

# **Advances in MRI Equipment Design, Software, and Imaging Procedures**

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## **Introduction**

Magnetic Resonance Imaging is now reaching towards middle age. As the scientific literature, conferences and patent awards have amply demonstrated, there are many advances in a wide range of areas since the first published MR image was presented in 1973 [1]. The purpose of this presentation is to sample various ongoing developments and explain their significance. Given the necessary constraints, it is impossible to touch on more than a small fraction of the exciting developments. Therefore, some significant topics have been ignored.

An incomplete explanation of what drives these advances stems from the need to solve clinical problems and challenges. The MRI community views these challenges from a wide range of perspectives and consequently, a range of solutions is developed. Specifically from the MRI commercial vendor perspective, we attempt to identify the needs of our customers and offer a selection of solutions. At the commercial level, customer requirements extend beyond clinical and scientific topics found at conferences and in journals, but administrative, logistical and financial, to mention only a few other types of customer requirements. All of these requirements must be considered as a whole and consequently the commercial MRI vendors have produced a wide range of products to address these needs. This presentation will show some of the solutions available in the USA. The marketing departments of commercial vendors also attempt to forecast, anticipate and even create new needs in order to stimulate further growth of the marketplace.

## **Magnets**

The magnet dominates the MRI system. It is the biggest, most expensive, and perhaps most demanding and controlling aspect of an MRI system. The ideal MRI magnet produces a perfectly homogeneous magnetic field. This can be accomplished theoretically by producing a spherically shaped surface current that varies with a sinusoidal spatial distribution [2]. Clearly such a closed structure is not patient friendly. Creative magnet designers have produced various other shapes with special current density distributions that can approximate the ideal. Cylinders (e.g. 1.5T scanners) and parallel plates (e.g. open scanners) are two common solutions.

The challenge in MRI is to shrink the magnet package for reduced cost and improved siting characteristics. A now commonplace strategy to improve the siting characteristics is placing the magnet into a counter-acting magnet so that the magnetic field experienced by the patient is preserved, but the magnetic field outside the magnet is dramatically diminished. Unfortunately, these “self-shielded” magnets produce a very strong spatial magnetic field gradient between the

inside and outside of the magnet that can exert a remarkable attractive force on ferromagnetic materials – the so-called “missile” effect.

Another trend in the medical imaging industry is to increase the “openness” of the system for improved comfort. Cylindrical systems have been designed with ever increasing aperture size.

Yet another trend is the insatiable need for Signal to Noise (SNR). One solution is increased field strength. After some 20 years of 1.5T as the maximum widely available commercial field strength in routine clinical use, 3T is now becoming widely available. There are also now a small, but growing number of commercially engineered whole-body 7T platforms available not to mention the wide range of commercial high field experimental imagers that are also available that is beyond the scope of this presentation. Open system designs have responded by also going up-field.

There have also been “mission specific” magnets designed to fill specialized needs. Interventional needs are being addressed by clever adaptations of existing magnet technologies and other creative ideas have been considered. The growth of medical imaging needs has also spawned sub-specialty systems, such as orthopedic extremity work and scanners dedicated to breast imaging. There are also research efforts on building magnets for one specific task, such as bone mineral densitometry studies of the calcaneus (heel) [3].

## **Gradients**

Gradients are heard, unfortunately, but not seen. Gradient developments can be loosely grouped into three categories: design of the windings, advances in power electronics and mechanical details. For the scope of this presentation, we will only consider the mechanical issues, the others being rather complex and/or esoteric.

Gradients are the primary spatial encoding mechanism, but not the only spatial encoding mechanism, as will be discussed in the rf sub-system section. The ideal gradient would provide a change in magnetic field strength, only in the Z direction, linearly with x and/or y and/or z position. Unfortunately it is not possible to produce such “pure” gradients. The laws of physics demand that we sacrifice the linearity of the gradient (often characterized by local and global linearity specifications) and the uniformity of the gradient (how much the gradient changes as one moves off the axis in question) to achieve the gradient performance (slew rate, amplitude) we seek. As the sophistication of MRI has increased, the consequences of the time varying magnetic fields has expressed itself in many undesirable ways; mainly eddy currents and acoustic noise.

To reduce eddy currents, it is now commonplace to have self-shielded gradients like self-shielded magnets. Conceptually, modern MRI systems use a dual layer gradient: the inner layer produces the requisite gradient fields inside the patient volume; the outer produces a countering magnetic field that effectively zeroes (200+ fold reduction) the time varying magnetic fields outside the gradient tube. Consequently, the time varying magnetic fields are not “seen” by the magnet housing and no countering magnetic fields/eddy currents are produced. In practice, the shielding is not perfect, so in more recent developments eddy currents are minimized and the

uniformity of the associated magnetic fields in the imaging volume is “improved” [4] so that gradient waveform pre-emphasis can be used to minimize the impact on imaging performance.

Acoustic noise is perhaps the signature complaint patients have about MRI, and it is getting worse as users demand more gradient performance. There have been considerable efforts to understand the noise producing mechanisms and developing solutions to reduce acoustic noise levels [5]. There have been improvements in mounting technique, damping materials, gradient material advances and recently, even placing the gradient tube in a vacuum tube in effort to lower acoustic noise. One research group even constructed a rotating gradient tube where the gradients remained on and provided spatial encoding while it rotated, akin to a CT scanner [6].

For completeness, it is useful to comment on the physiologic consequences of more powerful gradient systems and two relatively old solutions to the problem. Associated with more powerful gradients is the possibility of peripheral nerve stimulation (PNS). There are standards to limit stimulation [7] that consider the duration of stimulus and the rate at which the magnetic field changes (dB/dt). The shorter the stimulus, the faster the magnetic field has to change to cause a stimulus. One way to reduce dB/dt is to make the gradient shorter because B gets bigger linearly with position. That has also matched the shortening of magnets. Additionally, so-called “dual” gradients have been developed where there is a short, higher performance central region provided by one of the segments of the gradient tube and another mode of operation with the standard full region gradient. Yet another solution is insert gradients, typically for head imaging, where improved gradient performance and more favorable physiologic stimulation conditions are realized through a physically smaller gradient tube.

## **RF (Transmit and Receive)**

Ongoing developments in the RF subsystem are probably the most profound changes in MRI system development in the last several years. In the traditional block diagram of an MRI system, the large body coil supplied the relatively uniform perturbing RF pulse and another smaller volume or surface coil detected the time varying relaxation signature, spatially encoded by the gradient subsystem. It was a significant advance when the concept of multiple receiving elements, the phased array coil, was carefully studied [8] and implemented commercially. Shortly before [8] was published, another paper [9] demonstrated that it was possible to use the spatial response characteristic of coil as another spatial encoding mechanism. Unfortunately this remarkable concept was far ahead of its time, as multi-channel receiver capability did not exist. Indeed, the concept could only be tested by acquiring data from each channel, one at a time. Ten years later SMASH [10] and SENSE [11] were developed. These two methods proposed to accelerate image acquisition by reducing the number of phase encodes needed and use the coil spatial response characteristics to synthesize the missing k-space lines (SMASH) or remove the aliasing ambiguity (SENSE) in the image domain. (Collectively, these methods are called “Parallel Imaging” because the image formation process of various sub-regions of the image happens at the same time). A few years later the first commercial implementation of SENSE became available and the profound implications started to become quite apparent very quickly. Utilizing these benefits with existing hardware rapidly demonstrated the benefits of enhancing the receive capability of the hardware and the need for coils and reconstruction algorithms optimized for the new parallel imaging concept.

With such a significant focus on receiver capabilities, not only have the number of receive channels gone up and coil designs re-optimized, but MRI systems are starting to go fully digital. As analog-to-digital (A/D) technology has improved, driven in part by the consumer electronics industry, bit depth and speed have increased to the point where it is possible to eliminate intermediate analog frequency steps in the receive process and digitize the signal directly at the Larmor frequency [12]. This has the benefit of improving signal and image quality by eliminating some stages in the electronics. It also brings the benefit of easily switching frequencies for multi-nuclear work. For example, one device company has recently announced a 100 MHz, 16 bit A/D unit [13]. While MRI systems above 50Mhz (approximately 1.2T) will produce an aliased signal, this poses no problem because the correct frequency range is known and the aliasing can be compensated.

Conceptually, one might think that what works in receive also works in transmit with regards to parallel imaging. Thus, we have transmit-SENSE [14] and transmit-GRAPPA [15] where GRAPPA is the commercial k-space based parallel imaging method of choice. To repeat, historically the RF excitation was accomplished by a large body coil with a uniform transmit characteristic, or smaller volume coils, such as head or knee for performance or artifact reduction reasons, also with good uniformity characteristics. The underlying concept of transmit-SENSE is utilizing the non-uniform spatial characteristics for performance gain. Given spatial non-uniformities, it is now possible to craft special RF pulses with deliberately designed spatial characteristics. So-called “spatial-spectral” RF pulses have been available for a long time [16] but the combined rf and gradient waveform profiles were long. Transmit-SENSE provides a time efficient solution that can be used to accelerate image acquisition even further. The development of transmit-SENSE parallels the development of parallel imaging in other respects as well. For the first few years, transmit-SENSE concepts were experimentally simulated one channel at a time. Now, experimental multi-channel transmit hardware has started to become available. One resourceful engineer has even produced the outline of a near DIY (do it yourself) version [17].

As with any new technology with commercial potential, there is cost vs. benefit considerations. Transmit-SENSE is so new that it has not come out in a commercial package, yet. Research will continue on this exciting development and perhaps we might see a commercial implementation some time soon.

## **Applications/Procedures**

As has been discussed in the technology portion of the presentation, MRI hardware has rapidly evolved due to the demands of customers. The hardware advances have been broad because the range and sophistication of MRI applications continues to grow on a broad front. Because of time/space constraints a few selected topics are discussed here while some noteworthy developments have been completely ignored, such as molecular imaging, on the assumption that some of the really big trends are going to be well covered in other sessions.

## **UTE – Ultrashort TE imaging**

UTE, or microsecond TE, is an elegant new development [18]. It is the synthesis of various concepts and methods that have logically been combined to utilize the advances in MRI hardware. Shorter TE requires more powerful gradients, k-space trajectories that start at the center of k-space to keep TE as short as possible, and self refocused RF pulses to minimize dead-time between the effective center of the RF pulse and the start of data readout. For these efforts, we are rewarded with the ability to see very fast signal decay components that are traditionally considered to be impossible in MRI, such as cortical bone. In some situations, it is also necessary to acquire a second image with longer TE and subtract the two images to isolate the desired short decay signal components. Some tissues have a multi-exponential decay characteristic and a subtraction process can be used to isolate the short component.

## **Quantitative MRI**

The benefits of quantification are well understood by all, so it seems hardly necessary to even mention it. However, it can be challenging to be quantitative in MRI and hence advances in quantitative MRI are important. While spectroscopy is outside the scope of this presentation, the paper by Bottomley [19] is a useful description of some of those challenges for one specific type of application.

Recognizing the importance of this topic, the conference organizers have scheduled a continuing education presentation in this series on this topic and I will not discuss it here.

## **How we use the MR scanner**

Improvements in MR image quality do not always come from hardware or software/sequence advances. Image quality improvements can be realized by advanced training for technologists, ensuring the equipment works to specification, and by providing automation facilities to help the functioning of the scanner, thereby relieving the technologist of some factors. Recently some new features have become available on some commercial platforms that fall into this category.

Sometimes it is necessary to monitor the condition of a patient over an extended period of time. Diagnostic power may be improved if the scans, collected up to months apart, could be aligned to the exact same anatomic position. Skilled technologists can do this task with old films in hand. It is also possible to automate this process with software. For example, a brain examination protocol could learn the desired orientation characteristics after a few human guided examples by referencing to obvious anatomic landmarks. Not only are all patients scanned with the same protocol scanned with the same alignment, but subsequent scans at a later date are performed identically. This consistency may also feed into quantitative MRI if, for example, the response of tumor volume to treatment is being followed [20].

Another example of optimized MR scanner usage follows from the inevitable trend towards a high degree of specialization and infrequently used protocols. A rare case may present that the technologist is unfamiliar with, or requires physician input. One can imagine a large hospital campus and the physician is elsewhere. One vendor has introduced a remote scanning capability

whereby a technologist and/or physician could directly yet remotely collaborate with the technologist in charge with patient and scanner [21].

## **Add-ons**

A typical marketing “trajectory” for a maturing market segment involves continued specialization and optimization for niche applications. MRI is no different in that regards. Some of the specialization comes from the MRI vendors themselves as the library of protocols is expanded and refined, and some of the specialization is coming from other companies producing “add-on” packages. Some packages are self-supporting (e.g. some fMRI stimulus packages or CAD systems), while others require some level of integration (e.g. some types of interventional packages) with the system and yet other packages are sold to the MRI vendors for total integration (e.g. a cardiac function analysis package, focused ultrasound for tumor destruction). A couple of packages will be discussed in the presentation. Links provided below under “other companies” are self-explanatory.

Then there is the extension to “bolting-on” more hardware. While combination imaging scanners have been around for many years, the magnetic field of an MR scanner is a hostile environment and consequently the advances have not been as significant, in the commercial sense. There have been efforts to combine x-ray with MRI [22] and PET with MRI in a variety of different ways. Some methods have considered inserting PET detection into an existing MRI unit [23] and another solution has been splitting the magnet and installing PET detection integral to the magnet [24]. These efforts have the same motivation as other dual imaging modalities: increased accuracy of image registration.

In addition to the combination of imaging modalities, there have also been efforts to combine image and therapy. This can range from using MR images from a system specially configured for radiation treatment planning purposes [25], to placing an MRI in one room and a cath lab in another room with a common patient table and sliding door between the two rooms, to integrating a linac with an MRI [26].

## **Branching out**

We all have heard of unusual applications of MRI: veterinarian, material sciences etc. One of the more unusual applications I have heard about relates to analyzing the moisture distribution in nylon carpets [27]. MRI is now increasingly being used for drug research and the various types of “-ohmics” research. Drugs are very expensive and take a long time to bring to market. Some are a major business success. Drug companies are anxious to look at any technologies that might decrease the gestation time and increase the commercial window of opportunity before patent coverage expires. Drug companies are interested to see if MRI can help “see” the endpoint a little sooner than traditional means. If MRI can shorten the time it takes to see/confirm trends, then this might shorten development time and increase the time available for commercial exploitation.

While I have largely ignored the important contributions made by research MRI units in this presentation, I provide one small example of research that introduces a new paradigm for parallel

imaging, and provides a “production line” like way to statistically analyze animal research models using imaging methods [28]. In this one of a kind system, up to 19 mice are imaged simultaneously; each mouse being positioned inside its own coil. Very high resolution images can be acquired in a time efficient manner and large numbers of mice can be imaged to study a range of questions ranging from tumor growth studies, to the consequences of engineered genetic changes etc. This type of research is building new tools and new approaches that we might find, one of these days, on whole body MRI units.

## **Conclusions**

The problem giving a presentation on advances is that the conclusion is expected to discuss futures. Given the myriad number of factors that influence the development of MRI it would be unwise to attempt such folly. But one trend will continue: the hunt to find answers to clinical questions with greater speed, accuracy, precision and cost effectiveness.

## **Acknowledgements**

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<http://www.auroramri.com/>  
<http://www.esaote.com/>  
<http://www.fonar.com/>  
<http://www.gehealthcare.com/>  
<http://www.hitachimed.com/>  
<http://www.imris.com/>  
<http://www.odinmed.com>  
<http://www.onicorp.com/>  
<http://www.medical.philips.com/>  
<http://www.medical.siemens.com/>  
<http://www.medical.toshiba.com/>

For those interested in research type MRI systems (not discussed in this presentation),

<http://www.varianinc.com/>  
[bruker-biospin.de](http://www.bruker-biospin.de)

And other companies discussed in this presentation:

<http://www.confirma.com/>  
<http://www.insightec.com/>  
<http://www.invivocorp.com/>  
<http://www.robinmedical.com/>

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