Gradient Systems
(Syllabus for ISMRM 2013 MR Engineering Educational Session)

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Introduction

Gradient coils put the "I" into MRI; they enable spatial encoding of the NMR signal for the production of images. Spatial encoding in MRI is achieved by the superimposition of linearly-varying magnetic fields upon the uniform static magnetic field. In this way the NMR frequency also varies linearly with spatial position, and so Fourier transformation of the received signal produces a projection of the signal intensity along one axis [1]. All three spatial dimensions can be encoded by superimposition of three orthogonal linear gradient fields in myriad pulse sequences.

"The gradients" is a term that is regularly used to refer to the hardware subsystem that contains the gradient coils, but often additionally contains the room-temperature shim coils, the passive shims and cooling mechanisms. "A gradient coil" is an arrangement of wires that, when energised, produces a magnetic field gradient.

This syllabus covers the requirements, design, performance and limitations of gradient coils as well as an introduction to some of the recent trends and developments. It is assumed that the reader has a basic knowledge of MRI and electromagnetism. An inexhaustive list of references is provided for the inquisitive reader.

Syllabus

- Electromagnetic design of gradient coils.
  - Magnetic field gradient generation [2].
  - Inverting the Biot-Savart law: an ill-posed inverse problem.
  - How to get the most gradient field out of your gradient coil for a given current: efficiency.
  - Inductance and resistance as limits to coil efficiency [3, 4].
  - Tackling eddy currents using active magnetic screening/shielding [5, 6].
  - Internal Lorentz forces and how to balance the resulting torque [7, 8].
  - The discrete wire approach to designing gradient coils [9, 10, 11, 12].
  - Designing coils with a continuous current density using the stream-function trick [13, 14, 15, 16, 17].
  - Algorithmic approaches to solving the multi-objective problem [9, 18, 11, 19, 20].
- Characterising the performance of a gradient coil design by simulation and experiment [4].
  - Primary gradient magnetic fields.
  - Coil impedance.
  - How to use an appropriate figure-of-merit the compare across gradient coil designs [3].
  - Magnetic shielding [21].
  - Vibration and noise [22].
  - Heating and temperature [23].
  - Peripheral nerve stimulation [24].
- Recent trends and developments in gradient coils.
  - Insert gradient coils and dual gradient sets provide different performance options [25, 26].
  - Coils with non-standard geometry: short coils, asymmetric coils and gradients for hybrid MR devices [27, 28, 29].
  - Non-linear encoding [30, 31].
  - How to control the wire spacing and temperature in gradient coils [20, 32, 33].

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