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Parallel Imaging Reconstruction I: Cartesian

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Syllabus

The goal of this presentation is to briefly introduce the central concepts in parallel imaging reconstruction for *k*-space data that is sampled on a Cartesian grid.

Cartesian Sampling

Cartesian sampling refers to an acquisition in which Fourier-encoded or *k*-space data is sampled on a rectangular lattice with regular spacing, i.e., on a set of points defined on a Cartesian coordinate system. This basic sampling scheme is commonly used because of its straightforward implementation and because the mapping of the *k*-space data into the image domain via a uniform Discrete Fourier Transform can be carried out extremely efficiently and rapidly with the Fast Fourier Transform algorithm—which is a major advantage of Cartesian sampling methods.

Parallel Imaging with Receive Coil Arrays

Parallel imaging is a broad category of data acquisition and image reconstruction techniques that exploit the redundant information obtained when measuring *k*-space data with an array of radio frequency (RF) detectors (a.k.a., a "phased-array" of RF coil detectors). The foundation of hardware design considerations and software image reconstruction approaches required when using these receive coil arrays was originally laid out in a now-classic article by Roemer *et al.* [1]. In this article, the authors described how each coil element in the detector array *in parallel* receives the Fourier-encoded image from a different perspective and a different region of the imaged object, and how these individual images can be combined to form a full image that optimizes the final image signal-to-noise ratio (SNR) provided two additional pieces of information: the spatial *sensitivity profile* of each individual coil element in the image domain, and the *noise covariance* of the thermal noise measured between all pairs of coil elements. It was demonstrated that arrays of small coil elements placed close to the object being imaged could provide dramatic improvements in image SNR compared to conventional single-channel volume coils.

Accelerated Parallel Imaging

Beyond the SNR benefits afforded by receive coil arrays, the partially redundant information collected by the coil array can also be exploited to *accelerate* the image encoding by skipping some of the encoding steps during the acquisition and then estimating this missing information during image reconstruction, thereby reducing the time required for the acquisition [2–5]. In the Cartesian sampling setting, this acceleration consists of uniformly undersampling the *k*-space data in some region of *k*-space, which leads to a violation of the Nyquist criterion and consequently results in aliasing in the image domain. So, for example, to accelerate a single two-dimensional, Cartesian-sampled, Fourier-encoded image acquisition by a factor of 2, every other *k*-space phase encoding line would be omitted during the measurement, which effectively halves the image field of view; similarly, to accelerate by a factor of *R* only every *R*th line is acquired. The goal of accelerated parallel imaging reconstruction algorithms is to remove the aliasing from the resulting image data by leveraging the partially independent information about the imaged object from the array of RF coil detectors.

Two Categories of Accelerated Parallel Imaging Methods

There is a wide variety of accelerated parallel imaging methods that each estimate this skipped data in different ways in order to remove the image aliasing. What these algorithms have in common is that they all require some information about the spatial sensitivity profile of each coil element in the array. Accelerated parallel imaging reconstruction methods can be lumped into two categories: methods that require explicit estimates of the coil sensitivity profiles of the array, and “auto-calibrated” methods that can estimate the coil sensitivity profiles from a small amount of Nyquist-sampled calibration data that is acquired together with the image data. Of all of the accelerated parallel image reconstruction methods available, the two methods that are most commonly used are the SENSE method [6–8] and the GRAPPA method [9, 10], which are both implemented and made available by the MR scanner manufacturers for online reconstruction of accelerated parallel imaging data. The SENSE method is an example of a reconstruction approach that requires explicit estimates of the coil sensitivity profiles and is a natural extension of the original parallel imaging combination methods introduced by Roemer *et al.* [1]. The GRAPPA method is an example of an auto-calibrated approach that is based on SMASH theory [11–14]. For these reasons, the central concepts of accelerated parallel imaging reconstruction will be presented via a detailed discussion of these two well-known algorithms.

Benefits and Applications of Cartesian Parallel Imaging

Today, due to the ubiquity of receive coil arrays and the availability of online image reconstruction methods, accelerated parallel imaging is routinely used in conventional imaging in both standard clinical and research settings. Accelerated parallel imaging not only shortens scan session duration and enables faster temporal sampling in dynamic imaging [15], but it has also been applied to improve image quality by, for example: reducing image artifacts [16–20], enhancing image resolution [21], reducing vulnerability to susceptibility distortion while reducing voxel sizes in echo-planar imaging [22, 23], and increasing the sensitivity of diffusion-weighted imaging by shortening the echo time [24].

Errors and Error Characterization in Accelerated Parallel Imaging

While accelerated parallel imaging has many apparent benefits, it is also important to consider the limitations of the approach. The degree of acceleration is fundamentally limited by the number of coil elements in the array, and in practice the acceleration factor is far smaller than the number of elements for conventional parallel imaging methods using Cartesian sampling. The ability of these methods to synthesize data that is skipped during the accelerated acquisition is primarily limited by the degree of independence between the information carried by the elements of the array—the more unique the coil sensitivity profiles, the more degrees of freedom are in the coil array data and the more flexibility the array has to estimate missing data [25]. Two types of errors gradually arise when the acceleration increases beyond the capacity of the array: *statistical* errors in the form of noise amplification imparted by the reconstruction process, and *systematic* errors in the form of unresolved aliasing artifacts in the image domain. There is an intrinsic loss of SNR inherent in any accelerated acquisition relative to conventional, fully-sampled acquisitions due to the reduced number of *k*-space samples acquired for each image. The intrinsic SNR penalty is the square root of the acceleration factor R. The additional noise amplification (beyond the intrinsic $\sqrt{R}$) has been well characterized for the SENSE algorithm [6], where it is primarily dependent on the geometry of the coil array; for this reason the level of noise amplification at a particular image pixel is denoted as the geometry factor or *g-factor* at that pixel. G-factor maps across all image pixels can therefore provide an estimate of the noise amplification incurred by the SENSE image reconstruction. Analogous noise amplification maps can be estimated for the GRAPPA-like reconstruction algorithms [26–30]. Unresolved aliasing artifacts can also arise and are primarily due to errors in the estimates of the coil sensitivity profiles; these errors can be more challenging to detect, but error estimates based on artifact power and bias calculations have been proposed [28, 31, 32].

New Directions: Massively Parallel Imaging with Cartesian Sampling

New techniques are emerging that are capable of dramatically increasing the acceleration for parallel imaging which also employ Cartesian sampling schemes. Three-dimensional image encoding provides two phase encoding directions along which to accelerate which enables either higher acceleration factors or reduced errors at conventional acceleration factors [7, 33]. Accelerated parallel imaging can therefore be employed for three-dimensional single-shot “echo-volumar imaging” (i.e., the three-dimensional generalization of echo-planar imaging) that can collect an entire *k*-space volume with each excitation while maintaining a short total acquisition time [34, 35]. Some techniques have been demonstrated that omit the phase encoding in one direction entirely, thereby using acceleration factors that are far beyond the number of elements available in modern RF coil arrays through incorporating heavy amounts of prior information via regularization to make the image reconstruction tractable [36–39]. Similar approaches have been taken with multi-slice two-dimensional imaging that exploit the three-dimensional acceleration capabilities of modern RF coil arrays by acquiring multiple slices simultaneously then extracting each of the superimposed slices using accelerated parallel imaging reconstruction techniques [40–42]. These massively accelerated acquisitions and associated image reconstruction methods are still under development, but their potential to dramatically reduce acquisition times and thereby substantially boost temporal sampling rates makes them attractive for high-temporal-resolution functional neuroimaging applications [34–38, 41, 42].

For More Information…

For those interested, there are many in-depth reviews of parallel imaging methodology and applications (e.g., Refs. 43, 44) and comparisons between the existing methods (e.g., Refs. 45–50). While this presentation is focused specifically on parallel imaging methods for Cartesian sampling acquisition, advanced techniques for more general acquisition schemes that are not constrained to Cartesian sampling grids will be discussed in the following presentation.

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