NMR imaging in biology and medicine

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Over the last thirty years nuclear magnetic resonance (NMR) has become a quite indispensable analytical and structural tool in physics, chemistry and other disciplines. More recently it has been applied as a method for providing internal images of biological systems, and in this role enjoys the advantages of being non-invasive, of penetrating bony structures without attenuation, of not using ionizing radiation, and being without known hazard.

In conventional NMR spectroscopy as practised in Physics and Chemistry, a small specimen, typically less than 1 ml, is placed in the spectrometer coil and its NMR spectra, relaxation times and other parameters are recorded. The specimen is usually homogeneous, the magnetic field is highly uniform, and the NMR spectrum and other characteristics are generated by the whole specimen. In NMR imaging the reverse is the case. The object of interest, for example human anatomy, is heterogeneous and its structure is to be determined and displayed. The magnetic field is deliberately non-uniform ; different parts of the specimen are labelled by the particular field strength they experience, and the NMR spectrum records the spatial distribution of the NMR signal from the specimen.

The intrinsic NMR linewidth of the strongly responding biological components in living systems is narrow, typically a few Hz. If, therefore, a linear magnetic field gradient of order 1 gauss cm^{-1} is superposed on the usual highly uniform magnetic field, the NMR spectrum provides a one-dimensional (1D) profile or projection of proton density along the direction of the gradient.

For an image or picture, one requires at least a two-dimensional (2D) representation of nuclear density. Better still, one would like to have a 2D image of a thin defined plane in the object ; a stack of such images of coplanar slices in the object then provides a complete three-dimensional (3D) representation of the object.

The first practical realization of a 2D NMR image came from Lauterbur (1). By applying the gradient along a number of different directions relative to the object, a series of different 1D profiles were obtained, and these were combined by computer to give a 2D projection image of the object using procedures closely similar to those of CT X-ray scanning.

In CT X-ray scanning the narrow pencil beams of X-rays define a thin imaging slice. On the other hand in NMR imaging the whole object within the NMR coil is irradiated, and the

method as so far described does not provide a thin imaging plane ; the resulting image is therefore a 2D projection of nuclear density on a plane normal to the axis about which the gradient directions are rotated. In this situation the projection-reconstruction approach may be extended to provide 3D images by applying the gradient in many directions isotropically. This has been done (2) though not as yet with high spacial resolution.

The severe computing exercise involved in 3D projection-reconstruction is usually circumvented by methods which define a thin imaging slice in the object either by use of an alternating gradient (3, 4) or by selective irradiation (5, 6, 7). A 2D image may then be generated in the defined plane either by projection-reconstruction in that plane (8), or by defining a strip in the plane which is scanned electronically through the plane (9, 10). Other approaches apply the principles of 2D Fourier transform NMR spectroscopy to gradients applied in two or three dimensions (11) or to gradients of the rf field (12), or they contour the laboratory magnetic field in such a way that only one small volume element is at resonance, which is scanned through an object plane to generate an image (13).

The first NMR image was obtained from two tubes of water (1). Subsequently images have been obtained of increasingly good quality of vegetables (4), fruit (14), and small animals (10, 13-15). The first human NMR image was a live finger (17), soon followed by a live human hand (10), wrist and forearm (18-20). These developments called for magnets with a larger aperture, and with the availability of apertures of 60 cm diameter or more, the first whole-body human images became possible. The first proton NMR images of a human chest were published in 1977 (21), followed by the human abdomen (22) and the human head (23-25). The quality and resolution of the best NMR images now approaches that of CT X-ray images. Although NMR images do at present take longer to acquire than X-ray images, the acquisition time is decreasing and the fastest good quality human images now take about two minutes (24). Development is proceeding on still faster methods (26).

The ideal image would have an excellent signal/noise ratio, a good spatial resolution and a very short acquisition time. However these three desirable attributes are mutually interdependent and conflicting, and a compromise has to be made. Good quality images call for an array of 128 x 128 picture elements, with a signal/noise of at least 30/1.

The type of magnet selected depends very much on the size of the objects to be imaged. For objects not larger than 10 cm in extent, an iron-core electromagnet may be used similar to those used in conventional NMR spectroscopy but with a larger gap. For larger objects such as the human head or body such magnets are less suitable.

The ideal frequency of operation for NMR imaging of the whole human body is not a subject on which there is as yet general agreement. In NMR spectroscopy the signal/noise ratio improves with increasing frequency ν of operation, typically as $\nu^{3/2}$. It is therefore desirable to operate at the highest

frequency consistent with the avoidance of significant attenuation and phase shift in the living tissue. Calculations based on the electrical impedance of rat tissue (27) suggest an upper limit of the order of 10 MHz corresponding to a magnetic field of 2.4 kilogauss for proton NMR. A number of air-core water-cooled electromagnets have been constructed for whole-body NMR imaging which generate a field of about 1 kilogauss with some 15 kW of power. Superconducting magnets of large aperture and of higher field strength are available with the added attraction of excellent field stability and zero electrical power consumption (28).

Protons have been the favourite nuclei for NMR imaging to date an account of their very favourable NMR characteristics coupled with the high concentration of hydrogen in biological systems. Nevertheless other nuclei are of interest for NMR imaging, for example ^{19}F and ^{31}P. In conventional NMR spectroscopy with homogeneous liquids interest centres on the high-resolution spectrum of lines generated by the nuclei in different molecular environments, each with their characteristic electron-shielded chemical shift. In NMR imaging using protons, the high-resolution features of the spectra are normally obscured by the field gradients which are applied. However for other nuclei, for example ^{31}P, the chemical shifts of molecules of interest in biological metabolism are much larger and attempts are being made to generate images of specific molecular species in living systems (29).

The attraction of NMR as a method of medical imaging rests partly on its freedom from hazard and in particular its avoidance of ionizing radiations, and also on its ability to measure and map parameters such as relaxation times which are potential pathological discriminators. The practical outcome depends on the assessment by the medical profession of its value in clinical situations. Clinical trials in a number of centres are currently envisaged, and several commercial enterprises are now actively engaged in this field of research. The cost of an NMR tomographic system is not expected to exceed that of an X-ray CT scanning system.

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