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Asymmetric gradient coil design for use in a short, open bore magnetic resonance imaging scanner

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ABSTRACT

A conventional cylindrical whole-body MRI scanner has a long bore that may cause claustrophobia for some patients in addition to being inconvenient for healthcare workers accessing the patient. A short-bore scanner usually offers a small sized imaging area, which is impractical for imaging some body parts, such as the torso. This work proposes a novel asymmetric gradient coil design that offers a full-sized imaging area close to one end of the coil. In the new design, the primary and shielding coils are connected at one end whilst separated at the other, allowing the installation of the cooling system and shim trays. The proposed coils have a larger wire gap, higher efficiency, lower inductance, less resistance and a higher figure of merit than the non-connected coils. This half-connected coil structure not only improves the coils' electromagnetic performance, but also slightly attenuates acoustic radiation at most frequencies when compared to a non-connected gradient coil. It is also quieter in some frequency bands than a conventional symmetric gradient coil.

1. Introduction

A conventional long-bore cylindrical whole-body magnetic resonance imaging (MRI) scanner is claustrophobic for some patients, thus making them uncomfortable during scanning. One method to make the scanner more open is to enlarge the diameter of the bore. However, this will increase the cost of the magnet and influence the uniformity of the magnetic field. Another method is to move the region of interest (ROI) towards one end of the main magnet [1]. An asymmetric gradient coil design is focused on this to overcome the claustrophobia problem and is paired with an asymmetric magnet design concept [2,3].

Gradient coils are a critical part of an MRI scanner, providing a means of frequency-encoding in the region of interest (ROI). With the development of MRI techniques, the gradient field must be strong and pulsed quickly to enable rapid imaging [4,5]. However, fast, strong gradient switching can induce significant acoustic noise, making some patients uncomfortable [6,7]. These issues can be attenuated to some extent by an appropriate coil design scheme, low inductance, low eddy current loss, low acoustic noise level, and so on.

Recent developments in gradient coil design methods allow for the design of arbitrary geometries [8–12] that provides many possibilities for improving the gradient coil performance. For example, the ultra-short gradient coil was designed with three-dimensional (3D) geometry for ultra-short cylindrical MRI systems, where the length of the gradient coil can be controlled throughout the design process [13]. However, compared with standard long gradient coil sets, the short, layered gradient coils (both having the same ROIs, design methods, border conditions and similar coil patterns, and so on) tend to have a dense coil pattern. The gradient field generating arcs (x, y coils) are competing for space with the return wires, making some wire-wire distances too narrow to manufacture. In addition, thermal heating can be a problem and the inductance may be higher. Coils with two ends connected were proposed to allow the current flow from the primary surface to the shielding surface [8,14]. Under the same design parameters, this method can relax the current distribution to some extent compared with the conventional non-connected primary and shielding coils, because some return path wires are laid on the connected surface. However, this design has a higher complexity in terms of the mechanical design.

Apart from considering the electromagnetic performance of the gradient coil design, the amount of noise generated by the coil also needs to be considered in the design process to improve patient comfort for seriously ill or anxious patients [7,15–18]. With respect to the acoustic noise level reduction of the gradient coils, traditional methods for coping with this problem include wearing earplugs, earmuffs or even a helmet [19] or applying a damping

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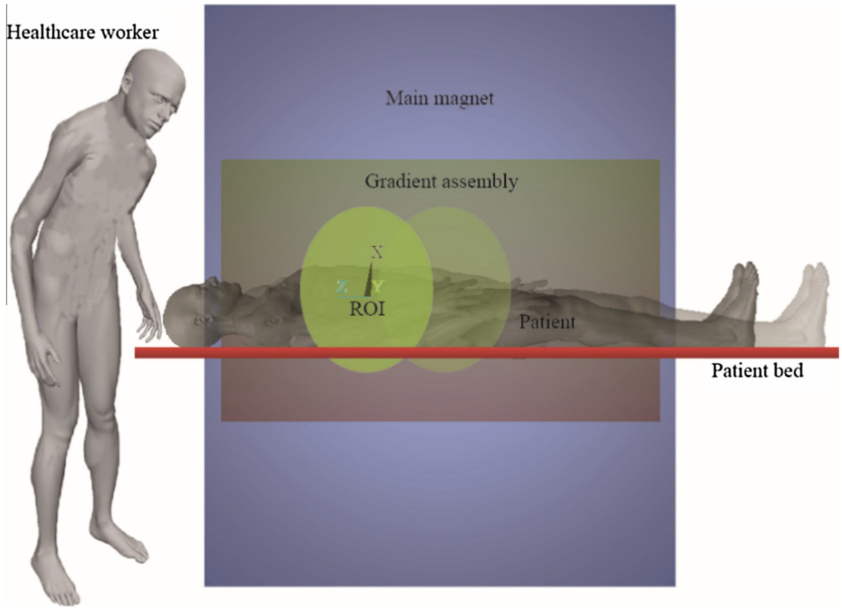

Fig. 1. Asymmetric MRI scanner ROI located near one end. A symmetric counterpart (including the ROI and patient) is plotted in a light colour for comparison.

treatment on the gradient assembly [20,21]. Some scanners use a vacuum device to block the airborne noise propagation to the patients' ears [22,23]. Active actuators are also reported to be mounted on the ends of the gradient assembly to reduce the noise radiation [24]. In addition to these methods, a more straightforward method for acoustic noise reduction is to design the gradient coil by minimising the force/torque at the source [25].

In this work, we propose a novel asymmetric gradient coil design pattern matching an asymmetric magnet design concept [2]. The primary and shielding surfaces of the gradient coil were connected at one end, but separated at the other, to allow for the installation of the cooling device and shim tray, which also provided more space for the coil wire distribution. An equivalent magnetisation current method was applied to the design of the gradient coil [8]. For the acoustic analysis, the finite element method (FEM) was used, where the gradient coil was inserted into an epoxy resin. The electromagnetic performance and acoustic radiation intensity of the designed asymmetric gradient coil were

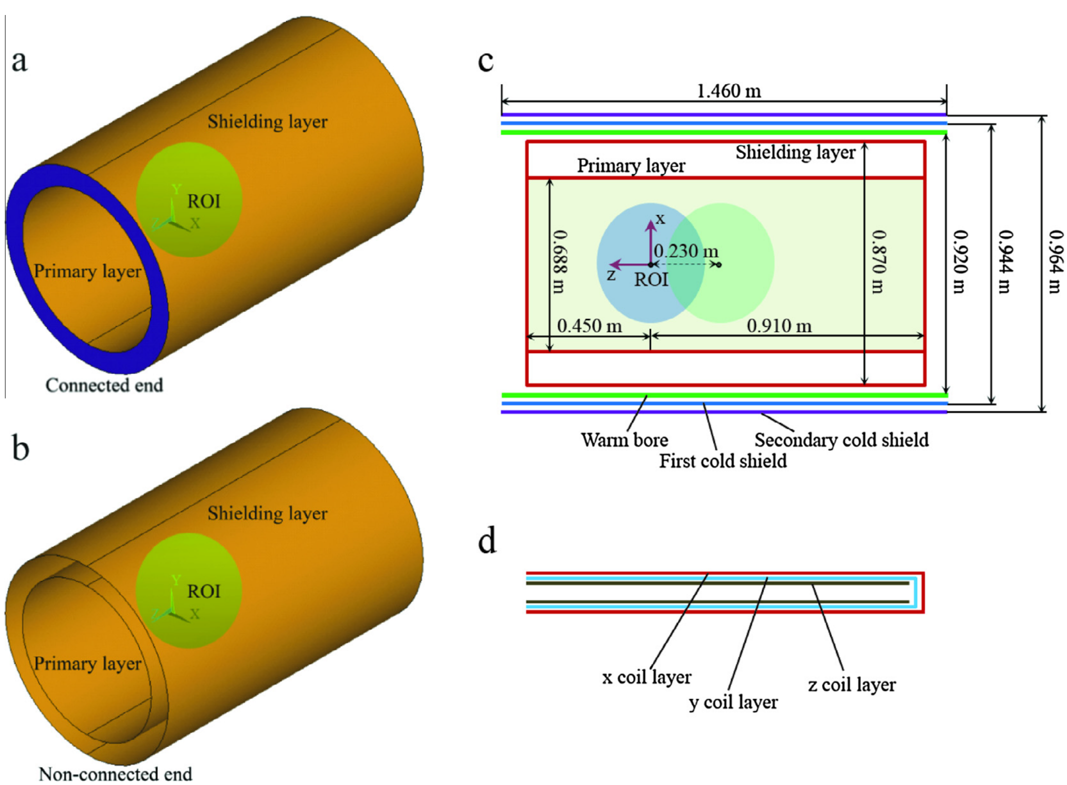

Fig. 2. Asymmetric gradient coil configurations: (a) current density surface of the connected coil, (b) current density surface of the non-connected coil, (c) dimensions of the designed x coils and the cryostat, and (d) diagram of the coil layers in a gradient assembly. The ROI shift size is 0.23 m.