Slant-slice imaging with an inhomogeneous field

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Introduction: Slant-slice imaging is an acquisition technique for efficient, low-SAR imaging with an inhomogeneous background field. We give a description of our method in several illustrative cases and an analysis of the resolution and SNR. We provide the result of a simulation done in a conventional 1.5T clinical scanner (Siemens Sonata) by leaving a (linear) gradient field on throughout the acquisition.

Theory: Let B_0 denote a strong, stationary magnetic field in a region of space D such that the level sets of $\|B_0(x,y,z)\|$ are graphs over a rectangular region of the plane; in particular $\nabla\|B_0\|$ does not vanish within D. Assume that we can also generate, possibly non-linear, auxiliary gradient fields G_1, G_2, (note that these are magnetic fields, not their projections in the B_0-direction) so that, within D, the function $\Psi:[x,y,z]\to[\|B_0(x,y,z)\|,\langle G_1,B_0(x,y,z)\rangle,\langle G_2,B_0(x,y,z)\rangle]$ is a 1-1, invertible map onto a cuboidal region of space. In [1] it is shown that, in principle, the field B_0 can be used as the background field in an MR-imaging system, wherein the measurements are interpreted as the Fourier transform of the spin density function, with appropriate relaxation terms, composed with a change of coordinates defined by Ψ. Several other approaches to imaging or spectroscopy in similar circumstances appear in the literature, see [2,3,4]. In these approaches, stroboscopic acquisition techniques, requiring many refocusing pulses, or matched inhomogeneous B_1-fields are employed. In this abstract we show that by combining the permanent background gradient with an auxiliary gradient to define the slice select direction, and using the other gradient for phase encoding, gives an acquisition technique with the SAR and efficiency of spin-warp imaging, using a fairly arbitrary background field.

Methods: (a) Linear Model Case: Suppose that $B_0=(0,0,b_0)+(*,*,g_z z)=(0,0,b_0)+G_0$, $G_1=(*,*,g_x x)$, $G_2=(*,*,g_y y)$, with b_0 large compared to g_x, g_y and g_z; $*$ denotes field components that are negligible compared to b_0. Note that G_0 is a permanent gradient in B_0 that is present throughout the experiment. One possible sequence is, in essence, a standard spin-echo imaging sequence, except that during selective excitation, the field G_1 is applied, and during the readout, $-G_1$ is applied. Note that the slice select and readout gradients are therefore $G_0 \pm G_1$, respectively. Phase encoding is done using multiples of G_2. A timing diagram is shown in **Figure 1**. As shown in **Figure 2**, the slice select direction is $(g_x,0,g_z)$, while the readout occurs along lines orthogonal to $(-g_x,0,g_z)$. If w is the slice profile, then, ignoring the third dimension, the measured signal is:

$S(t)=\int_D \rho(x,z)w(\gamma(g_x x+g_z z))e^{-i\gamma t(g_z z-g_x x)}dxdz$. This can be interpreted as the Fourier transform of $\bar{\rho}$, which is ρ averaged along lines making an angle $\theta=\cos^{-1}\left(2\nu(1+\nu^2)^{-1}\right)$, with the slice select direction; here $\nu=g_x/g_z$. There are many other possible sequences using this general scheme, utilizing one or two refocusing pulses-per-line in k-space.

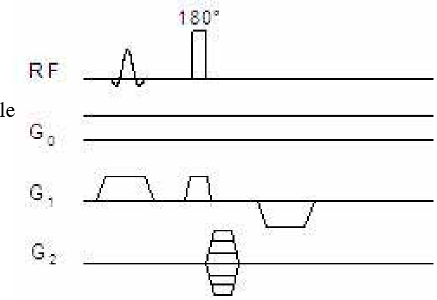

Figure 1: A timing diagram for use with an inhomogeneous background field.

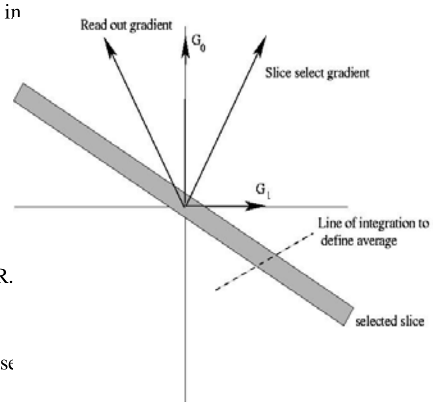

Figure 2: Slice selection and averaging in slant-slice imaging.

(b) SNR and Resolution: The SNR and maximum attainable resolution are determined primarily by the angle θ, rather than the absolute size of G_0.

Resolution is directly affected by the slant of the lines, with respect to the slice select direction, over which ρ is averaged. Provided that the maximum frequency sampled satisfies $k_{\max}<(2d)^{-1}\cot\theta$ (d is the slice thickness), then $\Delta x \approx (2k_{\max}\cos\theta)^{-1}$. The loss of resolution can, in part, be compensated for by decreasing d and increasing $k_{\max}$. The size of the total gradient $g^2=g_x^2+g_z^2$ does not have a direct effect on the SNR, though the angle, θ constrains the product $dk_{\max}$. As θ tends to $90°$, the slice thickness must go to zero, and this diminishes the SNR. These considerations place a limitation on the maximum angle θ at which this approach can be expected to offer a time efficiency advantage over stroboscopic techniques.

(c) Non-linear case: Provided B_0, G_1, G_2 satisfy the conditions above, then the sequence described in the linear case can be used to acquire data that has an interpretation as the Fourier transform of a non-linear average of a non-linear slice of ρ, composed with a coordinate transformation determined by Ψ. The spin density can then be reconstructed by an inverse Fourier transform followed by a change of coordinates.

Results: Figure 3 shows an image of a GE phantom made in a Siemens 1.5T scanner with a permanent gradient of about 10mT/m and $g_x=g_z$. This 512x512 acquisition took approximately 3 minutes, with four scans per-line.

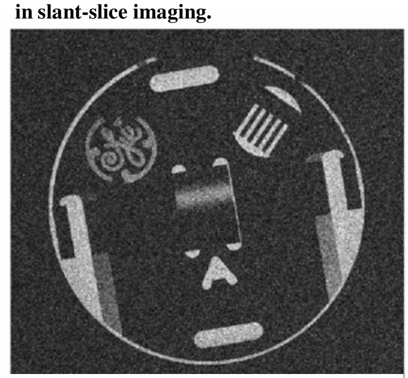

Figure 3: Image of GE phantom made with permanent background gradient.

Conclusion: Slant-slice imaging is a time and SAR efficient acquisition technique for MR-imaging that gives high resolution artifact free images with a strongly inhomogeneous B_0-field. The principal limitation of the method is a requirement that the size of the auxiliary gradients, G_1, G_2, be within about an order of magnitude of the size of the permanent gradient G_0.

References:

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