WEEKEND EDUCATIONAL COURSE
MR Physics for Physicists (Saturday, 30 May 2015)

RF Coils & B1 Mapping

Pierre-François Van de Moortele
CMRR, University of Minnesota, Minneapolis MN, USA
pfvdm@cmrr.umn.edu

The following points will be developed during this lecture:

About RF Coils

- RF coils are designed to efficiently exchange RF energy at Larmor frequency with an imaged sample for spin excitation (Transmit RF Coil) and/or signal reception (Receive RF Coil)
- These interactions are critically determined by the geometry of the coil and its spatial relationship with the sampled target as well as by its electronic circuitry
- The large variety of RF coil designs can be categorized along several criteria, including:
    - Transmit only, Receive only, or Transmit and Receive (Transceive) coil
    - Surface coil versus Volume coil
    - Single element coil versus coil array (multiple element)
    - Type of current carrying element (loop, stripline, dipole)
- Using an array of independent small surface receive RF coils rather than a large, single channel volume receive RF coil has become the norm on MR clinical scanners mostly because of large gains in Signal to Noise Ratio and of spatial encoding capability for Parallel Imaging acceleration
- Using an array of surface transmit RF coils rather than a large, single channel volume transmit RF coil is especially beneficial at high and ultra high magnetic field to address large heterogeneity inherently observed in excitation profiles with conventional volume RF coils.

About Coil sensitivity profile

- Parallel imaging acceleration techniques (SENSE, GRAPPA,…) require a precise characterization (or calibration) of the complex sensitivity profile or each receive RF coil element in a Receive Array.
- Likewise, Multi-Transmit RF pulse designs making use of a multi-channel transmit array require the calibration of the complex transmit B1 field of each transmit RF coil for the purpose of RF pulse design (Transmit SENSE, parallel Excitation,…)

About B1 Fields

- Some fundamental differences can be identified between Transmit ($B1^+$) and Receive ($B1^-$) B1 fields:
    - It is possible to measure the absolute magnitude of a Transmit B1 profile
    - It is not possible to *directly* measure the absolute magnitude of the Receive B1 profile of a coil because the measured signal is always weighted by the density of the source of spin, which, in most cases, is represented by the “proton density” or MR-visible water content. When absolute values are required (e.g. quantification) it is necessary to establish a reference signal.

- During signal reception, the complex MR signal carried by one given receive coil channel can be sampled independently to the other receive coil channels
- By contrast, transmitting on multiple channels simultaneously inherently results in a single complex transmit profile reflecting complex interferences (destructive or constructive) between the complex transmit B1 profiles of all the transmit coil elements. At very high field this can result is very substantial excitation profile heterogeneity through space

About B1 Mapping (introductory remarks)

- "B1 mapping" most often refers to "Transmit B1 mapping" whereas
- At low magnetic field (i.e. when the ratio between RF wavelength and the size of the imaged sample is well above one), the principle of reciprocity allows to utilize the measured Transmit B1 field as an acceptable approximation of the Receive B1 field for a given RF coil structure. This is very useful for e.g. quantification purpose.
- At high (3T) and especially ultra high (7T and above) magnetic field, spatial distortion of the B1 field occurs, due to the RF wavelength becoming smaller than the imaged organs or sample, together with the lossy and dielectric properties of biological tissues.
- One consequence is that at high and ultra high field there is no standard reference available for a uniform B1 field such as obtained with a large body RF coil at 1.5T for example
- Another consequence of these distortions is that Transmit and Receive B1 profile are not any more equivalent to each other for a given RF coil.

About $B1^+$ Mapping (methods)

- For many years since MR scanners started to be developed B1+ maps have been obtained with MR sequences that were either very long (because of a very long TR to insure thermal equilibrium before every next excitation) or significantly biased when shorter TRs were used. Obtaining a B1+ map within a single slice could easily take about 10 or 15 minutes at very limited spatial resolution.
- Over the large 15 years or so, however, an incredibly large number of new B1+ mapping methods have been proposed.
- The main challenges faced by B1+ mapping methods can be summarized as follows:
    - Speed (i.e. acquisition time) especially when covering a volume or multiple slice together with multiple RF coil elements (transmit Array with parallel excitation RF Pulse design)
    - SAR: Multiple solution highly efficient to accelerate B1+ mapping result however in fairly high SAR levels that can become impractical as the magnetic field increases
    - Flip angle range. It is much more challenging to develop a B1+ mapping method capable of covering flip angles from, say, 5 degrees up to 270 degrees, than just from 15 to 180 degrees for example. A large coverage of flip angle, however, becomes even more necessary as the trend is to utilize RF coil arrays where each individual channel that needs to be mapped is actually a surface coil with much larger range of excitation flip angle than a conventional volume RF coil
    - Biases: it is interesting to observe that even among some of the most popular B1 mapping techniques, many are subjected to some form of bias or inaccuracies, especially regarding susceptibility induced B0 deviation, Slice profile, RF amplifier linearity, etc.

MR Physics involved

- Although a fairly large array of MR physics principles have been exploited to develop the many B1+ mapping methods available today, all of them rely, a way or another, on some level of non-linearity between actual B1+ strength and the measured signal variation. (the non linear component can relate with signal magnitude, phase accumulation, frequency, etc.)
- In this lecture we will examine and illustrate several of the multiple B1+ mapping techniques that have been proposed
- The methods to be examined will include:
  - Double angle method + modifications/variations
  - Spin Echo
  - Stimulated Echo
  - Signal nulling
  - Signal maximizing / Signal fitting
  - Magnetization Preparation
  - Actual Flip Angle mapping in the steady state
  - DREAM
  - MPRAGE
  - Phase accumulation based B1 mapping
    - Phase Sensitive Excitation
    - Bloch Siegert
    - Frequency Modulated Pulse
  - Super shot T2* B1 mapping (Radial)
  - Interference Mapping in a Transmit Array
- For each of these techniques we will emphasize the pros and cons (time, SAR, sensitivity to B0 offset, precision, suitability for very high field)

Reference

- A comprehensive list of references and reading suggestions will be provided at the lecture to the audience