

Optimization Strategies for Gradient Magnetic Field Uniformity in Magnetic Resonance Imaging Systems

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Abstract: The gradient magnetic field is a core component of magnetic resonance imaging (MRI) systems, and its uniformity is directly related to spatial resolution, signal-to-noise ratio, and lesion detection accuracy, making it a key factor constraining imaging quality. At present, the gradient magnetic field in clinical and research MRI systems is susceptible to disturbances arising from coil design, electromagnetic interference, and mechanical deformation, and its uniformity often fails to meet the requirements of high-precision imaging. To address this issue, this paper systematically reviews the evaluation indices and influencing mechanisms of gradient magnetic field uniformity, and proposes targeted optimization strategies from four dimensions: coil structure design, electromagnetic compatibility, mechanical stability, and post-processing calibration and compensation, including novel coil design approaches.

Keywords: Magnetic resonance imaging; gradient magnetic field; uniformity optimization; eddy current compensation; conformal technology

Introduction

Magnetic resonance imaging (MRI), with its advantages of non-invasiveness and high spatial resolution, has been widely applied in medical diagnosis and research. As the core component enabling spatial encoding of signals in MRI systems, the uniformity of the gradient magnetic field directly affects imaging quality and diagnostic accuracy. Therefore, in-depth research on optimization strategies for gradient magnetic field uniformity is of great significance for improving the performance of MRI systems, ensuring the quality of clinical diagnosis, and promoting the development of medical research.

1. Core Role of Gradient Magnetic Fields in MRI Systems and the Uniformity Evaluation Framework

1.1 Core Functions of Gradient Magnetic Fields and Their Relationship with Imaging Mechanisms

Gradient magnetic fields constitute the core mechanism for spatial localization of MRI signals. By superimposing linearly varying magnetic fields onto the main magnetic field, spins at different spatial positions experience different resonance frequencies, thereby enabling three-dimensional spatial encoding along the x-, y-, and z-axes. The switching speed and uniformity of gradient magnetic fields jointly affect



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imaging efficiency and image quality. Rapid gradient switching can shorten imaging time and meet the requirements of dynamic imaging, while a highly uniform gradient magnetic field ensures that protons with identical resonance frequencies correspond to the same spatial location, thus avoiding image artifacts and geometric distortion. Moreover, the performance of gradient magnetic fields is closely associated with imaging sequences. In specialized sequences such as diffusion-weighted imaging, gradient field uniformity is critical to sequence sensitivity and data accuracy, directly influencing the detection of subtle lesions and the quantitative analysis of metabolites.

1.2 Core Evaluation Indicators of Gradient Magnetic Field Uniformity

The evaluation of gradient magnetic field uniformity should integrate quantitative metrics with actual imaging performance. Key quantitative indicators include gradient linearity, magnetic field intensity error, and spatial consistency. Gradient linearity reflects the degree to which the magnetic field varies linearly with spatial position; for clinical-grade MRI systems, the deviation is generally required to be within 2%. Magnetic field intensity error affects the accuracy of spatial encoding and should be controlled within 1%. Spatial consistency indicates the uniform distribution of the gradient magnetic field within the imaging volume and is typically assessed by the ratio of the standard deviation to the mean magnetic field intensity across the region of interest. In addition to these quantitative measures, practical evaluation must also incorporate image quality assessment. By observing the geometric accuracy and signal uniformity of images obtained from standard phantoms, gradient magnetic field uniformity can be indirectly evaluated to ensure consistency with clinical application scenarios^[1].

1.3 Thresholds of Gradient Magnetic Field Uniformity and Their Clinical Significance

A large body of clinical evidence indicates that deviations in gradient magnetic field uniformity beyond certain thresholds can significantly degrade imaging quality. When the uniformity deviation exceeds 3%, head imaging is prone to artifacts along the skull boundaries, adversely affecting the diagnosis of subtle intracranial lesions. In abdominal imaging, non-uniform gradient fields can result in blurred organ

boundaries, thereby reducing the accuracy of tumor staging. In research applications, such as functional magnetic resonance imaging (fMRI), the uniformity deviation of the gradient magnetic field must be controlled within 1%; otherwise, it may interfere with the detection of blood oxygen level-dependent (BOLD) signals and compromise the accuracy of brain functional localization^[2]. Therefore, strict control of gradient magnetic field uniformity deviations is not only a technical requirement for improving image quality, but also a fundamental prerequisite for ensuring clinical diagnostic accuracy and promoting the in-depth development of medical research.

2. Core Factors Affecting Gradient Magnetic Field Uniformity in MRI Systems

2.1 Defects in Coil Structure Design

Coil structure design is a core factor determining gradient magnetic field uniformity. Traditional gradient coils typically adopt a cylindrical symmetric structure, which simplifies the design process but tends to cause magnetic field intensity attenuation at the periphery of the imaging region, resulting in reduced uniformity. Insufficient precision in coil winding directly leads to deviations in magnetic field distribution. For example, non-uniform winding spacing and fluctuations in conductor diameter can produce localized anomalies in magnetic field intensity, while improper allocation of coil turns may cause gradient field linearity deviations to exceed acceptable limits.

In addition, inappropriate coupling design among the gradient coils, main magnetic field coils, and radiofrequency coils can induce superimposed magnetic field interference, further degrading the uniformity of the gradient magnetic field.

2.2 Electromagnetic Interference Factors

Electromagnetic interference represents a major external factor affecting the uniformity of gradient magnetic fields in MRI systems. Internally, multiple sources of interference coexist. Current fluctuations in the main magnetic field coils and high-frequency signal radiation from radiofrequency coils can couple electromagnetically into the gradient coils, causing transient fluctuations in the gradient magnetic field^[3]. External environmental interference is also non-negligible. Large-scale medical equipment in hospital settings (such as CT scanners and linear accelerators),

harmonics from power supply systems, and voltage fluctuations in external power grids may affect the stability of the gradient magnetic field through power lines and spatial radiation. In addition, eddy currents generated during gradient coil switching can induce opposing magnetic fields in surrounding metallic components. When superimposed on the intended gradient field, these induced fields can severely degrade uniformity, a problem that is particularly pronounced in high switching-rate systems.

2.3 Mechanical Deformation and Assembly Errors

Mechanical deformation and insufficient assembly precision can directly lead to a deterioration in gradient magnetic field uniformity. During operation, gradient coils generate Joule heat, causing an increase in coil temperature. If the thermal management and heat dissipation design are inadequate, temperature variations can result in thermal expansion and contraction of coil materials, leading to deformation. Such deformation alters the spatial positioning of coil windings and disrupts the uniformity of the magnetic field distribution. Furthermore, mechanical vibrations during equipment transportation and installation may cause relative displacement between the gradient coils and other components. During assembly, precision deviations in coil support structures and stress release in fastening elements can induce subtle coil deformations. These mechanical factors can collectively result in permanent deviations in gradient magnetic field uniformity^[4].

2.4 Insufficient Magnetic Field Calibration and Compensation

Post-calibration and compensation of gradient magnetic fields are critical to ensuring uniformity. Inappropriate calibration methods or the absence of effective compensation mechanisms can leave inherent deviations uncorrected. Traditional calibration approaches often rely on a static calibration mode, in which calibration is performed only once during the initial installation of the system. Such methods are unable to cope with uniformity fluctuations caused by coil aging and environmental changes during long-term operation. The limited precision of compensation algorithms also constrains optimization effectiveness. For instance, conventional linear compensation algorithms are inadequate for correcting nonlinear

magnetic field deviations. Moreover, some low-cost MRI systems are not equipped with real-time compensation modules, making it impossible to dynamically correct magnetic field fluctuations and thus difficult to maintain uniformity at a stable level. In addition, insufficient precision of calibration phantoms and non-standardized calibration procedures can lead to distorted calibration data, further degrading gradient magnetic field uniformity.

3. Optimization Strategies for Gradient Magnetic Field Uniformity in MRI Systems

3.1 Optimization of Coil Structure Design: Establishing a Solid Foundation for Uniformity

Optimization of coil structure design is a fundamental measure for improving gradient magnetic field uniformity. The adoption of novel topological structures—such as composite coil configurations based on combinations of Helmholtz and Maxwell coils—can enhance magnetic field linearity within the imaging region by optimizing the distribution of coil turns and winding spacing. Finite element simulation techniques can be employed to construct three-dimensional coil models and simulate magnetic field distributions under different structural parameters, enabling precise optimization of the spatial layout of coil windings and reduction of edge-field attenuation^[5]. High-precision winding processes should be adopted, using automated winding equipment to control conductor spacing errors within 0.1 mm, thereby ensuring uniform winding distribution. Conductors with low temperature coefficients should be selected to minimize the impact of temperature variations on coil structure. In addition, optimizing the coupling distance and shielding design between gradient coils, the main magnetic field coils, and radiofrequency coils can reduce superimposed magnetic field interference, thereby enhancing gradient magnetic field uniformity at the structural level.

3.2 Electromagnetic Compatibility and Anti-Interference Optimization: Blocking Interference Transmission Pathways

To address electromagnetic interference, a multi-level electromagnetic compatibility (EMC) protection system should be established. Within the MRI system, gradient coils can be enclosed in shielded cavities, with shielding materials composed of a composite structure combining high-conductivity copper foil and high-permeability

permalloy to block internal electromagnetic radiation. An additional grounded shielding layer between the gradient coils and radiofrequency coils can further reduce inter-coil coupling interference. Adaptive electromagnetic shielding technologies can also be introduced. By using sensors to detect interference signals in real time, the shielding layers can be driven to generate opposing magnetic fields, thereby canceling the effects of external interference on the gradient magnetic field. The gradient coil driving circuitry should be optimized through the use of low-noise power supplies and filtering circuits to minimize magnetic disturbances caused by current fluctuations. Surge protectors and harmonic filters can be added to power supply lines to suppress interference originating from the external power grid. To mitigate eddy current interference, eddy current compensation coils can be arranged around the gradient coils. By detecting eddy current-induced magnetic fields in real time and outputting compensating currents of opposite polarity, the destructive effects of eddy currents on gradient magnetic field uniformity can be effectively counteracted.

3.3 Enhancement of Mechanical Stability: Mitigating the Effects of Deformation

Mechanical stability can be improved from both material selection and assembly process perspectives. High-strength composite materials with low coefficients of thermal expansion should be used for coil support structures to reduce deformation caused by temperature variations and mechanical stress. Temperature sensors can be embedded within the coil windings to monitor temperature changes in real time. In combination with active cooling systems, coil operating temperature fluctuations can be controlled within ± 2 °C, thereby minimizing thermal deformation. Assembly processes should be optimized by employing laser positioning technologies to achieve high-precision coil assembly, with assembly errors controlled within 0.05 mm. Elastic fastening structures can be used to release stresses generated during assembly and prevent permanent coil deformation. During equipment transportation and installation, dedicated buffering and protective devices should be designed to reduce the impact of mechanical vibrations on coil structures. In addition, a periodic maintenance mechanism should

be established, with inspections and recalibration of coil structures and assembly precision conducted every six months to promptly correct uniformity deviations induced by mechanical deformation.

3.4 Optimization of Calibration and Compensation Technologies: Dynamic Correction of Deviations

A comprehensive calibration and compensation framework integrating “static calibration + dynamic compensation” should be established. Static calibration methods can be optimized by employing high-precision three-dimensional phantoms in combination with MR-based localization techniques to accurately acquire magnetic field intensity data at multiple points within the imaging volume, thereby constructing a magnetic field deviation model. Based on this model, nonlinear fitting algorithms can be applied to generate calibration parameters that correct the intrinsic magnetic field deviations of the gradient coils. Dynamic compensation technologies should be introduced by embedding magnetic field sensors within the gradient coils to collect real-time magnetic field intensity data. In conjunction with deep learning algorithms, magnetic field fluctuation trends can be accurately predicted, enabling compensation coils to output dynamically adjusted compensation currents and achieve real-time correction of magnetic field deviations^[6]. Furthermore, adaptive calibration algorithms can be developed to automatically adjust calibration parameters according to the requirements of different imaging sequences and imaging regions, thereby improving calibration adaptability.

3.5 Multidimensional Collaborative Optimization: Enhancing Overall Optimization Effectiveness

Optimization in a single dimension is insufficient to achieve maximal improvement in gradient magnetic field uniformity; therefore, a multidimensional collaborative optimization framework is required. Through finite element simulation platforms, multiple factors—such as coil structure, electromagnetic interference, and mechanical deformation—can be integrated to establish multiphysics coupled simulation models. These models enable simulation of the synergistic effects of different optimization strategies and facilitate precise matching of optimization parameters. On the basis of hardware optimization, software algorithm enhancements can be incorporated.

For example, iterative reconstruction algorithms can be employed to further correct residual magnetic field non-uniformities and improve overall image quality. In addition, an optimization performance evaluation system should be established, comprehensively considering indicators such as gradient linearity, magnetic field intensity error, and imaging quality, and enabling dynamic adjustment of optimization strategies.

4. Key Challenges and Future Directions in Gradient Magnetic Field Uniformity Optimization

4.1 Analysis of Core Challenges

At present, the optimization of gradient magnetic field uniformity faces three major challenges. First, in high-field MRI systems, increased coil current density intensifies electromagnetic coupling and thermal effects, making the trade-off between uniformity optimization, heat dissipation, and electromagnetic interference suppression increasingly prominent. Second, in dynamic imaging scenarios, it is difficult to simultaneously satisfy requirements for high gradient switching speed and high uniformity. Rapid switching tends to induce magnetic field fluctuations, thereby degrading uniformity. Third, low-cost MRI systems are constrained by budget limitations, which restrict the adoption of high-precision materials and advanced calibration techniques, significantly increasing the difficulty of uniformity optimization. In addition, long-term factors such as coil aging and environmental variations lead to gradual and dynamic degradation of gradient magnetic field uniformity. Achieving long-term stable optimization under these conditions remains an urgent issue to be addressed.

4.2 Targeted Solution Directions

In response to the challenges outlined above, several targeted solution directions are proposed. The development of novel coil materials with high electrical conductivity and enhanced thermal dissipation performance, combined with liquid-cooling technologies, can help balance the demands of high current density and effective heat management. Model predictive control (MPC) algorithms can be introduced to accurately forecast magnetic field fluctuations during gradient switching processes and apply compensation in advance, thereby achieving coordinated optimization

of switching speed and field uniformity^[7]. For low-cost MRI systems, lightweight calibration algorithms and simplified shielding structures should be developed to ensure basic gradient magnetic field uniformity while maintaining cost control. In addition, a long-term monitoring framework for gradient magnetic field uniformity can be established. By leveraging Internet of Things (IoT) technologies to continuously collect coil status data and applying big data analytics to predict uniformity degradation trends, proactive maintenance and recalibration can be implemented, enabling long-term stable optimization.

Conclusion

The optimization of gradient magnetic field uniformity in magnetic resonance imaging (MRI) systems is a complex and systematic engineering task, involving multiple dimensions such as coil design, electromagnetic compatibility, mechanical stability, and calibration and compensation technologies. Although current efforts face challenges including intensified trade-offs under high magnetic field strengths, the difficulty of balancing switching speed and uniformity in dynamic imaging, and optimization constraints in low-cost systems, targeted solution pathways—such as the development of novel materials, the introduction of advanced algorithms, and the establishment of long-term monitoring frameworks—offer promising prospects. Through these approaches, effective improvement in gradient magnetic field uniformity can be achieved, thereby laying a solid foundation for the further development and broader application of MRI technology.

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