Parallel imaging is now a clinically standard set of techniques for the reduction of imaging time using RF coil arrays for partial spatial encoding. Even though all of these techniques solve essentially the same set of linear imaging equations, the various paths taken toward this inverse problem distinguishes the various parallel imaging methods from each other. In this talk, we will focus on the basic mechanics of parallel imaging as well as some details about the implementation of these methods. Specifically we cover advanced methods to obtain coil sensitivity information. Finally, we will discuss how non-Cartesian (e.g. projection reconstruction and spiral trajectories) impact a parallel imaging reconstruction.

All parallel imaging methods solve the same basic set of imaging equations: $S = Ex$ where S is the received signals, and x is the target image. The E matrix contains all of the encoding functions used in the imaging experiment. In a normal completely gradient based acquisition, this matrix would be the simple Fourier harmonics used in the acquisition. However, in parallel imaging, we include the additional modulations provided by the imaging array. Once we have constructed the matrix of encoding functions, we only have to invert the matrix to obtain the desired image. In image domain methods such as SENSE, this is performed through a direct matrix inversion that is optimized for SNR. One of the most difficult components of image domain methods is the estimation of the coil sensitivity profiles. Pruessmann et al [1] proposed what has become the standard method to deal with noise in the coil sensitivity maps in the SENSE method. The method is based on a special acquisition designed for coil sensitivity calibration which collects information from both the array and a coil with homogeneous sensitivity. Upon division of these two images, a pure map of coil sensitivity would be obtained in the absence of noise. Alternatively, Walsh et al [2] proposed using an adaptive matched filter for normal array combination to optimize the suppression of background noise which can also be used for calculation of coil sensitivity maps in parallel imaging. The method is based on the calculation of the local signal and noise covariance matrices at each pixel in the image. Walsh et al showed that the eigenvector of these covariance matrices provides a nearly optimal estimate of the coil sensitivity. The primary advantage of this method is that it works without a body coil image. The method can also be used in many cases to form an intensity normalization for the reconstructed image. Another robust alternative for real-time imaging is to use an interleaved sampling scheme, such as TSENSE [3]. In this way, the entire k-space is periodically sampled and can be used for coil sensitivity estimation.

In k-space based methods such as GRAPPA [4], we instead view this as a convolution in k-space. We typically solve GRAPPA reconstructions in two steps. In a first step, a set of fully-sampled data is collected and a set of convolution weights are determined. For example, a typical GRAPPA reconstruction fits a set of shifted k-space lines in all coils to a single shifted line in a single coil:

$S_j(k+m)=\sum_{b} \sum_{i}^{N_c} w(i,j,b,m)S_i(k-b)$ where each w(I,j,b,m) is a weight for each line. As in SENSE, one normally converts this into matrix form which can be solved through standard methods. Once the weights are determined, any missing line can be estimated through simple forward application of this equation.

Both of these methods have been extended to non-Cartesian variants [5,6], and these will be discussed in detail during this lecture.

References:

1. K. P. Pruessmann, M. Weiger, M. B. Scheidegger and P. Boesiger, “SENSE: Sensitivity Encoding for Fast MRI,” *Magnetic Resonance in Medicine*, Vol. 42, 952 – 962, 1999

2. D. O. Walsh, A. F. Gmitro and M. W. Marcellin, “Adaptive Reconstruction and Enhancement of Phased Array MR Imagery,” *Magnetic Resonance in Medicine*, Vol. 43, No. 5, pp. 682 – 690, 2000.

3. Kellman P, Epstein FH, McVeigh ER, Adaptive sensitivity encoding incorporating temporal filtering (TSENSE). Magn Reson Med. 2001 May; 45(5):846-52.

4. Griswold MA, Jakob PM, Heidemann RM, Nittka M, Jellus V, Wang J, Kiefer B, Haase A.Generalized autocalibrating partially parallel acquisitions (GRAPPA). Magn Reson Med. 2002 Jun;47(6):1202-10.

5. Pruessmann KP, Weiger M, Bornert P, Boesiger P.,Advances in sensitivity encoding with arbitrary k-space trajectories. Magn Reson Med. 2001 Oct;46(4):638-51.

6. Seiberlich N, Ehses P, Duerk J, Gilkeson R, Griswold M. Improved radial GRAPPA calibration for real-time free-breathing cardiac imaging. Magn Reson Med. 2011 Feb;65(2):492-505