Gradient Coil Design – Safety Aspects
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Introduction
Gradient coils are a key component of any magnetic resonance (MR) system design. They are designed to produce the spatially linear magnetic fields required during, and essential to, the imaging process. Over the years, gradient coils and related MR components have been pushed to ever higher levels of performance. This has largely been driven by the progression and requirements of new imaging applications. Advancements such as active-shielding, water-cooling and high power switch-mode gradient amplifiers have contributed greatly to enhanced performance. However, as gradient electrical power increased, the design of these relatively complex, pulsed, electromechanical coil structures became more challenging and concerns such as peripheral nerve stimulation (PNS) and acoustic noise came to the forefront. While there are a number of safety aspects in MR system design, those that relate mainly to, or are influenced by, the gradient coil design will be reviewed for modern system design.

Peripheral Nerve Stimulation
Time-varying magnetic fields induce an electric field according to Faraday's law and the electric field can excite certain tissues with thresholds that are frequency dependent. At human whole-body scale, the gradient coils are pulsed at very high current and voltage levels to provide large peak gradient strength with short rise time. Large portions of the body are thus exposed to rapidly switched magnet fields that can, in some cases, cause peripheral nerve stimulation (PNS). Efforts are made in practice to minimize the likelihood of uncomfortable PNS through design measures, e.g. by paying attention to peak fields, and through predictive and output control algorithms in the scanner software. In practice the linear volume of the gradient coil is generally matched to that of the homogeneous volume of the main magnet and this provides certain benefits. It is, however, still generally possible to cause PNS as gradient power is increased and, thus, software control measures are taken in modern systems to reduce the likelihood of uncomfortable PNS.

The primary international standard for MR safety is IEC 60601-2-33 ‘Particular requirements for the safety of magnetic resonance equipment for medical diagnosis’ and allows establishing the gradient output limits of a specific design based upon an experimental study, or to use a set of default values provided in the standard. In practice, the approach of directly determining the limits is more commonly used. In some research cases, specialty gradient coils are used, e.g., head insert gradient coils, to provide increased performance over a limited region of space. Less of the body is exposed in this case, and although likelihood of PNS may be reduced, this approach limits the applications. While PNS is the main tissue stimulation effect observed in practice, it is noted that the IEC standard also calls out limits related to the prevention of cardiac stimulation and this must also be given attention during design and assessment.

Additional Safety Aspects in Gradient Coil Design
In addition to PNS, there are a number of other safety aspects in gradient coil design given the high power nature of the device. These include acoustic noise, electrical safety, mechanical, and flammability considerations. When combined with performance and functional requirements, such as peak strength, slew rate, linearity/imaging volume, eddy current characteristics, orthogonality, integrated shims, etc., the design problem becomes multi-faceted and involves multiple disciplines. Materials must be selected to balance mechanical properties against electrical and thermal properties. Mounting approach and choices can influence acoustic noise and/or vibration transfer to other structures. Material choices are further constrained by the need for low/no eddy current generation and no deleterious effect on the main Bo field. Composite materials are thus common in many gradient coil designs. Thermal protection against overheating is another consideration, for which, built in temperature sensors are generally used to provide a control or limiting measure. These aspects will be further reviewed along with the basic topic of PNS.