Specialty Area: MR Physics for Physicists

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Highlights:

- Water is the primary constituent of most tissue and its proton MR signal provides a powerful surrogate of tissue anatomical structure.
- Regional differences in water proton spin relaxation properties are a principal mechanism used to generate contrast in clinical MRI.
- The phenomenological formalism of Bloch, introduced nearly 70 years ago, represents a valuable starting point to characterize and understand fundamental macroscopic features of nuclear spin relaxation in vivo.
- Spin relaxation properties are determined by complex molecular dynamics driven by thermal Brownian motion which generate fluctuating magnetic fields with a rich spectral density.
- The B_0 dependence of tissue relaxivity provides insight into relevant spectral density.

Title: From Bloch to Lauterbur: Spin Relaxation and the Origin of MR Tissue Contrast

Target Audience: Magnetic resonance scientists, engineers, and physicists

Learning Objectives: To more completely appreciate the molecular origins of water proton signal properties that determine MR tissue contrast, gain insight into fluctuating magnetic fields at the molecular level and how these depend on heterogeneous media, and to develop an understanding of MR relaxation agents and how these work.

Discussion: Detailed knowledge of regional variations in spin relaxation properties play a central role in clinical and basic science MR applications. Relaxation weighted acquisitions represent the primary approach to generate outstanding soft-tissue contrast in MRI and are the work-horse of the clinic to identify pathology. The development and refinement of imaging biomarkers to investigate normal physiology and to improve disease characterization is a fundamental aspect of MR science and these approaches rely on detailed knowledge of relaxation properties. Quantitative relaxographic measurements have the potential to provide unique information on tissue structure including the characterization of discrete molecular environments, tissue compartmentation, chemical composition, and equilibrium exchange. Given the prominent role relaxation characteristics play in all aspects of biological MR it is important to gain appreciation of underlying principles governing relaxation behavior.

Fundamental concepts in spin relaxation theory were developed early in NMR's history[1,2] based on simple models and have been refined over the past seven decades to explain finer aspects of NMR relaxation behavior in biological systems.[3-5] Although spin relaxation mechanisms in condensed heterogeneous systems (such as tissue) are complex and not completely understood, the application of basic relaxation theory is a reasonable starting point to capture basic characteristics.

Given sufficient time in a strong external magnetic field a spin system will come to thermal equilibrium with its surroundings (i.e. the lattice) and populations of the nuclear spin energy states will be described by the Boltzmann distribution. At equilibrium the resulting magnetization from such a system is longitudinal and there is no transverse component. A radiofrequency pulse can perturb this equilibrium and create a transient state in which longitudinal magnetization is reduced and transverse magnetization created. Relaxation is the process through which equilibrium is restored, and time constants are defined separately for the transverse and longitudinal components based on the respective kinetics of their return to equilibrium. For water protons in tissue, relaxation is driven by fluctuating magnetic fields at the appropriate frequency generated primarily by intra- and inter-molecular water protons as they undergo Brownian motion. At the molecular level, tissue is characterized by highly complex water-macromolecular interfaces including extended surfaces, cavities, and laminar structures which contribute to a broad span of water residence times that typically range from nanoseconds to hundreds of microseconds and longer. Exchange is thought to be rapid between most of the macromolecular sites and bulk water (i.e. water several molecular diameters distant from macromolecule surfaces); that is, water can sample all possible equivalent sites with exchange rate constants much greater than intrinsic site $1/T_1$ values. Further complexity is added by the fact that all of these sites include a small fraction of exchangeable protons. Taken together, timescales for auto-correlation of local magnetic fields sensed by water protons vary from ~picoseconds to ~milliseconds and these contribute to a rich spectral density. A manifestation of this richness is a large difference in transverse and longitudinal time constants and a marked magnetic field dependence[5-7] observed for longitudinal relaxation time constants of tissue water protons. Fortuitously, typical tissue water proton transverse and longitudinal relaxation timescales (milliseconds to seconds) are particularly well-suited to investigate many biologically relevant processes.

References

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5. Koenig and Brown. NMR Encycl. 6:4108-4120 (1996).
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7. Rooney, Johnson, Li, Cohen, Kim, Ugurbil, and Springer. Magn. Reson. Med. 57:308-318 (2007).