**Institution:** The University of Nottingham

**Unit of Assessment:** 9

**Title of case study:** Optimising Gradient and Shim Coils for Next-Generation Magnetic Resonance Imaging Systems

## 1. Summary of the impact

Theoretical and computational methods for optimising the design of gradient and shim coils with arbitrary shapes and topologies were developed in collaboration with Magnex Scientific as part of a CASE award (2004-07). The resulting software was licenced to Agilent (who now own Magnex Scientific), for whom it has opened up new market opportunities in the supply of novel magnetic resonance imaging systems, leading to £3.4M sales since 2009. The software has also been used by Paramed Medical Systems to improve their ‘open’ magnetic resonance imaging systems, which are optimised for orthopaedic imaging, allow vertical subject posture, and facilitate image-guided treatment, as well as offering a better patient experience. Our work has thus resulted in impact in the economy and healthcare.

## 2. Underpinning research

The use of gradient and shim coils is integral to the operation of magnetic resonance imaging (MRI) systems. The three gradient coils found in each scanner are used to produce magnetic fields that vary linearly with position along three orthogonal axes. These field gradients are crucial for the spatial encoding of the magnetic resonance signal - a process which forms the basis of MRI. Gradient coil performance strongly influences many aspects of magnetic resonance (MR) image quality, including the spatial resolution and achievable contrast. Shim coils are used to correct unavoidable inhomogeneities in the main static magnetic field that is also used in MRI. These inhomogeneities may arise from various sources, such as the magnetic susceptibility of a human subject, or imperfections in the magnet construction, and, if uncorrected, result in significant image distortions.

The Nottingham MRI group has a longstanding track record in the development of improved hardware for MRI systems, dating back to the early work for which Sir Peter Mansfield shared the 2003 Nobel Prize in Medicine or Physiology. This research activity has continued to the present day, with a particular emphasis on gradient and shim coil technology. Previous high impact work in this area includes the development in the late 1980s of actively-shielded gradient coils, which are now used in all MR scanners, and the subsequent establishment of methods for designing high efficiency coils. These developments formed the basis for the substantial improvement in gradient system performance in the 1990s, which first allowed the routine implementation of functional magnetic resonance imaging of the brain and other imaging procedures that rely on strong, rapidly switched gradients.

Since the late 1990s, the focus of our research has shifted to the development of methods for the design of coils with complex geometries or topologies that are required to enable new applications and advances in MRI. Until recently, gradient coils for MR scanners were designed using a simple parameterisation of the current density that represents the energised coil windings. This approach is well suited to the production of gradient coils that are wound on simple surfaces, such as the long cylinders used in early MR scanners, but cannot easily be applied to designing coils on more complex surfaces that may be truncated, folded, gapped or split. Research into these complex coil shapes was motivated by their requirement in novel MRI systems, including:

- scanners incorporating insert gradient and shim coils that can be used for enhanced imaging of particular target structures – for example, insert head gradient and shim coils that fit closely around the head
- ‘open’ MRI scanners which depart from the conventional tubular shape - these can enhance the patient experience through reduction of stress (particularly important for paediatric and obese patients) and can also be used for real-time monitoring of surgery and other complex processes; an example is the ‘MROpen’ system, developed by Paramed Medical Systems (see Figure), which allows imaging of human subjects in weight-bearing, vertical, postures
- hybrid systems, such as combined positron emission tomography (PET) and MRI scanners, and combined radiotherapy and MRI systems, in which the coils must be designed to be

compatible with the spatial arrangement and operation of the equipment required for the additional modality.

Boundary element methods (BEM) offer a powerful approach for coil design, allowing the generation of coils wound on arbitrarily-shaped surfaces, so as to produce any form of field variation that is consistent with Maxwell's equations. This approach involves meshing the current-carrying surface into an array of boundary elements and then setting the current density at each element, so as to minimise a functional that reflects the desired coil characteristics.

Between 2004 and 2007, *Bowtell* (a member of the Nottingham MRI group), working with CASE Ph.D. student, Poole, applied the boundary element approach to the inverse problem of designing coils on arbitrarily shaped surfaces that would produce specified magnetic field distributions. The outcome was a novel inverse BEM (IBEM) approach. This was implemented in software written by Poole, and combined with a powerful mesh-generating program, so as to allow the design and production of coils with completely arbitrary geometry [1]. Poole's studentship was funded by Magnex Scientific/Varian Inc.[i] and his Ph.D. work linked into an EPSRC-funded project which focused on applying techniques in computational mechanics to the design and analysis of gradient and radio-frequency coils for MRI [ii].

In 2007, Poole and *Bowtell* worked with Alun Lucas, Rob Hawkes and Adrian Carpenter (Wolfson Brain Imaging Centre at the Addenbrooke's Hospital in Cambridge), and Dan Green and Simon Pittard (Varian Inc., now Agilent), on the design and construction of coils for a hybrid PET-MRI system [2]. Combining PET and MRI within one instrument requires many engineering compromises as the equipment for the two modalities vies for the space closest to the sample/subject. Nevertheless, a combined PET-MRI system offers many potential benefits for clinical and pre-clinical imaging. In the configuration which was developed, the PET detectors reside in a gap between the two halves of a 1T split-magnet cryostat. The gradient and shim coils had to incorporate a 110 mm gap from which wires are excluded so as to avoid compromising the process of positron detection. It was not possible to produce coils with this gapped geometry using conventional methods of coil design, but Poole's IBEM software was able to cope with the complex coil shapes. It was used to design three, orthogonal, (magnetically) shielded gradient coils and a shielded, zero-order shim coil. These coils were constructed and tested in the hybrid PET-MRI system and successfully used in simultaneous PET-MRI experiments [2].

**Top:** Lumbar spine MRI scan (imaged under vertical compression) **Left**: Paramed's MROpen scanner.

**3. References to the research** (*denotes paper which best describes quality of research)

1) ***M. Poole and R. Bowtell**, *'Novel gradient coils designed using a boundary element method.'*, Concepts in Magnetic Resonance Part B **31**B, 162 (2007).
DOI: 10.1002/cmr.b.20091

2) ***M. Poole, R. Bowtell, D. Green, S. Pittard, A. Lucas, R. Hawkes, A Carpenter**, *'Split gradient coils for simultaneous PET-MRI',* Magnetic Resonance in Medicine **62**,1106 (2009).
DOI: 10.1002/mrm.22143

3) ***R. Bowtell and R. M. Bowley** *'Analytic calculations of the E-fields induced by time-varying magnetic fields generated by cylindrical gradient coils',* Magnetic Resonance in Medicine **44**, 782 (2000).
DOI: 10.1002/1522-2594

4) **R. Bowtell and A. Peters** *'Analytic approach to the design of transverse gradient coils with co-*

*axial return paths',* Magnetic Resonance in Medicine **41**, 600 (1999).
DOI: 10.1002/(SICI)1522-2594

5) **P. Mansfield, B. L. W. Chapman, R. Bowtell, P. Glover, R. Coxon, P. R. Harvey**, *'Active acoustic screening - reduction of noise in gradient coils by Lorentz force balancing',* Magnetic Resonance in Medicine **33**, 276 (1995).
DOI: 10.1002/mrm.1910330220

Grants

*i.* Magnex CASE studentship (01/10/2003-31/03/2007) £22,000

*ii.* *'Forward & inverse analysis of electromagnetic fields for MRI using computational mechanics techniques'* I.A. Jones, R. Bowtell, A. Becker, P.M. Glover, H. Power, EPSRC Grant GR/T22445/01 (1/2/05-3/1/2008) £208,925

**4. Details of the impact**

The strong track record of the MRI group in the development of gradient coil technology for magnetic resonance scanners led to the sponsorship by Magnex Scientific (manufacturer of magnets, gradient coils and shim coils for MRI) of a CASE studentship for Poole under the supervision of *Bowtell*. Poole's Ph.D. project, which commenced in 2004, focused on the development of insert gradient and shim coils for use in high-field MRI of the human head. The IBEM approach was developed as part of this work, so as to allow the design of coils wound on surfaces that fit more closely to the head than the body-sized cylinders used in most MRI systems. From 2005-2006, Poole developed a versatile suite of algorithms and subsequently an IBEM software package for designing gradient and shim coils on arbitrarily-shaped surfaces.

This software was demonstrated to our collaborators at Magnex Scientific during regular project meetings in 2006 (by this time, Magnex had been bought by Varian Inc.; Varian were then bought by Agilent in 2010 for $1.5bn; the manufacturing base has remained in Yarnton, Oxfordshire throughout the changes in ownership). It rapidly become clear to Varian that the IBEM software offered much greater versatility than the coil design programmes that they were then using. The facility to design and produce coils on gapped or split surfaces generated particular interest. To demonstrate the potential of the IBEM software, Poole worked with Dan Green (Varian) to generate novel, gapped, designs of shielded gradient and shim coils for a prototype hybrid PET/MRI system. These coils could not be designed using the software that Varian were using at that time.

Subsequently, Varian constructed these coils and supplied them commercially to Adrian Carpenter and colleagues at the Wolfson Brain Imaging Centre in Addenbrooke's Hospital (2008), paying a 3% royalty to the University of Nottingham. *Bowtell* and Poole published a paper [2] jointly with Carpenter's group and the Varian collaborators, describing the novel coil designs and the first experimental tests of their performance in the hybrid PET/MRI system. Having seen the value of the IBEM approach, Varian extended the agreement with the University of Nottingham in 2007, and this now allows them to use Poole's advanced design software, provided that they pay a 3% royalty on any coil sales arising from its use. Since 2008, Varian, and subsequently Agilent, have used the software to design a number of coil systems, including short head gradient coils for ultra-high field imaging, and gapped systems for use in combined radiotherapy/MRI systems. Agilent's Research and Development Manager for Gradient Coils [A] describes the impact on their business:

*"The ability of the software to account for complex gradient coil geometries allows us to explore the more challenging design aspects of bespoke and integrated systems, for instance hybrid MRI/PET and MRI applications in radiotherapy. Agilent's entry into these new markets has resulted in some £2.8 million in new system sales since 2009. We also offer some unique solutions to our customers in the university research sector; often their challenging requirements can only be met by the flexibility of the IBEM software. Sales for these upgrades are of the order £600k since 2009. Exploitation of these new markets would not have been possible without Nottingham's research into complex gradient coil design."*

In 2009, *Bowtell* established a new collaboration with Paramed Medical Systems (Genova, Italy) who sell 'open' MRI scanners. As described in Section 2, open MRI scanners offer several significant advantages over the conventional tubular design including: better patient experience, particularly for the paediatric, anxious or larger patient; weight bearing and postural diagnostics in, for instance, the upper neck (cervical) and lumbar spine cases (see figure); the potential for real-time monitoring of surgery. The Paramed systems are based on permanent (0.15T) and $MgB_2$ superconducting (0.5T) magnet technology, offering a cheaper alternative to whole body scanners. A Paramed scanner (MROpen; see Figure) was recently installed in the 'Upright MRI Centre', a private healthcare centre opened in Leeds in September 2012.

Scanners of this type use bi-planar gradient coils that are mounted on the magnet pole pieces and so are in close proximity to large amounts of highly permeable iron. The new collaboration, which also involved researchers at the Istituto Italiano di Tecnologia (IIT) in Genova, focused on adapting the IBEM approach to take account of the nearby magnetic material when designing coils, and was driven by Paramed's need to incorporate active magnetic shielding of their coils so as to improve system performance. Following Paramed's purchase of the IBEM software, it was modified, in collaboration with *Bowtell* and IIT researchers, and has subsequently been used in a number of development projects and products at Paramed, including their core product lines, the MROpen (see figure) and MRJ3300 (now known as MRInspire) scanners. Paramed have implemented new design processes as a result of the IBEM software which affect their complete product range (that currently provides a turnover of €8M/year) and will support future projected growth. These details, and the associated commercial advantages which result, are highlighted by the Research and Development Manager at Paramed [B]:

*"The availability of the IBEM software, modified by IIT and Paramed during and after collaboration with Nottingham School of Physics and Astronomy (since 2009), helped us to build a new design tool for optimizing gradient coil performances in presence of iron, which is an extremely important advantage for MRI system design"*

In summary, our numerical methods for the optimisation of gradient coils have been adopted by manufacturers of MRI equipment to enhance performance, functionality and patient care, thus generating impact in the economy and healthcare.

**5. Sources to corroborate the impact (available on request).**

A) Letter from Research and Development Manager, Gradient Coils, Agilent.
B) Letter from Research and Development Manager, Paramed s.r.l.