Superresolution from Coplanar Image Sequences in MRI

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Synopsis
Although successfully applied to satellite mapping and video surveillance and based on formal mathematical results, superresolution has recently been a very controversial topic in MRI and it has not been clear whether this set of techniques could indeed be applied to improve in-plane resolution from sequences of MR images. In this paper, we introduce both a scanning and a reconstruction method that successfully uses superresolution to improve resolution on sequences of coplanar images. Besides the improvement in resolution, the method also takes advantage of the chemical shift artifact to decouple water and fat signals.

Introduction
Non-invasive clinical MRI currently has a practical resolution limited to around 0.3 mm (300 microns). The characterization of very small anatomical structures, like vascular walls, atheromatous plaque, small ducts, and parathyroid glands is limited at such resolutions. Other techniques like intravascular MRI provide an increased resolution of up to 50 microns, but are invasive and of limited scope. We seek non-invasive alternatives to improve the resolution of MR imaging. For satellite mapping and video surveillance, superresolution techniques are used to produce very high resolution images from progressively shifted overlapping lower resolution images [1]. Early applications of superresolution to MRI used object modeling to generate image data from partial k-space data [2]. More recently, published attempts [3] to introduce to MRI the same satellite mapping superresolution techniques, that use spatially shifted images to increase in-plane resolution, involved important conceptual errors and were recently rebutted [4,5]. Indeed a spatial shift in image space is equivalent to a linear phase modulation in k-space. With spatially shifted MR images, the same k-space information is measured over and over again and the combination of these images simply improves SNR rather than truly increases resolution. In this paper, we avoid this conceptual flaw, and introduce both a scanning technique, that provides different measurements in a sequence of coplanar images, and a superresolution method to increase in-plane resolution in such a sequence.

Methods
We precisely control and vary from image to image the in-plane direction of the readout gradient to acquire multiple coplanar images with fields of view (FOV) at different orientations. For example, Figure 1 illustrates the combination of three such coplanar FOVs. Note that rotation of the FOV is usually accomplished as a post-processing step on most modern MR units, which is not what is done here. By varying the in-plane direction of the gradient fields, the measurement process is influenced and new information is acquired from image to image. Indeed the spatial location of the voxels containing spins affected in the same way by the gradient fields varies from image to image as the direction of the gradient fields is modified. Images in the same plane but using different FOVs can then be combined to achieve higher resolutions. Several optimization techniques can be used to combine a set of coplanar images into a single higher resolution image. We have implemented methods in three categories: back projection methods, set theoretic methods (POCS), and stochastic methods [6]. Our iterative algorithm for superresolution using backprojection, which also decouples water and fat signals, is described on the right [Images: mk: input images, W, w, F, f: water and fat images at high/low resolution; Operators: A: affine correction, C: chemical shift, D: downscaling, R: rotation, U: upsampling].

Results
To produce improvement of in-plane resolution by a factor of N in each of two orthogonal directions, at least NxN k-spaces need to be acquired. Ninety images of a dead rat brain at a pixel resolution of 470 microns were acquired on a 7 Tesla animal MRI unit (Varian Unity Inova) which allowed precise control of the direction of the readout gradient. Two separate images were reconstructed to nominal 60 microns pixel matrices by the algorithm: one illustrating the water content, and the other illustrating the fat content (Figure 2). The amount of detail on these images is very close to that of a comparison image with a true 60 microns resolution (achievable on the animal magnet, with a chemical shift artifact), and much higher than on the 470 microns resolution images. The algorithm converges weakly, but only ten iterations typically suffice to produce high quality images of increased resolution with good separation of the water and fat signals.

Discussion
We showed that with an appropriate acquisition technique significant enhancement of in-plane resolution can be achieved using superresolution techniques in MRI. Three categories of artifacts create limitations to imaging. First, we take advantage of the fact that the chemical shift artifact varies from image to image along the direction of the readout gradient to decouple water and fat signals in images, assuming two discrete components. Second, Gibbs ringing artifacts are present in the initial low resolution images due to the inverse Fourier transform on bandlimited data. An iterative method to reconstruct the image sequence from the initial k-spaces is currently being developed to reduce Gibbs ringing. Third, when the in-plane direction of the readout gradient is modified, gradient field hardware approximations also produce distortions in the resulting images, which are scanner dependent but are constant from study to study. We very closely approximate these distortions by affine transformations (A), computed once per scanner using a sequence of high resolution images obtained from a non-fat containing phantom. A full mathematical characterization of these distortions is under way. Our scanning and reconstruction technique is applicable to both planar and volume imaging, and is being extended to also handle motion correction. We are currently targeting the technique for vascular plaque characterization, with nominal in-plane resolutions approaching 10 microns.

References

Figure 2: MRI of dead rat at the level of the brain. From a sequence of coplanar images at a pixel resolution of 470 microns (left), separate images of water (middle) and fat (right) at a nominal pixel resolution of 60 microns are reconstructed by our approach. Motion was not an issue in this specific case.