MR Systems Engineering: **RF Interactions**

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TARGET AUDIENCE

- Researchers interested in Parallel Imaging, Multi-Band Imaging, Parallel Transmission, MR Engineering, High (3T) and Ultra High (7T) Magnetic Field MR, RF coil array design

PREREQUISITE

- The only prerequisite is to remember the two following basic facts:
  - a Complex Variable $\tilde{z}$ can be represented by a Phase φ and a Magnitude *A*, with:

$$\tilde{z} = Ae^{i\varphi}$$

  - the propagation of Radio Frequency (RF) waves in a physical media (e.g. human body) is affected by the shape and properties of this particular media (there is no need to know the nature or the details of such interactions)

IMPORTANT PREAMBLE

- **RF Interactions** impacts the vast majority of components involved in RF Transmit and RF Receive chains in an MR system.
- This lecture, however, will deliberately focus on RF Interactions occurring at the level of a sample imaged with **Receive and/or Transmit RF Coil Arrays consisting of multiple Receive and/or Transmit RF Coil Elements driven by individual RF Channels**.
- This lecture will mostly concern **Human MR Imaging in Humans** where RF wavelength can approach the size of, or be smaller than, the dimensions of the imaged sample.
- Most sections of this lecture will be supported by experimental results and simulations run in Matlab™ to illustrate different levels of RF Interaction concepts
- A complete bibliography would include hundreds of publication. Thus, a shorter list of papers will be found at the end of the present Syllabus, including numerous seminal paprts; additional updated references will be given at the end of the lecture.

HIGHLIGHTS

- RF Interactions occur *inside* and *outside* the imaged sample
- Such *inside* and *outside* interactions are *not independent* to each other

- At Ultra High Magnetic Field (≥ 7T), denoted UHF, RF wavelength becomes shorter than the largest dimensions of the imaged sample (in humans); as a result, the spatial complexity of RF Interactions inside the sample increases as the magnetic field increases
- Some fundamental differences between Transmit and Receive RF characteristics must be understood to properly develop and exploit multi-channel Receive technology on the one hand, and multi-channel Transmit technology on the other hand.
- RF Interactions occur in a complex domain; *Phase*-based and *Magnitude*-based modulations however do not have equivalent capability or scope of application.
- As a general rule the spatial complexity of spatial interference patterns between RF coil elements is the source or both ***additional issues*** (B1 inhomogeneity) and of ***additional potential solutions*** (Parallel Imaging, Parallel Transmission).
- Electro-Magnetic (EM) numerical simulations are remarkably reliable and accurate to model and predict the outcome of both Hardware and Software based methods to address RF Interferences both for RF Receive and RF Transmit technology.
- Controlling SAR levels while addressing transmit B1 inhomogeneity typically relies on using EM models to derive the complex Electric fields of each RF coil element.

Interactions in Multi-Channel RF Systems: for Better and Worse

BACKGROUND: THE IMPORTANCE OF MULTI-CHANNEL RF TECHNOLOGY

Using Receive RF coils made out of several coil elements (1) has enabled the development of Parallel Imaging techniques (SMASH, SENSE, GRAPPA, etc.) which, within just a few years became key players to shorten scanning time and/or increase imaging outcome per unit of scanning time in a large fraction of daily MR routine exams (2-4).

Later on, especially in the context of High and Ultra-High Magnetic Field (UHF) MR, multi-channel Transmit Strategies (B1 Shimming, Transmit SENSE, Parallel Excitation, Spoke Trajectories, kT-points, etc.) have been developed, capable of addressing major transmit B1 heterogeneity issues initially thought to be virtually unsolvable at UHF (5-9). Here again developing Transmit RF coils consisting of multiple RF coil elements was key to enable these techniques; note that in a significant number of cases the same RF coil elements can be used to transmit RF power and to receive RF signals, denoted ‘Transceiver’ coils in this case (10).

New developments are pushing further the capability of exploiting the increased spatial encoding capability offered by multi-channel technology, such as Simultaneous Multi-Band (MB) acquisitions. Originally proposed as a Receive acquisition strategy to shorten acquisition time (11), MB acquisitions approaches recently found a strongly renewed momentum in the context of very fast whole brain coverage at very high spatial resolution needed in applications such as the NIH funded Human Connectome Project (www.humanconnectomeproject.org) (12), and a large body of MR sequences has been developed, including new key concepts to improve the quality of Multi-Band based acquisitions (13-16).

Furthermore, it has recently been shown that, using appropriate RF pulse design strategies, pTX MB pulses can, at the same time, provide image acceleration enabled by multiple receiver coils for parallel imaging reconstruction, and address strong transmit B1 heterogeneity typically observed at HF and UHF (17).

The latter case can be taken as a timely example illustrating the interplay between Receive coil design, Transmit coil design, RF pulse design, MR sequence and Image Reconstruction.

Beside using a larger number of RF coil elements (18-23) and using different shapes and designs for each coil elements in order to impose different B1 penetration profiles, other innovations on the front of RF coil building are still impacting MR acquisition strategies such as z-encoding RF coils, so-called travelling wave regime, dipole radiative antenna, etc. (24-29).

It is important to recognize that the relative performance of all these different coil configurations combined with specific acquisition strategies can most of the time be interpreted as the direct result of specific RF Interactions between each RF coil elements and the sample as well as RF interferences between the transmit B1 (B1+) or receive B1 (B1-) fields of each coil element through the sample and that these interferences can be fairly accurately characterized through experiments and simulations (30).

A constant concern when using a large number of surface RF coils is to be able to map absolute Transmit B1 magnitude profiles for each Transmit coil in a reasonable amount of time despite of the number of channels and despite of the limited spatial extend over which a single RF coil element can achieve sufficient B_1^+ magnitude to provide reliable transmit B1 maps. Utilizing RF complex interferences to exploit both large and small flip angle can dramatically accelerate multi-channel Transmit B1 mapping; after being introduced and demonstrated in a transceiver array at 7 Tesla (31), this concept has been adopted and generalized in other studies as well (32) and can be adapted with most B1 mapping sequences.

During this lecture, different aspects of RF Interactions and their impact on MR acquisitions will be illustrated through a variety of RF coil configurations, RF pulse design and MR sequences.

OBJECTIVES / OUTCOME

After this lecture, attendees should be able to:

- List at least 3 key factors involved in shaping the B1 complex profile of a particular RF Coil (e.g. Larmor Frequency; size and shape (loop, stripline, dipole,…) of the coil elements; distance between RF coil and sample; electrical properties, size and shape of the imaged sample; …)
- Indicate that the complex transmit field in a transmit array at a point in time is the linear superposition of the individual complex transmit field of each RF coil in the array at this point in time

- List two significant electric properties of human tissues and tell one dominant effect on RF propagation for each of these two properties (lossy => RF attenuation, dielectric => shortening of RF wavelength)
- Indicate at least one fundamental difference in an MR experiment resulting from RF interferences when transmitting simultaneously through multiple RF coils (each fed by a separate transmit channel) versus receiving simultaneously through multiple receive coils through multiple independent Receiver channels (Interferences between transmit B1 fields cannot be alleviated, whereas Receive signals can be collected independently from each channel without being altered by the Receive profile of the other coils)
- Recognize that the distortion of B_1^+ and B_1^- field spatial distribution increases with B_0
- Recognize that performances of Parallel Imaging and Parallel Excitation increase as Larmor frequency increases as a consequence of complex B1 field distortion
- Identify the main source of signal dropouts in High and Ultra High Field MR images obtained with multiple transmit RF coils (RF Interferences between complex B_1^+ field of each coil element)
- Recognize that the Phase component of RF coil profiles has typically a larger role than the Magnitude component in artifact formation (signal dropout) and B1 encoding capability (Parallel Imaging, …)
- Understand that most of the time *Relative*, not *Absolute* B1 Phase maps are measured and that most of the time such Relative B1 phase maps are sufficient for the purpose of multi-channel RF pulse design or image reconstruction.
- Understand that applying different B_1^+ shimming solutions in a transmit RF Coil array can yield substantial modulation of forward/reflected power for each transmit coil as well as modulation of RF coupling between channels
- Understand that the latter observation can be described as the result of complex interferences between the Electric Fields of each RF coil element
- Understand that, unlike MR excitation and MR reception that are limited in space to locations where spins are at Larmor frequency, heating is induced by Electric fields in any location reached by the Electric profile of a coil (array). In other words, encoding gradients used to localize MR signals in space are transparent to Electric fields (and their complex interferences) and have no direct influence on SAR.
- Understand that the previous principle can be advantageously utilized to distribute SAR hot spots through space during an MR acquisition, thereby reducing max peak local SAR
- Understand that hot spot SAR locations cannot be immediately derived from B_1^+ maps
- Understand that constraining B1 Shimming or RF pulse design to reduce SAR typically relies on utilizing Electromagnetic simulations to derive complex Electric fields and calculate corresponding SAR values for a given B1 solution or RF pulse. (recently developed techniques to derive Electric field, Electric properties and SAR from B1 measurements are not yet standard methods)
- List at least two fundamental differences involved when manipulating Electric and B1 fields in a RF coil array (e.g. E field cannot be measured whereas $B_1^{+/-}$ field can be measured, E fields are not polarized whereas Transmit and Receive B1 fields, …).

DISCUSSION

RF Interactions, including B1 field Interferences, are more and more exploited to further optimize Receive and Transmit performances in MR experiments. In some cases, both Transmit and Receive component are intimately linked, such as Transceiver RF coils where each channel is a Transmitter and a Receiver, or in pTX Multi-Band acquisition where transmit RF pulse design can explicitly impact reconstruction performances (33). In some cases, RF coil arrays are using pairs of RF coil elements of different nature, with the purpose of minimizing RF Interactions inside each pair (RF coil coupling).

Importantly, the crucial role plaid by explicitly addressing RF Interactions does not only impact Ultra High Field scanners: even at 3T, Transmit B1 profiles are sufficiently heterogeneous to affect the final outcome of some acquisitions. It is thus expected that the large efforts pursued towards addressing UHF B1 issues (using or fighting RF Interactions, depending on the cases) will also translate in improving image quality on 3T scanners.

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