Postprocessing and Cross Validation

Modeling and Quantification

Basic (Physics) Principles of Quantification Using MR

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Learning Objectives:

- Basic principles of MRI
- Factors determining intensity and contrast in MRI
- Contrast agents in MRI

Nuclei with an odd number of protons or neutrons possess and non-zero magnetic moment, the most important representative being the hydrogen nucleus. These nuclear properties are exploited in nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI). MR images represent the weighted distribution of (hydrogen) nuclei within biological tissue, with weighting factors given by the relaxation properties of the nuclear magnet (describing how rapidly excess energy is dissipated and how strongly it interacts with neighboring nuclei), by its microscopic motion in an inhomogeneous magnetic field (diffusion, perfusion), and potentially by its involvement in chemical reactions. The resonance frequency depends on the local magnetic field at the site of the nucleus; hence spatial information is obtained by rendering the magnetic field strength location dependent through the transient application of magnetic field gradients.

MRI is inherently insensitive due to the low quantum energy involved. For typical field strength used in preclinical and clinical imaging only 0.001 to 0.005% of the nuclear magnets will contribute to the signals detected. This limitation governs important imaging parameters such as spatial and temporal resolution. For high resolution structural imaging, typical voxel dimensions are $50mm^3$ to $100\ mm^3$ for small animal and $1mm^3$ for clinical imaging. Temporal resolution may range from less than 1s to hours depending on the type of data acquired. It is important to realize that sensitivity, spatial, and temporal resolution constitutes canonical quantities: improving one of them would inevitably compromise the other ones.

The MR signal intensity is governed by parameters such as relaxation times, diffusion properties, and microcirculation, which all depend on the local tissue characteristics. This is the source of the high soft tissue contrast observed in MRI. By tailoring the data MRI acquisition, individual parameters may be emphasized such that a given structure can be represented with high contrast. With regard to quantitative characterization of tissue the measurement of these parameters becomes attractive: T1, T2 or diffusion maps represent tissue features and changes in these parameters indicate alterations in tissue structural or physiological properties.

The MRI signal intensity and hence contrast can be modulated by administration of contrast agents (CA), compounds that affect the relaxation properties of endogenous tissue (hydrogen) nuclei. Effective CAs must exert a strong local magnetic field. This is achieved by using compounds that contain at least one unpaired electron, the electron magnetic moment being 650 times that of the hydrogen nucleus. Typical CAs used in MRI are gadolinium (III) complexes (with 7 unpaired electrons) or Fe_xO_y nanoparticles (with up to 5 unpaired electrons per Fe). By coupling CAs to targeting moieties specific probes can be designed, which opens the door to molecular imaging applications. The effect of CAs on MRI relaxation rates is directly proportional to the total amount of CA in a voxel; hence generation of maps of the absolute relaxation times allows the quantitative determination of local concentrations of the CA provided the proportionality factor (the molar relaxivity) and the CA's distribution volume are known. The option to derive quantitative information is an important feature that is attractive for molecular imaging studies using MRI.