Foundations and Basic Methods

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SMASH[1] and SENSE[2] are now widely recognised methods for speeding up image acquisition by making use of the parallel data streams available when using coil arrays. The individual coils in an array are generally designed to have localised sensitivity so that they yield high signal to noise ratio (SNR) data from a limited region of space. Each coil is connected to a separate receiver resulting in parallel streams of data, each of which produces a separate image. Conventionally, images from each coil are combined to give a single final image which has high SNR and spatial coverage over the extent of the full array. SMASH and SENSE make use of extra information that the combination of localised sensitivities and independent signals provide. The result is partially parallel imaging (PPI) in which conventional spatial encoding with gradients, an inherently serial process, is partially replaced using spatial information inherent in the localised sensitivities of the coils in the array. PPI allows images to be obtained with fewer phase encode steps, the rate limiting factor in most MRI.

Hutchinson introduced the idea of Parallel Imaging more than a decade ago[3], but it attracted little attention until the SMASH technique was introduced by Sodickson *et al* in 1997[2]. In 1999 Pruessman *et al* introduced SENSE[3], which has become the most widespread method used to date. In both SMASH and SENSE the field of view (FoV) is reduced so it is smaller than the object being imaged (Fig 1), which results in aliasing. In traditional spin warp acquisitions the result is that each pixel in the reduced FoV image contains signals from several distinct spatial locations- if the FoV is reduced by a factor R, then locations (FoV)/R apart get mixed together. Although there are now too few distinct pixels to make an unambiguous image, the parallel signals from the coils in the receiver array result in *n* copies, where *n* is the number of coils. For SENSE the n reduced FoV images are combined with information about the spatial sensitivity profile of each coil to separate the aliased signals pixel by pixel and reconstruct a single full FoV image.

Reducing the FoV is achieved by missing out phase encode lines during data acquisition, so that the raw (k-space) data is sampled more sparsely. The SMASH technique uses the spatial properties of the receive coils to directly operate on the data in k-space. To do this the coil sensitivity profiles are combined together to mimic phase rotations introduced across the FoV during conventional gradient phase encoding. This allows the multiple copies of an acquired phase encoded line obtained from each of the coils to be combined to create the next phase-encoded line, which was missed out. The original form of SMASH imposed restrictions on coil geometry. Subsequent extensions, such as

SPACE RIP[4] and generalised SMASH[5], avoid this and provide results that are completely equivalent to SENSE. These latter methods, and generalised SENSE[6], also allow speed up of other acquisition strategies such as radial or spiral k-space scanning. A more general optimised form of the original SMASH concept is provided by GRAPPA[7].

PPI methods require information about coil sensitivity profiles. In SENSE and SMASH style methods this is usually obtaining by acquiring full field of view images with the subject *in situ*, but other coil calibration schemes are possible. Methods have been proposed to integrate the calibration data with the acquisition (e.g. VD-Auto SMASH[8]). These trade-off time gain per acquisition to achieve integration.

The increased speed of PPI comes at a price of reduced signal-to-noise ratio (SNR), which is intrinsically decreased when less data is acquired. However another effect can have a much more devastating impact on image quality. Unambiguous separation of aliased signals requires the coils to provide significantly different views of the region concerned. Coils placed around the outside of the body tend to have similar responses to aliased pixels close to the centre of the body and here pixel separation amplifies noise. The degree of noise amplification is known as the g-factor[2]. With current widely used PPI reconstructions g-factor amplified noise usually limits the maximum practical speed up factor to 3 or 4 in any single direction, irrespective of the number or design of coils in the array.

Notwithstanding this reduction in SNR, use of PPI can result in substantial improvements in image quality. Clearly reducing image acquisition time can decrease vulnerability to motion artefacts. Other benefits occur in single shot imaging, where reducing the required data allows fewer echoes to be collected. This can greatly decrease distortion and blurring due to off resonance effects in EPI and spiral imaging. Information from multiple coils can also be used to combat image artefacts, such as introduced by sequence or machine properties[10, 11], or subject motion[12].

References:

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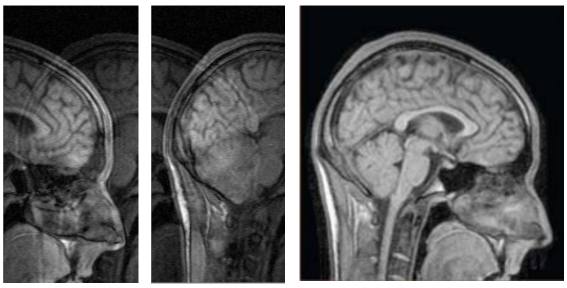

Figure 1. Aliased images (left and centre) from two local coils in an array are unfolded to one full image (right).