Gradients: What can they do?

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Highlights:

- Bo-field gradients allow spatial signal localization and encoding
- Bo-field gradients represent one of the core elements of MRI
- Bo-field gradients can generate physiological effects and sound

Target audience: – MR engineers, scientist and physicians interested in learning more about basic MR concepts

Outcome/Objectives: To be able to understand the basic principle of spatial encoding in MRI, based on field B_0 gradients, and to further understand their generation and corresponding constraints.

Purpose: The gradients are a key component of an MR system, serving multiple purposes: signal localization/spatial encoding, motion encoding, signal preparation and contrast manipulation.

Methods & Results:

The gradient system is one of the most important components of an MRI scanner. It allows the superposition of well defined, linearly in space varying, magnetic field components which can be controlled in time and space to the usually very homogenous main magnetic field (B_0). The gradient field (G) are usually be applied in all spatial directions allowing to make the Larmor frequency spatially dependent which is the key requirement for basic spatial signal localization or encoding.

Signal localization - Gradients are involved in localized signal manipulation, with the simplest example being slice selective excitation in which an appropriate RF pulse is played out simultaneously to a selection gradient. Thus, transverse magnetization is generated only from species, whose actual resonance frequency falls into the given RF pulse bandwidth, located perpendicular to the direction of the selection gradient. More sophisticated approaches allow for a huge variety of spatially selective excitation approaches or spatially selective longitudinal magnetization.

Signal encoding - After appropriate spatially selective signal excitation gradients furthermore allow spatial encoding, to facilitate in-plane (2D) or inner-volume (3D) spatial resolution. In the simplest but most robust Cartesian techniques this is done by frequency encoding, which means sampling the signal in presence of a stationary read-out gradient making the Larmor frequency spatially dependent, having additionally a spatially dependent phase shifts imprinted into the detectable signal via phase encoding, switching corresponding gradients orthogonal to the read-out direction. In this way gradients define and span the so-called k-space, that space in which signal encoding and sampling is performed. More sophisticated k-space trajectories are conceivable and data measured in k-space can be mapped by appropriate reconstruction into the spatial domain to form an image.

Higher Signal encoding - Gradient-based spatial encoding is achieved for a given voxel by the total phase accumulation (γrG) over time, proportional to the time integral of the scalar product of gradient and spatial coordinate (r). This is simple if the voxel does not move. However, in case of motion the voxel experiences different local magnetic fields in presence of a gradient, which can, if not compensated, result in an image artifact or which can be used as a higher-order encoding, visualizing moving signal components even measuring flow (velocity and acceleration). Flow means motion on a macroscopic scale. Deformation can be understood as motion on a smaller scale, but driving gradient pluses higher and longer allows to further sense motion on the microscopic scale, much smaller than the usual voxel size, addressing diffusion. This means if driven in the right way, gradients are able to encode even more hidden information into the signal (flow, deformation/elasticity and diffusion and its anisotropy) and measure it spatially resolved.

Spoiling - However, beyond signal generation and localization, gradients can be applied to spoil transverse magnetization. Transverse magnetization can be de-phased, or if even stronger gradients are involved diffusion processes can be employed to spoil residual signal. Thus, gradients can suppress residual signal after magnetization preparation and can be used to tailor image contrast by suppressing certain unwanted transverse coherences.

Generation of gradients - However, gradients have to be generated in an MRI. To avoid eddy currents in the magnet, self-shielded gradient coils are used in modern MR systems driven by high-power, highly accurate amplifiers. Gradients are working in the audio frequency range and are steered by driving units including pre-emphasis to compensate for residual eddy currents and cross-talk. Even if this system represents a highly engineered (and expensive) component, its performance depends on the application and is not perfect. Imperfections and simplifications (like Maxwell terms) can be modeled and measured and have to be taken into consideration if advanced sequences and clinical applications are designed.

Physiological Effects and Sound - Due to the high gradient switching rate and amplitudes significant field changes can provoke peripheral nerve stimulation. This unpleasant sensation limits the maximal slew rates and amplitudes in most of the modern MRI systems. Other constraints result from the design and the technical integration of the gradients into an MRI, which actually form a kind of bad loudspeaker generating a considerable level of sound and thus patient's and operator's discomfort.

Discussion & Conclusion:

Even if additional ways of spatial signal encoding are emerging like parallel reception and parallel transmission, which also could be considered to form gradients, the B_0 field gradient is and will be the workhorse in spatial encoding and forms the essential backbone also in future clinical MRI systems.