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Single-shot curved slice imaging

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Abstract

The feasibility of imaging a curved slice with a single-shot technique so that the reconstructed image shows an un-warping of the slice is examined. This could be of practical importance when the anatomical structures of interest can be more efficiently covered with curved slices than with a series of flat planes. One possible example of such a structure is the cortex of the human brain. Functional imaging would especially benefit from this technique because several planar images can be replaced by a few curved slice images. A method is introduced that is based on multidimensional pulses to excite the desired curved slice profile. A GRASE imaging sequence is then applied that is tailored to the k-space representation of the curved slice. This makes it possible to capture the in-plane information of the slice with a single-shot technique. The method presented is limited to slices that are straight along one axis and can be approximated by a polygon. Reconstruction is performed using a simple numeric Fourier integration along the curved slice. This leads to an image that shows the desired un-warped representation of the slice. Experimental results obtained with this method from healthy volunteers are presented and demonstrate the feasibility of the proposed technique.

Keywords: MRI; Curved slice; 2D RF pulse; Functional MRI; GRASE

1. Introduction

Magnetic Resonance Imaging (MRI) is normally restricted to planar slices, and hence the examination of extended anatomical structures generally requires the acquisition of 3D or multi-slice 2D data sets. Particularly in the case of objects that resemble a folded or distorted slice it may be advantageous to shape the slice profile so that it is matched to the object. Such a scheme may well be less time-consuming than a multi-slice experiment, and thus allow an improvement in temporal resolution, for example in functional MRI experiments.

Excitation of a curved slice may be performed by the application of 2D RF pulses [1,2] The most general case of an arbitrarily warped plane would require the application of a 3D pulse, which is generally impractical due to its extremely long duration. Therefore, the previous publications [3,4] and the following work are restricted to slices where curvature was only permitted in one dimension. These slices can be excited using a 2D pulse. The two selection gradients of the pulse are then played out in a plane that is perpendicular to the straight direction of the surface.

The first attempt to use curved slice selection to image non-coplanar anatomy was given by Börnert in [3]. It was proposed to utilize a set of 2D pulses which excite the curved slice with a certain phase or amplitude encoding scheme along the slice, e.g. Hadamard Encoding. With a set of N different pulses it is then possible to reconstruct an image that shows the unwarped slice with a resolution of N rows in the phase encoding direction. This technique allows arbitrarily oriented slices, but the scan requires N excitations for a single slice and is therefore of limited value for functional imaging.

The second publication to this theme excited a curved slice which was then imaged in projection on a flat 2D plane [4]. Although, the imaging experiment required to achieve this is then standard, there may be difficulties caused by the effective spatial resolution and intensity varying within the slice. One solution is to image onto a number of differently oriented planes, but

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the single-shot nature of the experiment will then be compromised. In this paper the possibility of imaging on a coordinate system in the slice-plane with a single shot technique is examined. The resulting image then has uniform resolution and represents an un-warping of the curved excitation slice onto a 2D plane.

2. Method

As proposed by Börnert and Schäffter [4] curvature was only permitted in one dimension. This simplification allows the application of 2D RF pulses for excitation. Acquisition can then be performed using a modified imaging sequence with the read gradient oriented parallel to the unrestricted dimension of the curved slice. The other two dimensions, which coincide with the RF-pulse's selection gradients, can then be interrogated by phase encoding in these directions. The problem then simplifies to determining where the important information is located in the plane that is spanned by the two phase encoding gradients. After that one has to find a suitable k-space trajectory that captures the curved-slice information so efficiently that all the necessary information can be acquired within a single-shot imaging experiment. For simplicity this plane will subsequently be referred to as the k-plane.

In a conventional 2D imaging experiment of a flat slice in which the k-plane was oriented perpendicular to an uncurved slice, the information from the plane would lie on a line through the origin of the k-plane. This simple relation between the location of the in-plane information in the spatial and frequency domain can be extended to arbitrarily curved slices. This is done by noting that each curved slice can be approximated by a sum of infinitesimal small plane segments. The in-plane information for each segment, i.e. that which is required to reconstruct an image, is then also a line through the origin of the k-plane. The location of the in-plane information of the curved slice in the k-plane is then given by the superposition of the single plane segments as this is the case in the spatial domain. This summation is justified by noting that the Fourier transform is linear, i.e. a superposition in the spatial domain can also be expressed by the equivalent in the frequency domain.

With this procedure to derive the distribution of in-plane information in the k-plane the representation of an arbitrarily curved slice is then a bowtie-shaped region centered about the k-plane origin. This is illustrated in Fig. 1, which shows that the subset of the k-plane which contains the in-plane information from the surface is confined to a region defined by the maximum angle subtended by the tangents to this surface. The acquisition can therefore be reduced to the corresponding range of spatial frequencies. It should be noted that the region containing the information on the intensity distribution of the RF-pulse is congruent to that which contains the in-plane information, but rotated about 90°. This has previously been noted by Hardy [2] in connection with the development of a multidimensional pulse to excite a warped slice.

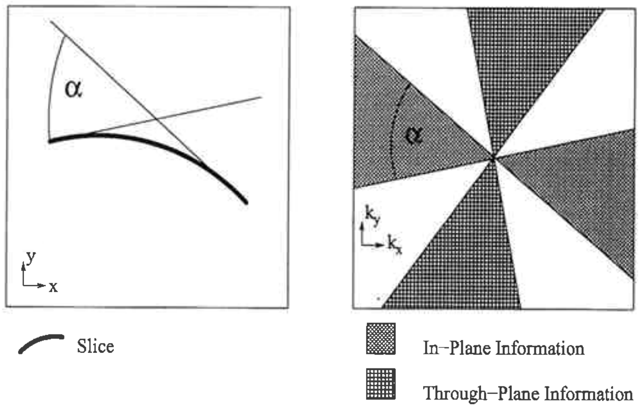

Fig. 1. k-plane representation of the curved slice. The left diagram shows an arbitrarily curved slice. The corresponding areas in the k-plane that contain the in-plane and through-plane information of the slice are displayed on the right.

The region of the k-plane containing the in-plane information may still be too large in practice to be comprehensively sampled by a single-shot technique. In order to further reduce the amount of information required the surface can be approximated by a polygon. The in-plane information is then confined to some lines through the origin, one for each segment of the polygon. Their orientation in the k-plane is parallel to that of the segments in the spatial domain. These segments may then be sampled equidistantly.This is displayed in Fig. 2.

The argumentation presented here is based on the assumption that there is a negligible variation in information through the slice for each segment, i.e. the contrast is constant over the slice profile for each point

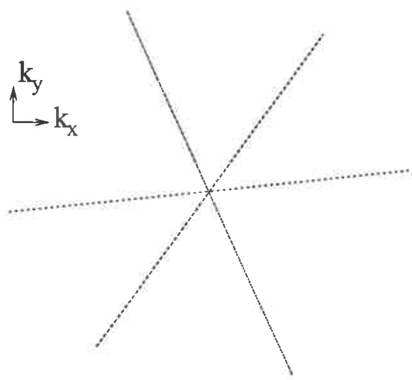

Fig. 2. k-plane representation of a polygon shaped curved slice. The dotted lines through the origin of k-space will be sampled equidistantly with an apropriate 2D phase encoding scheme.

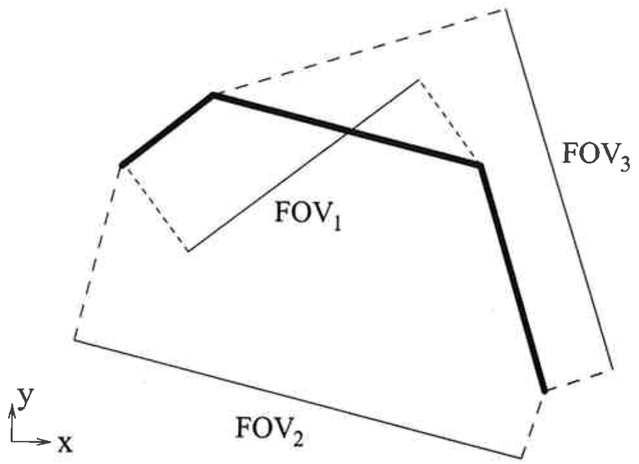

Fig. 3. Multiple field of views for a polygon shaped slice. A curved slice which is approximated by a polygon is shown. The FOV_j for each segment is defined by the total extent of the object along the direction of each segment. This determines the maximum k-space increment for this segment to avoid wrap-around artefacts.

in the slice. If this is true then the in- and through-plane information of a linear segment collapses onto two perpendicular lines in the k-plane, otherwise the information will be distributed over an area in the k-plane. This could lead to interference between the different segments and therefore produce artifacts in the reconstructed image. The second assumption is that there is a maximum intensity of the k-plane representation of the in-plane information at the origin, otherwise the lines containing the in-plane and through plane-information will be perpendicular but will not necessarily cross at the origin.

To avoid image artifacts the sampling theorem of the Fourier transform must be fulfilled. The field of view for each segment FOV_j is hereby defined as the maximum extent of the total curved slice in the jth segment's direction as is depicted in Fig. 3. This requires a minimum distant of

$$\Delta k_j = \frac{2\pi}{\mathrm{FOV}_j}, \tag{1}$$

between adjacent sampling points in the k-plane for the jth segment in order to avoid wrap-around. To obtain a resolution Δx that distinguishes between neighbouring points in the spatial domain the minimum sampled diameter of the k-plane is

$$k_D = \frac{2\pi}{\Delta x}. \tag{2}$$

The minimum number N_j of phase encoding steps which ensures no aliasing and gives the required spatial resolution for the jth segment is hence given by

$$N_j = \frac{k_D}{\Delta k_j} = \frac{\mathrm{FOV}_j}{\Delta x}. \tag{3}$$

The difference with a standard imaging experiment is that the number of data points, N'_j, which are then used to provide image information from a given segment is given by

$$N'_j = \frac{N_j L_j}{\mathrm{FOV}_j} = \frac{L_j}{\Delta x}, \tag{4}$$

where L_j is the length of the jth segment. As the other information is excluded from the final image there is a corresponding loss in efficiency compared to a standard experiment.

With these considerations the set (k_x^l, k_y^l) of phase encoding steps l can be found on the lines which are symmetrically placed around the origin of the k-plane, one for each segment of the curved slice. The total extent of each line segment is given by Eq. (2). This line is then sampled equidistantly with a minimum increment given by Eq. (1). However, the image quality increases as the increment decreases which will be discussed later in the Section 3.

The first step in the reconstruction procedure consists of a standard FFT in the read direction. For reconstruction in the phase encoding direction one should note that in general the k-plane positions of the two dimensional phase encoding steps do not lie on a Cartesian grid. Therefore, reconstruction cannot be performed using an FFT. Instead the frequency analysis is calculated by replacing the Fourier integral with the sum

$$\rho_{i,j} = \sum_l \mathrm{FFT}_j(S_{j,l})\, e^{(x_i k_x^l + y_i k_y^l)} \tag{5}$$

over all measured data points to calculate the (complex) image $\rho_{i,j}$. Here j denotes the frequency encoding direction, $\mathrm{FFT}_j(S_{j,l})$ is the Fourier transformed signal in this direction, and l denotes the different gradient echoes. This reconstruction mechanism requires the information about the positions (x_i, y_i) of the points within the slice.

3. Experimental

Experiments were performed on a Bruker 3T/100 Medspec system. The gradient coils deliver a maximum gradient strength of $45mT/m$ and a minimum rise time of 300 μs. RF excitation and signal acquisition were performed using a homogeneous birdcage resonator of 280 mm internal diameter. Following preliminary experiments on phantoms, in vivo experiments were performed on healthy volunteers who had previously given informed prior consent. The effective duration for a scan with a 64 × 64 matrix size for the curved slice was approximately 800 ms.

3.1. Pulse design

The 2D excitation pulse was calculated by assuming that the curved slice can be approximated by a number of discrete points (x_i, y_i) which are combined to form the surface profile. This is equivalent to the method described in [3] but without any encoding along the slice. The RF shape of the pulse can then be generated by the superposition of pulses for each of these points. Each of these sub-pulses can be calculated according to the small tip angle approximation given in [1]. The resulting equation for a pulse with the duration T_P and $t \in [0, T_P]$ is then given by

$$B_P(t) \sim \sum_i e^{i[x_i k_x(t) + y_i k_y(t)]} \tag{6}$$

with the k-plane trajectory

$$\begin{pmatrix} k_x(t) \\ k_y(t) \end{pmatrix} = k_0 r\left(\frac{t}{T_P}\right)\begin{pmatrix} \cos \Omega t \\ \sin \Omega t \end{pmatrix} \tag{7}$$

$$\Omega = 2\pi \frac{N}{T_P} \tag{8}$$

$$r(s) = \begin{cases} \sqrt{1 - \frac{4s}{3}} & s < \frac{1}{2} \\ 2\frac{1-s}{\sqrt{3}} & s \geq \frac{1}{2} \end{cases} \tag{9}$$

This is a spiral with N revolutions covering a circular region with radius k_0 of the k-plane. The radial function $r(s)$ is split into two intervals to optimize the perfomance of the pulse with respect to the given hardware constraints [5]. An additional time dependent factor that compensates for non-uniform sampling within the k-plane [6] was also applied in the experiments. The pulse represented by a digitized waveform of 2000 sampling points with $N = 14$ and a flip angle of $\pi/2$ was applied for 15 ms. With this Gaussian filtered pulse the thickness of the slice was approximately 8 mm. In the system used a difference of 72 μs between the RF and gradient channels exists, which if uncorrected would cause the excitation profile of the 2D RF pulse to rotate around the origin [7]. This was compensated by introducing a delay of this length into the sequence. Distortions of the 2D excitation profile due to eddy currents were not observed.

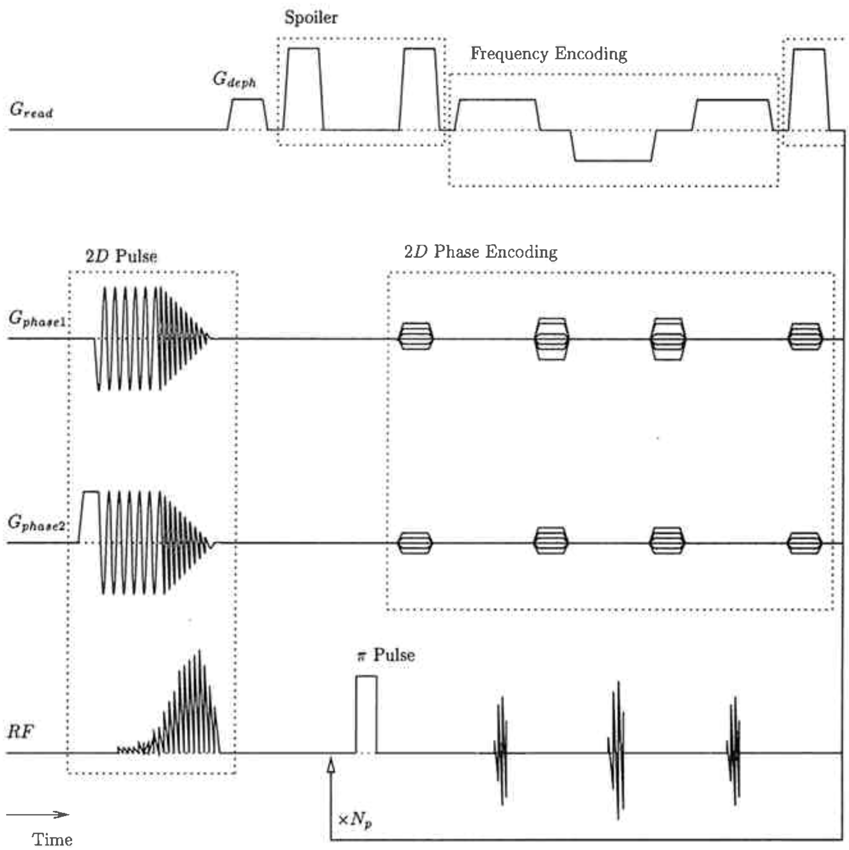

Fig. 4. Modified GRASE sequence used in this work with three gradient-echoes per spin-echo. As mentioned in the text the two selection gradients of the 2D pulse are coaxial with the 2D phase encoding gradient channels. The third gradient channel is used for frequency encoding and spoiler gradients. Refocusing is performed using a nonselective rectangular shaped pulse.

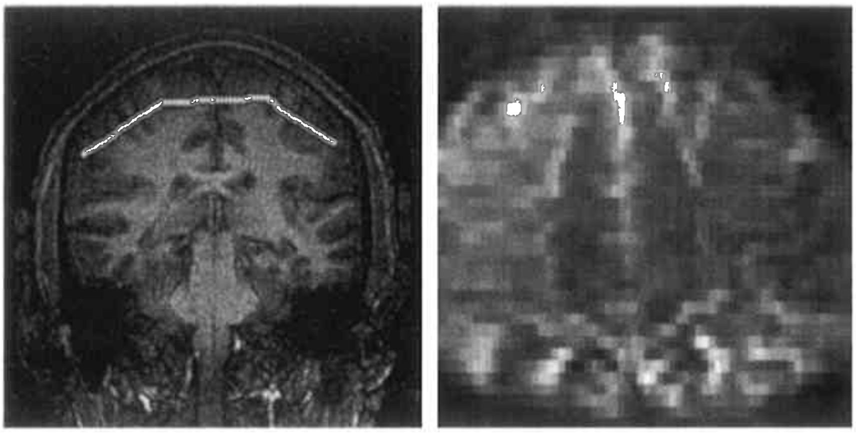

Fig. 5. The left image shows a coronal image on which the slice definition is shown. In this pair of images the segments only show a slight deviation from a straight line. Each white cross on the left corresponds to one vertical line in the image on the right. The image is truncated in the read direction to exclude regions without signal, and to allow equal scaling in the read and phase direction.

3.2. Data acquisition and processing

The imaging sequence is shown in Fig. 4. It is a modified GRASE sequence [8] with two phase encoding directions, one replacing the slice direction of a standard imaging sequence. The signal was acquired using a center out sampling strategy and the TIPE phase-encoding scheme [9]. With this technique the echoes with the highest intensity are placed innermost in the k-plane. The echo intensities were determined using a reference scan with disabled phase encoding gradients. This approach leads to a PSF that decays monotonically from the origin outward. This minimizes artifacts produced by the different echo intensities. The reference scan was also used to perform a point by point phase correction.

From the mathematical point of view it should be possible to reconstruct an image from

$$N_{\text{total}} = \sum_j \frac{FOV_j}{\Delta x} \tag{10}$$

phase encoding steps as mentioned in the previous section. However, it was experimentally determined that the image quality was improved by performing a higher level of oversampling in the k-plane, i.e. keeping the radius of the sampled region the same but reducing the increment. If a standard FFT algorithm had been used then this would just have resulted in an increased FOV, but using the algorithm of Eq. (5) an averaging is performed that effectively reduces the effects of errors in the echoes acquired early in the echo train. With the GRASE sequence used it was possible to obtain nearly 200 echoes within a single scan which lead to an oversampling factor of roughly 2.

The read direction of our experiments is oriented along the A–P axis. The imaging sequence consists of three gradient echoes per spin echo with TE = 11 ms. A total of 198 gradient echoes were acquired on an FOV of 25 cm.

The acquired signal was preprocessed by a filter that compensates the amplitude modulation of the gradient echoes caused by the GRASE sequence. This filter was adjusted so that it resulted in a Gaussian shaped intensity decay with respect to the radius in the k-plane, with the last echo having an intensity 5% of the first echo. The Convolution Theorem predicts that this will lead to a Gaussian shaped point spread function. As the diameter of the sampled k-plane is determined according to the distant Δx of adjecent pixels (Eq. (2)), the full width at half maximum will be roughly one pixel. The application of this filter is only justified if the signal to noise ratio of the last echo is adequate, which in these experiments was satisfied due to the relatively large slice thickness, and the small k-plane radii sampled.

4. Results

Results obtained from a healthy volunteer are shown in Fig. 5 and Fig. 6. In each case the left image shows an anatomical data set obtained using a modified MDEFT sequence [10]. The polygon consisted of three segments, in Fig. 5 only a small deviation from a flat slice was used, in Fig. 6a polygon form closer to that which could be used for imaging the cortex is used. Each white cross corresponds to one horizontal line of the reconstructed 64×64 magnitude image shown on the right. In the right image of Fig. 5 the following anatomical structures are visible: *Fissura sagitalis*, the *Sulcus frontalis superior* and less clearly the *sulcus precentralis*. Both images show a good image quality and signal to noise, albeit with some residual blurring in the phase-encoding direction.

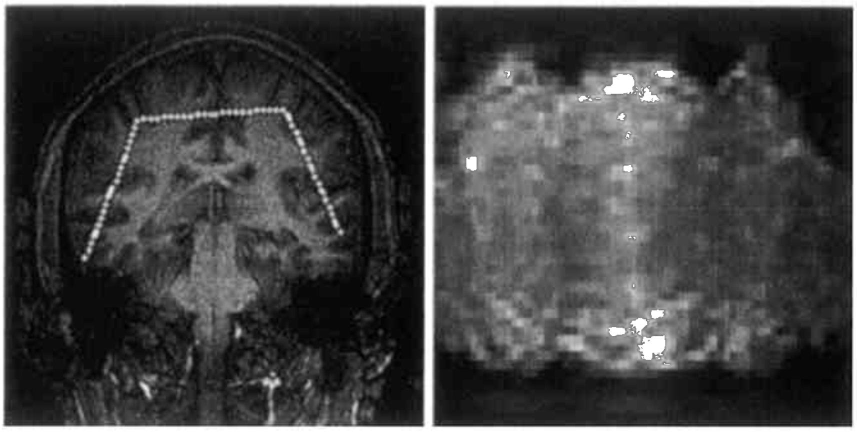

Fig. 6. Slice definition and unwarped image of a slice with more acute segments than shown in Fig. 5. As for Fig. 5 each white cross on the left corresponds to one vertical on the right. The image is also slightly truncated for the same reasons mentioned in Fig. 5.

5. Discussion

It has been shown possible to unwarp the image plane using single-shot imaging. Functional studies could benefit from this method. Especially in cases where several regions that form an anatomical unit but cannot be mapped simultaneously by means of a standard 2D imaging technique are to be examined. However, the application of 2D pulses, the non-standard imaging sequence and the unusual reconstruction procedure require a considerable overhead to perform the experiment. The requirement of a separate time-consuming reference scan for the phase correction and amplitude deconvolution can be neglected in the case of functional studies where one reference scan is sufficient for a large series of functional images. A further drawback is the relatively large slice thickness possible with our hardware configuration, and the small spectral bandwidth of the 2D pulse.

The reason for employing GRASE in this particular study was that the implementation of arbitrary phase-encoding schemes is more easily accomplished with GRASE than with EPI. But despite its high sensitivity the GRASE imaging technique is known to be artefact-prone [11]. The amplitude and phase modulation of this sequence depends heavily on the phase encoding scheme used. The TIPE technique [9] and the preprocessing filter can compensate the former but phase errors still produce artifacts. By oversampling the k-plane as done in this study, phase errors decrease with the number of gradient echoes. With other imaging techniques such as echo planar imaging (EPI) it could be possible to circumvent these difficulties. A further potential advantage of EPI is that it could be more readily used for multi-slice studies, as only one 2D RF-pulse per slice is required for this sequence. A multi-slice GRASE scheme of this nature would require refocusing pulses which were spatially selective in that they should not affect any of the other slices being examined. This would in practice be almost impossible to implement.

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