Session Title: MR Physics for Physicists

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Highlights

- Introducing a sample into a strong uniform magnetic field perturbs the field in and around the sample
- The Lorentz sphere construct provides a means of estimating fields at points within a molecule embedded in a macroscopic sample composed of other molecules
- Tissue magnetic susceptibility can create contrast that arises from subtle field perturbations generated by local variation in magnetic properties
- Utilizing this information as observed in gradient echo phase images allows to recover information from the underlying susceptibility distribution

Title: Static magnetic field: magnetic field (in)homogeneity, effects of susceptibility, demagnetizing field, and Lorentz sphere

TARGET AUDIENCE: MR researchers who are interested in understanding the relation between magnetic susceptibility, induced magnetization and applied field and possibilities to extract susceptibility from MR measurements.

OBJECTIVES: To review the relations between macroscopic average fields, magnetization and microscopic fields and to convey how information about tissue magnetic susceptibility can be recovered from gradient echo phase images.

Static magnetic field Static magnetic fields of modern MRI scanners are exquisitely homogeneous thanks to their advanced design and careful adjustments onsite. Introducing a sample or a subject into the scanner for imaging creates field distortions due to the fact that different materials (tissues, water, bone, air) exhibit differing susceptibilities resulting in different field strengths locally in the presence of the same external magnetic field. These materials then become sources of magnetic field within the static field created by the main magnet due to the interaction of the field with the magnetic moments of the molecules in the sample or subject and perturb the field in and around the sample.

Magnetic susceptibility Magnetic susceptibility can be loosely defined as the degree of magnetization in an object in response to an external magnetic field. There are several mechanisms by which materials become magnetized that involve nuclear and electronic spins and orbital motion of electrons. The most important mechanisms for biological tissue are Curie paramagnetism and Langevin diamagnetism. Placement of an object in the magnetic field of a scanner results in field changes that depend on the shape and orientation of the object and, in general, extend beyond the borders of the imaged object.

Local field The Larmor frequency of the nuclei is proportional to the local magnetic flux density at the nuclear sites including contributions from the electron and nuclear magnetizations. Care has to be exercised when trying to adapt macroscopic results for the magnetic flux density to the local microscopic distance scale which is appropriate to the individual nuclear spins. A nucleus at some position r is sensitive not only to the long-range environment, but also to its local environment. Consider the contribution of nearby dipoles within a volume δV centered at r that is smaller than the coarse-grained volume dV over which the macroscopic magnetic flux density is uniform, but is large enough to include many nuclear dipoles. If this volume is spherical and contains many dipoles that are randomly distributed but aligned parallel to each other, the magnetic field contribution of these nearby dipoles is nearly zero. Furthermore, when molecular diffusion is considered, the contributions of the nearest dipoles average to zero on an NMR timescale due to random reorientation of the inter-nuclear vec-

tor. From a local perspective, the dipole at r does not see a net field from the nearby dipoles and appears to reside within an empty cavity δV.

Sphere of Lorentz The Lorentz sphere is a construct, first introduced by Lorentz to electrostatics, that is used to estimate the local field (i.e., external microscopic field that is related to the immediate external environment of the host molecule in which the nucleus resides) from the macroscopic fields. To this end, the sample is conceptually divided into two regions, one which can be treated as a continuum (long-range region) and the second, the Lorentz cavity region or local region, where the atomic scale structure is taken into account. The cavity itself is typically chosen spherical and as pointed out before it is presumed that complete cancellation of the contributions of the nearest dipoles occurs within the cavity. The field within the small spherical hole inside the magnetized sample (created by carving out the small cavity) can be evaluated by subtracting the uniformly magnetized small spherical volume from the macroscopic field in the sample to give the effective field inside the cavity. Thus, a relationship between the macroscopic flux density and the local microscopic flux density is established.

Magnetic susceptibility mapping Gradient echo phase images have recently demonstrated their ability to provide impressive anatomical contrast complementary to the magnitude by directly reflecting local magnetic field changes induced by the distribution of magnetic susceptibility of the measured object. These fields may be considered as a result of a convolution between a susceptibility distribution and the field of a magnetic point dipole. It should thus be possible to directly relate the spatial variation of the NMR frequency to the spatial variation of susceptibility by reversing the convolution relation. There have been indeed various methods developed to reconstruct tissue susceptibility from phase (resp. frequency) information including Fourier domain based methods and iterative solutions in the spatial domain incorporating *a priori* information. Challenges, however, remain since the inverse problem is ill-defined and noise sensitive, and the resulting susceptibilities despite being quantitative have to be considered as relative values with respect to some reference substance.

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