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Design and Optimization of Low-field MRI Coils for Enhanced Signal-to-noise Ratios and Image Quality: Literature Review

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Abstract: Magnetic resonance imaging (MRI) is a vital tool in medical diagnostics, providing non-invasive, high-resolution images of internal body structures. In recent years, the global interest in the development of cost-effective, portable, and accurate MRI solutions has led to the development of low-field MRI systems. Nonetheless, low-field MRI is burdened by low image resolution and Signal-to-Noise Ratio (SNR), which limits their application. This article looks at the current state of low-field MRI, focusing on design and optimization of coils to increase SNR and image quality. Looking at coils (volume, surface, and phased array) used in low-field MRI, volume coils reveal homogenous signal reception but the absence of deep tissue sensation. Surface coils have larger SNR in superficial tissues and significantly lower SNR in deeper structures. The phased array coils are characterized by high SNR and can also be used for parallel imaging; however, the issue of mutual coupling between coil elements remains challenging. The SNR in low-field MRI can be enhanced by optimizing the shape of the coils through the use of high conductivity noise reduction and the machine learning algorithm. This work lays down the groundwork that would be used in subsequent studies on other developments and concerning issues pertaining low-field MRI coil design and optimization.

Keywords: Low-field MRI, coil design, medical imaging, resonance imaging technique, signal-to-noise ratio enhancement

1. Introduction

Magnetic resonance imaging (MRI) is a vital non-invasive instrument in medical diagnostics used to obtain complete images of tissues and organs within the human body. The MRI is considered to be a safe technique free from serious risks although injuries may sometimes happen in case of negligence of certain precautions (Umar & Atabo, 2019). Currently, the technique relies on the magnetic field, radiofrequency (RF) pulses, and gradients of above 1.5T to obtain images of the internal organs of the body. The magnetic resonance is based on the behavior of hydrogen protons in an external magnetic field [2]. This RF field is produced by the transmit coil and causes proton resonance in the biological tissues and the signal regenerated by the same coil MRI system is received (Sprawls, 2000). In recent years, low-field MRI systems (below 0.5T) equipped with high-performance gradients have been developed. Although high-field MRI systems are favorable for clearer images, low-field MRI systems are gaining traction for their lower operational costs, improved patient safety, and portability, particularly for remote settings (Arnold et al., 2023).

Notably, low-field MRI presents challenges such as lower image resolution and signal-to-noise ratio (SNR) linked to weaker magnetic polarization of protons (Coffey et al., 2013). The SNR is not determined solely by the static field strength, but by various factors, such as gradient coils and pulse sequence design (Arnold et al., 2023). Therefore, the coils that are used for the image acquisition function decisively in the image quality particularly in low field scanners since specific attention should be paid towards minimizing the RF-coil lose than the sample noise. The SNR decreases proportionally with the square of the magnetic field strength, which means that low-field systems require significant coil optimization to ensure clinically usable images. To achieve enhanced image quality, the design and optimization of MRI coils, which are crucial for both transmitting and receiving RF, have become a key area of research. The current paper delves into the latest advancements in low-field MRI coil design, focusing on how innovative coil structures, materials, and configurations can enhance SNR and image resolution. The paper further examines computational modelling techniques, future perspectives and gives a conclusion.

The significance of this study lies in establishing foundational framework for future investigations of developments and issues related to low-field MRI coil design and optimization. By stating the effective approaches to increase SNR and improve the quality of the images, it provides understanding of the ways to raise diagnostic reliability. It also reveals the possible gaps in existing research, paving the way for innovative coil designs tailored to low-field constraints. Such advancements can enhance diagnostic accuracy, particularly in low-resource or remote settings, contributing to more equitable healthcare access and supporting the ongoing development of portable MRI solutions.

2. Current Coil Designs in MRI

There are three primary types of coils used in MRI based on their shape: volume coils, surface coils, and phased array coils (Mispelter et al., 2015).

2.1. Volume Coils

Volume coils, often used for brain or body imaging, are mainly composed of Helmholtz and birdcage coils. They are used as both transmit and receive RF coils because they produce a uniform field in a large area including body parts. The “filling factor” provides an indication of the geometrical conformity of the volume RF coil to the object being imaged. These encompass the entire imaging region, providing uniform signal excitation and reception. The filling factor can be optimized by making coils that have a cross section which is similar to the human cross section (De Zanche et al., 2005), although there have been concerns about reducing patients’ comfort because of the proximity of the coil to the object. Poor sensitivity, especially for deep tissue imaging is a major setback for volume coils in low-field MRI.

2.2. Surface Coils

Surface RF coil which comes in circular, rectangular, or elliptical loops only require moderate homogeneity of the magnetic field to form images with high SNR. This makes it much smaller than the volume RF coil. To achieve such good SNR in the region of interest, the size and geometry of the RF coil must correspond to the depth of the sample under investigation (Haase et al., 2000). For special applications, for example in vertical B0 MRI systems, end-on surface RF coils with butterfly and figure-of-eight geometry for creating the transverse RF fields can be developed (Giovannetti et al., 2023). Local surface coils are used for localizations of specific areas of interest and provide higher

SNR than the volume coils for superficial tissues. A disadvantage, though, is the relative insensitivity of surface coils in deeper tissues especially at low field strengths.

2.3. Phased Array Coils

Phased array coils are currently the most investigated object in the frame of low-field MRI because they allow configuring advantages of several coils to enhance SNR and to shorten the time of acquisition. Phased array coils include multiple coils and each of them is situated over the imaging area, and can process its own signals separately. This array also allows multi-modality imaging strategies including sensitivity encoding (SENSE) and generalized auto-calibrating partially parallel acquisition (GRAPPA), which increases the speed of imaging without affecting SNR. Phased array coils are gradually employed in low field MRI application due to the coordination with parallel imaging and noise reduction (Roemer et al., 1990). Thus, research in phased array coils in low field MRI applications fundamentally rests on the element spacing, mutual inductance and independence of noise between the elements. For example, two consecutive points of the coil elements must have zero mutual inductance. The reductions of the interference of the overlapped elements with other elements of the array can be achieved through the connection of each coil element to a low input impedance preamplifier (Wright & Wald, 1997).

Subsequently, an ideal image reconstruction algorithm is required to be used to combine all the AC images into one image (Giovannetti et al., 2007). Phased-array RF coils are also applied in phased-array RF coils in parallel imaging techniques (Ohliger et al., 2013) or through variation of the magnetic field in the single-coil elements enabling the spatial encoding of signals and a shortening of acquisition time by up to a factor of three. Some other developments in the phased array coil technology include: decoupling techniques, coil element overlap, flexible and conformal coils. Properly decoupling individual coil elements is essential for preventing signal interference. Traditional passive decoupling uses capacitive or inductive networks, while more recent methods involve active decoupling circuits that dynamically adjust the decoupling based on the imaging requirements. The use of flexible coils that can conform to the shape of the human body has shown great promise for low-field MRI. Flexible coils improve the proximity of the coil elements to the region of interest, significantly enhancing the SNR for shallow tissues.

3. Enhancing Signal-to-Noise Ratios (SNR) in Low-Field MRI

Reducing SNR represents a significant problem in low-field MRI in achieving comparable image quality to high-field MRI. SNR depends on the design of the coil and therefore several strategies have been worked in this field.

3.1. Optimizing Coil Geometry

The geometry of coils and the distribution of the coil structure influence the uniformity of the transmitted RF field and the sensitivity of the received radio signal. Larger coils are often used in high-field MRI, but small and highly specialized coils are successfully implemented in low-field MRI due to the low B1 field strength in low-field MRI. Geometries such as loop-gap resonators and multi-turn solenoid coils have been known to optimize the SNR in low-field systems by exploiting the interface with the local magnetic field. (Coffey et al., 2013; Xuan et al., 2023).

3.2. Using High-Conductivity Materials

The desired properties of coils are low resistance and thus heat generation; hence the common use of high conductivity materials including Copper. Some of the newest works investigated deeper the

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potential of using superconducting materials, namely YBCO (Yttrium Barium Copper Oxide) for coil improvement. The use of superconducting coils at very low temperatures, and consequently with a negligible resisting coefficient, boosts the SNR. However, the use of superconductors in low field portable MRI still presents some difficulties mainly due to the need for cryogenic cooling (Aditya Ashok Bhosale et al., 2024; Aditya A Bhosale et al., 2024).

3.3. Noise Minimization Techniques

In low-field MRI, the most significant amount of noise is caused by thermal noise in the patient's body as well as the electronic noise in the detection system. Researchers have explored numerous methods for reducing noise, including the use of cryogenic preamplifiers, noise-matched coils and low-noise amplifiers (LNAs), (Felder et al., 2018; Resmer et al., 2010; Zheng et al., 2017). Also there are feedback mechanisms which have been adopted with the aim of cancelling electronic noises in real time so to enhance the quality of the low field MRI images (Koonjoo et al., 2021).

3.4. Applying Machine Learning Techniques

Many technical advances have come from applying machine learning (ML) techniques to the problem of image reconstruction, where the acquired inaccessible or raw data are converted into the final image. According to literature, the advances in this area include rapid reconstruction of high-dimensional raw data in a scope of milliseconds, improved final image and image contrast in highly under sampled data sets, and dynamic and multi-channel reconstruction (Qin et al., 2019). Hitherto, none of these SNR-boosting ML techniques have been employed on practical noisy MRI datasets collected at a very low magnetic field strength, a domain that poses technically challenging problems in scanning and recovery. Regardless, deep learning based image reconstruction methods are demonstrated to hold capabilities to solve low-field MRI low SNR problems. Koonjoo et al. demonstrated the application of the neural network architectural paradigm AUTOMAP (Automated transform by Manifold Approximation) in SNR enhancement and image denoising (Koonjoo et al., 2021).

4. Materials for Low-Field MRI Coils

Materials used in MRI coil construction directly impact the coil's efficiency, durability, and cost (Wald et al., 2020). Traditionally, copper has been the material of choice due to its high conductivity and low resistive losses. Nevertheless, as previously mentioned, the use of superconducting materials has gained traction in recent years, particularly for low-field MRI systems where maximizing SNR is critical. Research into superconducting materials like YBCO and MgB2 (Magnesium Diboride) has shown significant promise in increasing the SNR of low-field MRI systems (Patel, 2016). Superconducting coils operate at extremely low temperatures, resulting in minimal resistive losses and increased coil sensitivity (Lvovsky et al., 2013). However, the practical challenges associated with cryogenic cooling systems, particularly for portable MRI systems, limit their widespread adoption. Presently, composite materials consisting of a mix of conductive metals and flexible polymers are being explored for flexible coil designs. These materials offer the advantage of conforming to the patient's body while maintaining high conductivity. In addition, new developments in graphene-based materials have opened up possibilities for ultra-light, high-conductivity coil elements that could significantly improve low-field MRI performance (Aditya A Bhosale et al., 2024).

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5. Computational Modelling and Simulation for Low-Field MRI Coils

Modelling and simulation represent a quicker and cheaper method to review a design than building and testing prototype coils and making small modifications in iteration. A computationally oriented approach, such as computational modelling and simulation, has become critically essential in the construction and improvement of low-field MRI (Ghosh et al., 2019; Shen et al., 2022). To this end, there exist several simulation technologies including Finite Element Method software and electromagnetic solvers that can be used to simulate new coil prototypes and verify their feasibility for physical use. These simulations enable the optimisation of coil dimensions and the material the coil will be fabricated out of, together with sound reduction techniques. The current literature survey made it clear that simulation can reflect the MRI coil behavior in low field environments with high reliability (Arnold et al., 2023; Deidieva, 2024). For instance simulation of birdcage coils, loop-gap resonator and phased array has been used to model SNR, B1 field homogeneity and inter-coil mutual inductance. This works as an advantage when it comes to reducing cost and time when trying to develop new coils (Webb, 2016).

To analyze MR experiments, it is necessary to use quadrature coils as a transmitter-receiver of circular polarized magnetic fields. This reduces the level of power magnitude needed for transmission to half that which is required in linear polarized coils without also doubling the SNR. This quadrature coil design must be performed by reducing the degree of coupling between the coil channels: Kumar and Bottomley, 2008. This means that an effective coil design minimizes the chance of crosstalk between the X nucleus signals and the proton signals, using geometrical decoupling of the channels (Mispelter et al., 2015).

The influence of interactions with gradient and shim coils on the B1 field may lead to compromises of the SNR of the RF coil, as well as the occurrence of spurious resonant frequencies. Such an interaction can be minimized by employing a passive shielding system, which consists of ferromagnetic material sheets with high permeability or high-conductivity material (Giovannetti et al., 2014). However, it should be borne in mind that in the coil simulation and design stages, the shield has a complex effect on the resonance frequencies and the field distribution in the RF coil (Giovannetti et al., 2002).

6. Challenges in Low-Field MRI Coil Design

A number of challenges have been associated with low-field MRI coil design. First, since the square of the magnetic field strength is directly proportional to SNR, lower magnetic fields produce weaker signals. This places considerable pressure on coil design to compensate for the loss in signal. Achieving a sufficient SNR requires more sensitive coils, improved noise reduction techniques, and optimized coil geometries. Second, low-field MRI coils need to balance between localized sensitivity (to enhance SNR) and field homogeneity (for consistent imaging). Surface coils provide higher SNR for tissues near the surface but are less effective for deeper tissues. Whereas volume coils offer more homogenous coverage, they suffer from reduced sensitivity in low-field environments. Phased array coils, while effective, introduce challenges in mutual inductance and noise correlation between the elements, which can reduce the overall image quality if not managed properly. Third, although superconducting materials like YBCO and MgB2 offer promising enhancements in SNR by minimizing resistive losses, they require cryogenic cooling (bulky, expensive, and energy-intensive), making them impractical for portable low-field MRI systems. Alternatives like high-conductivity copper or advanced composites offer a balance between performance and practicality, but the full benefits of superconductors are still unattainable without overcoming these logistical challenges. Fourth, physical and anatomical constraints can limit the flexibility and effectiveness of coil designs. For example, rigid birdcage or solenoid coils may not fit snugly around a patient's body, reducing

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their proximity to the region of interest and, consequently, the SNR. Flexible coils that can conform to the patient's body have been developed, but ensuring durability, flexibility, and consistent performance is difficult, especially for coils used repeatedly in clinical settings.

7. Future Research Directions

Future research directions in low-field MRI coil design and optimization should consider coils with high-SNR, large field-of-view, specialized applications, integrated with optimum materials, and to consider the application of advanced computation methods to amplify the coils efficiency with specific references to low-field MRI. Further investigations on flexible coils fabricated from new composite materials or printed conductive structures must be conducted. These coils, allow better match to the convolutions of the patient's anatomy increasing the distance from the coil to the region of interest improving SNR with maximum comfort to the patient. It would therefore be a major advance if superconducting coils that do not need cryogenic cooling systems could separately be developed. Exploring new materials to improve low-field MRI coil performance. For example, Graphene based materials have recently been researched due to their conductivity, lightweight construction as well as flexibility. Research into hybrid coil designs may be a promising avenue towards finding the solution for both SNR and homogeneity issues.

Hybrid coils can switch between configurations based on the depth and location of the target tissue, enhancing both SNR and field uniformity during imaging. This would enable the system to serve both surface coil depth responsiveness for the shallow tissues and the homogeneity indicator of the volume coil for deep tissues. Finally, the use of AI and machine learning methods to solve coil design problems is still an emerging field. It is possible to perform geometrical transformations on coils, select proper materials and configurations of decoupling networks as well as study the SNR using AI.

8. Conclusion

This review highlights the crucial issue of MRI coil design and development, taking into account the inherent drawbacks of low-field MRI as well as the ability to improve SNR and image resolution respectively. From the literature review, critical concerns including the geometry of the coil, available materials, array configurations, and methods of noise abatement were examined. The review also confirms that the improved geometry and material coil designs enhance SNR and spatial resolution in low-field MRI and reduce some of the performance deficits vis-à-vis high-field MRI systems. In addition, higher multi-coil and phased-array aspects were also shown to enhance structural image resolution, which strongly advocated the versatility of low-field MRI for various clinical applications such as portable and affordable imaging systems. Altogether, these results stress that coil design and optimization have remained the driving forces in establishing low-field MRI as a more efficient diagnostic approach. However, there are certain limitations in the current research study that are worthy of consideration. It also lacks actual studies, which makes the analysis unable to substantiate or quantify the efficiency of various forms of coil optimization. Also, the review took into consideration only the published English language articles, which makes the discussion neglect recent and emerging technologies and solutions in MRI coil. Future studies should involve methods that compare the optimized coil designs on phantom scans, and SNR and image quality in true low-field MRI conditions. Extending the literature review time frame, as well as integrating recent advances in coil design utilizing, for instance, artificial intelligence, or other recent material science breakthroughs would add another level of understanding to practical application.

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