Section B and C

Volume-26

Contents

13. METHODS IN BIOLOGY

G. ELECTROPHYSIOLOGICAL METHODS **1**

H. METHODS IN FIELD BIOLOGY **77**

I. COMPUTATIONAL METHODS **85**

13. METHODS IN BIOLOGY

G. ELECTROPHYSIOLOGICAL METHODS

MAGNETIC RESONANCE IMAGING

Magnetic resonance imaging (MRI), or Nuclear magnetic resonance imaging (NMRI), is primarily a medical imaging technique most commonly used in Radiology to visualize the structure and function of the body. It provides detailed images of the body in any plane. MRI provides much greater contrast between the different soft tissues of the body than does computed tomography (CT), making it especially useful in neurological (brain), musculoskeletal, cardiovascular, and oncological (cancer) imaging. Unlike CT, it uses no ionizing radiation, but uses a powerful magnetic field to align the nuclear magnetization of (usually) hydrogen atoms in water in the body.

Magnetic resonance imaging was developed from knowledge gained in the study of nuclear magnetic resonance. In its early years the technique was referred to as nuclear magnetic resonance imaging (NMRI). However, as the word *nuclear* was associated in the public mind with ionizing radiation exposure it is generally now referred to simply as MRI. Scientists still use the term NMRI when discussing non-medical devices operating on the same principles. The term Magnetic Resonance Tomography (MRT) is also sometimes used.

MRI physics

When a person lies in a scanner, the hydrogen nuclei (i.e., protons) found in abundance in the human body in water molecules, align with the strong main magnetic field. A second electromagnetic field, which oscillates at radiofrequencies and is perpendicular to the main field, is then pulsed to push a proportion of the protons out of alignment with the main field. These protons then drift back into alignment with the main field, emitting a detectable radiofrequency signal as they do so.

Since protons in different tissues of the body (e.g., fat vs. muscle) realign at different speeds, the different structures of the body can be revealed.

Contrast agents may be injected intravenously to enhance the appearance of blood vessels, tumors or inflammation. Contrast agents may also be directly injected into a joint, in the case of arthrograms, MR images of joints. Unlike CT scanning MRI uses no ionizing radiation and is generally a very safe procedure. Patients with some metal implants and cardiac

pacemakers are prevented from having an MRI scan due to effects of the strong magnetic field and powerful radiofrequency pulses.

MRI is used to image every part of the body, but is particularly useful in neurological conditions, disorders of the muscles and joints, for evaluating tumors and showing abnormalities in the heart and blood vessels.

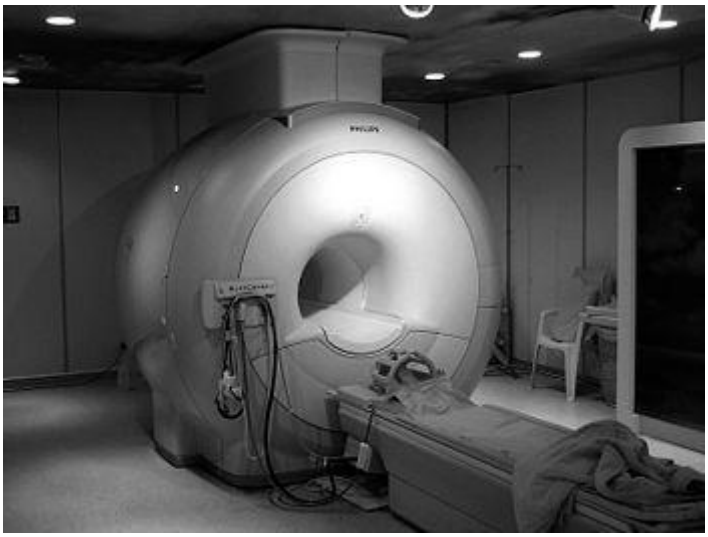

Fig.6: Modern 3 tesla clinical MRI scanner

Subatomic particles such as protons have the quantum mechanical property of spin. Certain nuclei such as ^{1}H (protons), ^{2}H, ^{3}He, ^{23}Na or ^{31}P, have a non–zero spin and therefore a magnetic moment. In the case of the so-called spin-1/2 nuclei, such as ^{1}H, there are two spin states, sometimes referred to as "up" and "down". Nuclei such as ^{12}C have no unpaired neutrons or protons, and no net spin: however the isotope ^{13}C does.

When these spins are placed in a strong external magnetic field they process around an axis along the direction of the field. Protons align in two energy eigenstates (Zeeman effect) one low-energy, and one high-energy, which are separated by a certain splitting energy.

In the static magnetic fields commonly used in MRI, the energy difference between the nuclear spin states corresponds to a photon at radio frequency (rf) wavelengths. Resonant absorption of energy by the protons due to an external oscillating magnetic field will occur at the Larmor frequency for the particular nucleus.

When the radio frequency pulse is turned off, the transverse vector component produces an oscillating magnetic field which induces a small current in the receiver coil. This signal is called the free induction decay (FID). In an idealized nuclear magnetic resonance experiment,

the FID decays approximately exponentially with a time constant T_2, but in practical MRI small differences in the static magnetic field at different spatial locations ("in homogeneities") cause the Larmor frequency to vary across the body creating destructive interference which shortens the FID. The time constant for the observed decay of the FID is called the T_2^* ("T 2 star") relaxation time, and is always shorter than T_2. Also, when the radio frequency pulse is turned off, the longitudinal magnetization starts to recover exponentially with a time constant T_1

In MRI, the static magnetic field is caused to vary across the body (a field gradient), so that different spatial locations become associated with different precession frequencies. Usually these field gradients are pulsed, and it is the almost infinite variety of rf and gradient pulse sequences that gives MRI its versatility. Application of field gradient destroys the FID signal, but this can be recovered and measured by a refocusing gradient (to create a so-called "gradient echo"), or by a radio frequency pulse (to create a so-called "spin-echo"). The whole process can be repeated when some T_1-relaxation has occurred and the thermal equilibrium of the spins has been more or less restored.

Typically in soft tissues T_1 is around 1 second while T_2 and T_2^* are a few tens of milliseconds, but these values vary widely between different tissues (and different external magnetic fields), giving MRI its tremendous soft tissue contrast.

Imaging

A number of schemes have been devised for combining field gradients and radiofrequency excitation to create an image. One involves 2D or 3D reconstruction from projections, much as in Computed Tomography. Others involve building the image point-by-point or line-by-line. One even uses gradients in the rf field rather than the static field. Although each of these schemes is occasionally used in specialist applications, the majority of MR Images today are created either by the Two-Dimensional Fourier Transform (2DFT) technique with slice selection, or by the Three-Dimensional Fourier Transform (3DFT) technique. Another name for 2DFT is spin-warp. What follows here is a description of the 2DFT technique with slice selection.

Slice selection is achieved by applying a magnetic gradient in addition to the external magnetic field during the radio frequency pulse. Only one plane within the object will have protons that are on–resonance and contribute to the signal.

A real image can be considered as being composed of a number of spatial frequencies at different orientations. A two–dimensional Fourier transformation of a real image will express

these waves as a matrix of spatial frequencies known as k–space. Low spatial frequencies are represented at the center of k–space and high spatial frequencies at the periphery. Frequency and phase encoding are used to measure the amplitudes of a range of spatial frequencies within the object being imaged. The frequency encoding gradient is applied during readout of the signal and is orthogonal to the slice selection gradient. During application of the gradient the frequency differences in the readout direction progressively change. At the midpoint of the readout these differences are small and the low spatial frequencies in the image are sampled filling the center of k-space. Higher spatial frequencies will be sampled towards the beginning and end of the readout filling the periphery of k-space.

Image contrast and contrast enhancement

Image contrast is created by differences in the strength of the NMR signal recovered from different locations within the sample. This depends upon the relative density of excited nuclei (usually water protons), on differences in relaxation times (T_1, T_2 and T_2 *) of those nuclei after the pulse sequence, and often on other parameters discussed below under "specialized MR scans". Contrast in most MR images is actually a mixture of all these effects, but careful design of the imaging pulse sequence allows one contrast mechanism to be emphasized while the others are minimized. The ability to choose different contrast mechanisms gives MRI tremendous flexibility. In the brain, T_1-weighting causes the nerve connections of white matter to appear white, and the congregations of neurons of gray matter to appear gray, while cerebrospinal fluid (CSF) appears dark. The contrast of white matter, gray matter and cerebrospinal fluid is reversed using T_2 or T_2 * imaging, whereas proton-density-weighted imaging provides little contrast in healthy subjects.

In some situations it is not possible to generate enough image contrast to adequately show the anatomy or pathology of interest by adjusting the imaging parameters alone. In this case a contrast agent may be administered. A contrast agent may be as simple as water, taken orally, for imaging the stomach and small bowel. However, most contrast agents used in MR are selected for their specific magnetic properties. Most commonly, a paramagnetic contrast agent (usually a gadolinium compound) is given. Gadolinium-enhanced tissues and fluids appear extremely bright on T1-weighted images. This provides high sensitivity for detection of vascular tissues (e.g. tumors) and permits assessment of brain perfusion (e.g. in stroke). There have been concerns raised recently regarding the toxicity of gadolinium-based contrast agents and their impact on persons with impaired kidney function.

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