must have an odd number of protons or neutrons, so the nucleus has a net spin and net magnetic moment. Such atoms include ^1H, ^{13}C, ^{19}F, ^{23}Na, ^{31}P and ^{39}K, which are found in biologically interesting molecules.

In the MRI system shown in Fig. 4B.6, the superconducting magnet surrounds the patient and produces a magnetic field ranging from 0.05 to 2 T ($1\,T = 10^4$ gauss, compared to the Earth's magnetic field of about 0.5 gauss). The nuclear magnetic moments of the nuclei in atoms such as ^1H will interact with this field to cause the moments to line up in the field. Not all will be aligned to the same degree and they will precess about the field with the Larmor frequency $\omega = \gamma B$, where γ is the gyromagnetic ratio for the nucleus and B is the external field strength. The random orientation and precession of these magnetic moments gives a net moment, M, along the direction of B.

An external magnetic field, B_1, applied perpendicular to B and rotating with the Larmor frequency will cause this moment M to change its direction. This rotation field is fortunately in the radiofrequency (RF) range. The lower frequencies (MHz) for MRI are not strongly absorbed in tissue as are the microwave frequencies for electronic Larmor frequencies, so RF radiation can be used for imaging of deep structures without tissue damage from the heating that occurs with microwaves. An RF transmitter can be applied to rotate M with respect to B; typically 90° or 180° are chosen in MRI studies for the rotation angle. When the RF field is turned off, the moment gradually returns to its original direction (spin relaxation) through thermal agitation and the electronic magnetic fields. The power of MRI is related to the fact that the relaxation rates depend on the electronic fields, which are very sensitive to subtle differences in chemical structures. Thus, differences in the relaxation rates can be used to distinguish healthy, normal functioning tissue from diseased or damaged tissue. The relaxation times are measured by a pickup coil (receiver), which gives a signal that is a function of the changing direction of M. This signal is then interpreted by the computer to give views of different areas and of different depths of the same area. But how do you view different positions, since each nucleus in a given molecule looks the same at different depths? The gradient fields shown in Fig. 4B.6 allow you to view different depths and positions. The gradient magnetic field can alter the primary field slightly as a function of distance in all three directions. Changing the primary field as a function of position changes the Larmor frequency as a function of position and so changes the signal detected.

The Vanderbilt University MRI facility with a superconducting external magnet is shown in Fig. 4B.7. Most MRI studies have been done on hydrogen. When one uses hydrogen for MRI, there is also the complication that the hydrogen may be bonded in different substances in different ways and so have different chemical environments (electronic magnetic fields). This complication is used to advantage to identify the presence and amounts of different compounds at the site of interest. More recent applications have involved other nuclei to expand the types of studies that can be made. For example, it is known that during metabolism different phosphorus compounds are used by body cells. One can determine whether the cell metabolism is normal or abnormal by measuring the relative amounts of these phosphorus compounds. In addition, much attention is given to the development of contrast agents given orally or intravenously that can enhance signals from a particular organ or region. These agents involve paramagnetic ions, paramagnetic complexes, or molecular oxygen involving ions such as gadolinium and manganese. Dynamic contrast studies may be used to study the function of an organ.

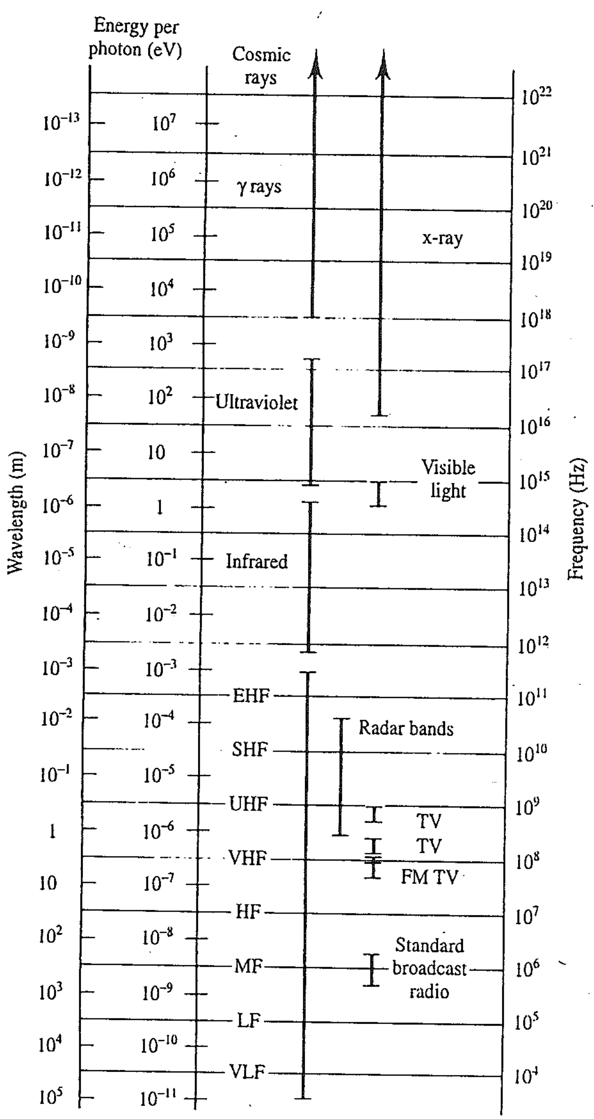

FIGURE 4B.5
The electromagnetic spectrum is identified by wavelength, energy, and frequency. The names given to certain regions of λ (or ν) are shown. Some of the terminology is for example UHF = ultra high frequency, and LF is low frequency.

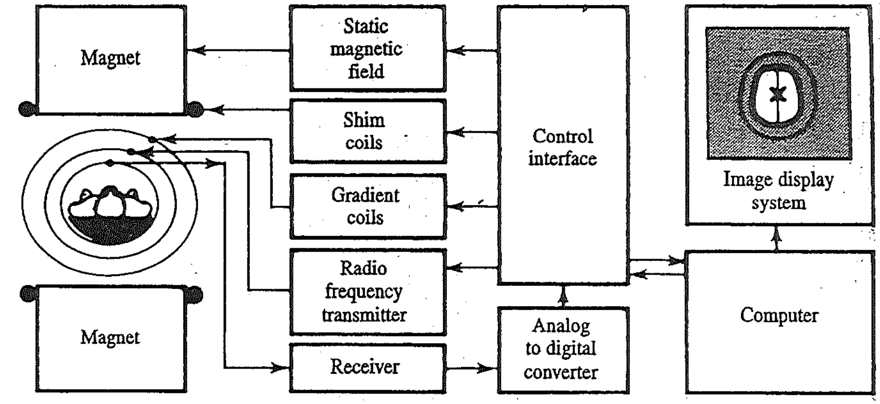

FIGURE 4B.6
Schematic of typical MRI system components. (Courtesy of Vanderbilt University Medical Center.)

Already MRI is applicable to a wide spectrum of problems. Many tumors and other abnormalities in the brain and chest and abdominal organs can be identified, including their size and shape. Since bones do not give an MRI signal, high-quality spinal images of the brainstem and spinal cord are obtained. These can eliminate the need for myelograms in many cases. On the other hand, bone marrow does give a signal that can be used to study bone abnormality. Three different MRI scans of the head of one of the authors are shown in Figs. 4B.8 and 4B.9. In Fig. 4B.8 a sagittal (side) view of the brain is shown. The white, outer surface is the scalp tissue; the next dark area is the outer surface of the skull, the inner white area is bone marrow, and the next dark area is the inner surface of the skull. Two different top views emphasizing different features are shown in Fig. 4B.9. The detailed quality of today's MRI scans is significantly improved, especially when viewed directly on screen rather than in copies such as Figs. 4B.8 and 4B.9.

Blood flow is very important in the health of a patient. Clinical applications of MRI include measurements of blood flow in all vascular regions of the body with specific focus on neurovascular systems. MRI angiograms are routine now. In summary, MRI is now a major, new clinical diagnostic tool in medicine and is rapidly expanding into new areas.