MR Physics for Physicists

From Bloch Equation to MR Contrast: Relaxation and Physical Bases of Tissue Contrast

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Highlights

- Contrast in MRI is derived mainly from variations in the relaxation properties of tissues and how they change with pathological conditions
- Semi-classical theory of dipole-dipole interactions predicts how relaxation rates depend on detailed molecular dynamics of water molecules
- Relaxation reflects the average effects of water interactions with multiple, heterogeneous constituents of tissue and water compartmentation

Relaxation processes are important because much of the contrast that is apparent in clinical MR images of soft tissues used for radiological diagnoses usually arises from the heterogeneous distribution of tissue proton relaxation rates. The Bloch equations define the relaxation rates for recovery of the longitudinal magnetization ($R_1=1/T_1$) and decay of the transverse magnetization ($R_2=1/T_2$) following an RF excitation. The sensitivity of MRI to pathological changes and variations in tissue composition which underlies its clinical usefulness most often relies on detecting small changes in these water relaxation rates. Thus it is of practical importance to understand the mechanisms responsible for proton relaxation in heterogeneous media such as tissues, and to be able to explain the changes that occur in tissue relaxation in disease.

It should be emphasized that many detailed aspects of relaxation in complex biological media are not well understood in a quantitative sense, by which we mean that there do not exist adequate models that can be used to account precisely for the observed relaxation in many practical cases. Furthermore, since tissues are heterogeneous, have complex internal structures, and vary widely in their detailed composition, and because different pathological processes involve different types of change in tissue composition and character, it is often not possible to explain observations of changes in relaxation in terms of specific underlying causes. However, we do possess a reasonably complete understanding of the various basic processes and factors that contribute to relaxation in simple solutions and aqueous biological media. Changes in relaxation that occur, for example in disease, will then correspond to structural or chemical modifications that in turn modulate one or more of these contributing processes.

Biological tissues are largely composed of water, so understanding relaxation in pure water is a reasonable first step to understanding relaxation in more complex situations. Relaxation may occur whenever nuclei experience appropriately time-varying magnetic fields, just as they may undergo changes under the influence of excitatory RF fields. The Bloch equations show that if nuclei are exposed to magnetic fields fluctuating at the resonant frequency, then in a rotating frame they will experience rotations about those fields. Bloembergen, Purcell and Pound {1} first described how magnetic interactions between the dipoles of hydrogen nuclei within the same water molecule or between molecules expose nuclei to weak, fluctuating local fields that can induce transitions between energy levels and/or cause a loss of phase coherence i.e. promote relaxation. Many relaxation effects can be interpreted in terms of these fundamental dipole-dipole interactions and the manner in which they are modulated by e.g. changes in temperature, frequency of measurement, or as a result of the addition of other molecules. The efficiency of relaxation by dipolar effects depends on how well the spectral composition of the locally fluctuating fields matches the resonance frequency of the relaxing nuclei, which is determined by the correlation time that characterizes their temporal variance. The addition of proteins and other macromolecules in solution increase relaxation rates because dipolar interactions in the vicinity of slowly moving structures are more efficient. The effects of those local interactions are then spread by exchange around the rest of the medium. Compartmentation restrictions may limit the extent to which this can occur, giving rise to multiple relaxation rates within the same voxel. Other contributions to relaxation may come from the presence of paramagnetic species such as metal ions or molecular oxygen which generate very intense local magnetic fields. Other mechanisms for modulating the magnetic fields experienced by nuclei include exchanging between sites of different chemical shift (i.e. resonant frequencies), and diffusion within a magnetically inhomogeneous medium. These processes have their own characteristic dependences on field as well as other parameters that characterize the medium.

{1} N. Bloembergen, E.M. Purcell and R.V. Pound (1948), Phys. Rev. **73**, 679