Session Title: MR Physics for Physicists

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Highlights

- Equilibrium magnetization represents a balance between magnetic and thermal energy.
- Relaxation depends on the interaction of water spins with their neighbors.
- The density matrix provides a simple way to understand the behavior of spin systems.

Title: Application of Quantum Mechanics and Statistical Mechanics--Equilibrium Magnetization, Relaxation, and Density Matrix

Target Audience: Investigators with a background in Physics who want to understand the basis of MRI

Outcome/Objectives: Attendees will learn the determinants of equilibrium magnetization, a simple quantum picture of relaxation, and how the density matrix can be used to understand the evolution of magnetization during an experiment.

INTRODUCTION: MRI image quality depends on signal strength and contrast between tissues. These in turn depend on physical properties of the spin system: equilibrium magnetization represents an upper limit on the magnitude of the signal and relaxation is the most common source of image contrast. Identification of the physical factors that determine these quantities, and the ability to predict changes in magnetization through time, are critical for understanding the fundamental limits of MRI as well as opportunities to improve image quality and provide new information.

EQUILIBRIUM MAGNETIZATION: If quantum energy levels (e.g., m_z = ½ and -½) have different populations, then the spin system will possess a net magnetic moment. When spins are in thermal equilibrium with their surroundings, at temperature T, the populations are dictated by the Boltzmann distribution: the lower energy state will have slightly higher population, giving the spin system a net magnetic moment parallel to the applied B_0 field. As field strength increases, the energy difference between states also increases, which makes the population difference and the equilibrium magnetization larger. Hence, higher field scanners polarize the sample more, providing a larger initial magnetization for MRI and MRS measurements.

RELAXATION: A transition between quantum states involves energy exchange between a spin and its surroundings. Neighboring atoms form a large reservoir of potential partners for exchange, and are collectively called the 'lattice', a term originating in solid state NMR. If spins are disturbed from equilibrium, exchange will gradually bring them back into thermal equilibrium with the lattice—this process is called relaxation. Relaxation rates for tissue water depend on the molecular environment, and hence differ between tissues, providing valuable biomedical information.

THE DENSITY MATRIX: The density matrix provides a convenient statistical estimate of the physical properties of a spin system. Transverse magnetization is of particular interest, because it is the quantity that is measured in NMR. The density matrix can be used to describe equilibrium magnetization and calculate the evolution of magnetization under the influence of external magnetic fields and for systems of coupled spins.

CONCLUSION: The combination of statistical and quantum mechanics provides predictions of equilibrium magnetization and the time dependence of magnetization (including relaxation) under the influence of magnetic fields. These phenomena play important roles in all MRI and MRS experiments.

REFERENCES

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