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Anisotropic field-of-view shapes for improved PROPELLER imaging[☆]

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Abstract

The Periodically Rotated Overlapping Parallel Lines with Enhanced Reconstruction (PROPELLER) method for magnetic resonance imaging data acquisition and reconstruction has the highly desirable property of being able to correct for motion during the scan, making it especially useful for imaging pediatric or uncooperative patients and diffusion imaging. This method nominally supports a circular field of view (FOV), but tailoring the FOV for noncircular shapes results in more efficient, shorter scans. This article presents new algorithms for tailoring PROPELLER acquisitions to the desired FOV shape and size that are flexible and precise. The FOV design also allows for rotational motion which provides better motion correction and reduced aliasing artifacts. Some possible FOV shapes demonstrated are ellipses, ovals and rectangles, and any convex, pi-symmetric shape can be designed. Standard PROPELLER reconstruction is used with minor modifications, and results with simulated motion presented confirm the effectiveness of the motion correction with these modified FOV shapes. These new acquisition design algorithms are simple and fast enough to be computed for each individual scan. Also presented are algorithms for further scan time reductions in PROPELLER echo-planar imaging (EPI) acquisitions by varying the sample spacing in two directions within each blade.

Keywords

PROPELLER; Motion correction; Trajectory design; Anisotropic field-of-view; PROPELLER EPI

1. Introduction

The Periodically Rotated Overlapping Parallel Lines with Enhanced Reconstruction (PROPELLER) acquisition method and reconstruction scheme [1,2] is arguably one of the most valuable new techniques available for magnetic resonance imaging (MRI). This is because it provides robust motion correction, resulting in sharp images even when motion is present. This is particularly valuable for imaging uncooperative or pediatric patients who may move substantially during an exam [3]. Diffusion imaging is another application that not only benefits from this motion correction but also from PROPELLER's additional ability to correct for phase errors, generally due to motion during the diffusion gradient [4–7]. The disadvantage of PROPELLER imaging is that it requires increased scan times over traditional, Cartesian imaging trajectories.

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In PROPELLER, image data are acquired on a trajectory that is a hybrid of the radial and Cartesian sampling schemes and derives advantages from both schemes. The trajectory consists of radial “blades” in k -space which each cover a common central region. This repeated central sampling, a characteristic of radial sampling schemes, allows for correction of in-plane motion between blades and trajectory errors due to timing delays, eddy currents, or gradient imperfections. Each blade consists of a Cartesian sampling scheme of equally spaced lines, resulting in a uniformly sampled overlapping region. This Cartesian sampling yields low-resolution images for each blade, each of which contains the entire object so that full motion correction can be performed.

The blades are normally acquired with equiangular spacing, which results in an isotropic, circular region of support, known as the field of view (FOV). Aliasing artifacts will degrade the image quality if the entire object is not contained within this FOV. Many objects have noncircular shapes, and the scan efficiency can be improved by tailoring the FOV to the object. Varying the FOV shape has been developed for other non-Cartesian trajectories, such as spirals [8] and projection reconstruction [9,10]. Noncircular FOV shapes in PROPELLER can be achieved by introducing variable blade angles and line spacings, an idea first introduced in Ref. [1]. Recently, an exact formulation of the variable blade parameters in a closed-form solution has been derived for elliptical FOVs [11,12]. Their work has demonstrated the effectiveness and advantages of variable FOV shapes, as well as showing their integration into the PROPELLER acquisition and reconstruction methods.

This article presents algorithms that allow for a variety of anisotropic FOV shapes. This work is similar to previous work [11,12] but allows for nonelliptical shapes and will have reduced aliasing artifacts when motion is present. Presented is a generalized algorithm that designs both PROPELLER and PROPELLER echo-planar imaging (EPI) blades for a large class of FOV shapes of all sizes with room for the anticipated rotational motion, resulting in the most efficient acquisition trajectory possible. The algorithm is relatively fast because it is based on simple mathematical operations, allowing for designs on a scan-by-scan basis. In this article we present simulation results demonstrating the effectiveness and improvements of our method.

2. Theory

Sampling theory tells us that the sample spacing defines the FOV that can be supported without aliasing. Furthermore, both the FOV and the resolution of a sampling trajectory are determined by the point spread function (PSF), which is the Fourier transform (FT) of the sampling pattern. The sampling of a PROPELLER blade can be separated into two components: the pseudoradial and pseudoangular sampling, both of which are illustrated in Fig. 1. The pseudoradial component is defined by the spacing between adjacent samples within a line, Δk_r . The pseudoangular component is defined by the spacing between adjacent lines, Δk_α .

The pseudoangular sampling of the lines, as shown in Fig. 1A for a blade along the k_x axis, is

$$P_\alpha(k_x, k_y) = \text{rect}\left(\frac{k_x}{(N_r - 1)\Delta k_r}\right) \times \sum_{n=1}^L \delta\left(k_y - \left(n - \frac{L+1}{2}\right)\Delta k_\alpha\right), \quad (1)$$

where L is the number of lines per blade and N_r is the number of samples per line. The pseudoangular sampling PSF, also shown in Fig. 1A, is

$$FT\{P_\alpha(k_x, k_y)\} = C_\alpha \text{sinc}((N_r - 1)\Delta k_r x) \times \sum_{n=1}^L \exp\left(i2\pi\left(n - \frac{L+1}{2}\right)\Delta k_\alpha y\right), \quad (2)$$

where C_α accounts for scaling factors. This sum of exponentials results in a peak at $y = \frac{1}{\Delta k_\alpha}$ which will cause aliasing and limit the FOV.

The pseudoradial sampling along the lines, shown in Fig. 1B, is

$$P_r(k_x, k_y) = \text{rect}\left(\frac{k_y}{(L - 1)\Delta k_\alpha}\right) \times \sum_{n=1}^{N_r} \delta\left(k_x - \left(n - \frac{N_r+1}{2}\right)\Delta k_r\right), \quad (3)$$

and its PSF is

$$FT\{P_r(k_x, k_y)\} = C_r \text{sinc}((L - 1)\Delta k_\alpha y) \times \sum_{n=1}^{N_r} \exp\left(i2\pi\left(n - \frac{N_r+1}{2}\right)\Delta k_r x\right), \quad (4)$$

where C_r accounts for all scaling factors. This sum of exponentials results in a peak at $x = \frac{1}{\Delta k_r}$ which, in addition to the pseudoangular sampling aliasing, also limits the FOV. The pseudoradial sampling FOV limitation is identical to the readout anti-aliasing filtering that is usually performed along the acquired k-space lines.

The dimensions of the PSF main lobe are inversely proportional to the blade size, shown by the exaggerated illustrations in Fig. 1. These dimensions are $\frac{1}{(N_r-1)\Delta k_r}$ in x and $\frac{1}{(L-1)\Delta k_\alpha}$ in y for this blade orientation [Eqs. (2) and (4)]. The smaller dimension (x) is equivalently $\frac{1}{2k_{\max}}$, where

$$k_{\max} = (N_r - 1)\Delta k_r / 2 \quad (5)$$

is the maximum extent in k -space. This dimension corresponds to the image resolution. The full blade sampling, $P(k_x, k_y)$, is the product of the pseudoangular and pseudoradial sampling patterns:

$$P(k_x, k_y) = P_\alpha(k_x, k_y) P_r(k_x, k_y), \quad (6)$$

resulting in a convolution of Eqs. (2) and (4). This results in repetitions of the PSF main lobe, as illustrated in Fig. 1C.

Rotation of a blade yields an identical rotation of the blade PSF, so with a full set of blades at different angles, their main lobes and peaks will combine to form a PSF whose outer peaks determine the FOV shape. The PSF main lobe, in the center of k -space, determines the total image resolution. However, the shape of the PSF outer peaks is not necessarily the same as the supported FOV shape because the object is convolved with the PSF. Convexity of the outer peaks shape will ensure that convolution results in an identical FOV shape. The symmetry of the trajectory also means that the supported FOV shape must be circularly pi-symmetric [FOV

$(\alpha)=\text{FOV}(\alpha+\pi)$. This is because of the PSF peaks that appear on opposite sides of the main lobe.

3. Methods

The purpose of this work is to design a PROPELLER acquisition trajectory that will support varying FOV shapes and sizes. The algorithms presented design a set of blades defined by the total number of blades, N , and, for the n th blade, the number of lines, $L[n]$; the line spacing, $\Delta k_\alpha[n]$; the number of samples along the lines, $N_r[n]$ and the blade angle, $\alpha[n]$. This is done sequentially based on the desired alias-free FOV in a manner similar to the 2D projection-reconstruction trajectory anisotropic FOV design [10].

In many PROPELLER acquisitions, such as those using a fast spin-echo (FSE) acquisition [3,4], the number of lines and samples per line is constant across all blades. A primary design algorithm for these types of acquisitions is described in section 4. However, in some types of acquisitions, such as EPI [6,7,13], it is possible and advantageous to vary these parameters. A variable L design algorithm allowing for these variations is also presented in section 5.

4. Primary design algorithm

In this algorithm, the number of lines and samples per line are constant for all blades: $L[n]=L$ and $N_r[n]=N_r$. The number of samples per line must satisfy

$$N_r \geq 2k_{\max} \max(\text{FOV}(\alpha)) \quad (7)$$

where $\text{FOV}(\alpha)$ is the desired FOV as a function of angle. The required inputs to the algorithm are L and $\text{FOV}(\alpha)$, yielding outputs of the blade angles, $\alpha[n]$ and the line spacing $\Delta k_\alpha[n]$.

The alias-free FOV for a given blade was derived in Eq. (2) and can be described simply as

$$\text{FOV}\left(\alpha[n] + \frac{\pi}{2}\right) = \frac{1}{\Delta k_\alpha[n]}. \quad (8)$$

for the n th blade. The adjacent blades are geometrically constrained by

$$\alpha[n+1] - \alpha[n] = \tan^{-1}\left(\frac{L\Delta k_\alpha[n]}{2k_{\max}}\right) + \tan^{-1}\left(\frac{L\Delta k_\alpha[n+1]}{2k_{\max}}\right), \quad (9)$$

which is illustrated in Fig. 2 and $k_{\max}$ is defined in Eq. (5). Note that the actual blade width is $(L-1)\Delta k_\alpha$ (Fig. 1B), while $L\Delta k_\alpha$ is used in Eq. (9). By including the width of an extra line in the design, there will be some space between the outermost lines of adjacent blades. This space is allowable for the prescribed FOV and is desirable so there is less oversampling.

The prescribed FOV should differ slightly from the actual object to allow for rotation of the object. If this is not done, rotations will put the object outside of the FOV and result in aliasing. This can be directly incorporated into the design by instead of using Eq. (8), choosing Δk_α as

$$\Delta k_\alpha[n] = \frac{1}{\max(\text{FOV}(\alpha[n] \pm \delta_\alpha + \frac{\pi}{2}))}, \quad (10)$$

where δ_α is the maximum expected rotation in either direction. When $\delta_\alpha \geq \pi/2$, the result is a circular FOV.

The PROPELLER design algorithm is described in Fig. 3. An initial blade angle, α_0 , must be specified. After initialization of $\alpha[0]$ and $\Delta k_\alpha[0]$, $\alpha[n+1]$ and $\Delta k_\alpha[n+1]$ are sequentially solved for using Eqs. (9) and (10) and a numerical method in Step 2. Once the set of blades provides sufficient coverage of k -space by covering an angular width of π , circular symmetry is imposed on the trajectory. This is accomplished by applying a scaling factor, S , which scales $\alpha[n]$ and $\Delta k_\alpha[n]$. S is calculated based on the angular separation between blades as shown in Fig. 3, Step 4. Scaling actually distorts the FOV shape because it is also applied to $\alpha[n]$. So if the scaling factor is greater than $1+\delta_S$, where δ_S is the scaling factor tolerance, Steps 1–4 of the design process will be repeated with a slightly larger FOV size (Step 5) with the condition that the number of blades may not increase. We determined empirically that $\delta_S=0.01$ is appropriate. When the design repeats, the FOV size is scaled by $1+\varepsilon_{\text{FOV}}$, where ε_{FOV} is the FOV growth factor. This factor is initially set to $\varepsilon_{\text{FOV}}=0.01$ and is halved whenever the number of blades increases until the design converges. Once the scaling factor is sufficiently small (within the scaling factor tolerance), the blade angles and line spacings are scaled for symmetry in Step 6. The resulting set of blades will contain duplicate blades at $\alpha[0]=\alpha_0$ and $\alpha[N]=\alpha_0+\pi$, so the repeated blade is removed in Step 7.

5. Variable L design

This design is an extension of the primary design algorithm where both $L[n]$ and $N_r[n]$ are not fixed, and there is a modified system of equations that must be solved. The radial sampling constraint in Eq. (7) is replaced by a variable constraint, based on Eq. (4), to determine $N_r[n]$:

$$\frac{2k_{\max}}{N_r[n]} \leq \frac{1}{\text{FOV}(\alpha[n])}. \quad (11)$$

Equation (9) is also modified to allow for variable $L[n]$:

$$\alpha[n+1] - \alpha[n] = \tan^{-1} \left(\frac{L[n]\Delta k_\alpha[n]}{2k_{\max}} \right) + \tan^{-1} \left(\frac{L[n+1]\Delta k_\alpha[n+1]}{2k_{\max}} \right). \quad (12)$$

The total number of sample points per blade, N_{blade} or the blade acquisition time, T_{blade} is specified for consistency across blades and to limit the maximum number of lines. They are incorporated into the algorithm with the constraints:

$$L[n]N_r[n] \leq N_{\text{blade}} \quad (13)$$

$$L[n]N_r[n]t_s + (L[n] - 1)T_{\text{blip}}[n] \leq T_{\text{blade}} \quad (14)$$

$$L[n]N_r[n]t_s + L[n]2T_{\text{ramp}}[n] \leq T_{\text{blade}}, \quad (15)$$

where t_s is the sampling duration, T_{blip} is the duration of an EPI line-switching blip and a function of $\Delta k_\alpha[n]$, and T_{ramp} is the ramp time to reach the readout gradient amplitude and depends on $N_r[n]$. In this design, the “corner” aliasing lobes, which are shown in Fig. 1C at $x=\pm 1/\Delta k_r$, $y=\pm 1/\Delta k_\alpha$, are also included as constraints by:

$$\text{FOV}\left(\alpha[n] \pm \tan^{-1} \frac{\Delta k_r}{\Delta k_\alpha}\right) \leq \sqrt{\frac{1}{\Delta k_r^2} + \frac{1}{\Delta k_\alpha^2}}. \quad (16)$$

The primary design algorithm, shown in Fig. 3, is modified slightly for a variable $L[n]$ design. Step 1 requires additional initializations of $L[0]$ and $N_r[0]$ based on Eq. (13) or Eqs. (14,15) and Eqs. (7) and (4). Step 2 is modified to use Eqs. (8) and (11,12) to solve for $\alpha[n+1]$, $\Delta k_\alpha[n+1]$, $L[n+1]$ and $N_r[n+1]$. This system of nonlinear equations can be solved by any method, and we have used the Gauss-Newton method.

6. Reconstruction

The PROPELLER reconstruction procedure incorporates motion correction and data fidelity constraints and accounts for the non-Cartesian nature of the trajectory [1,4]. When acquiring anisotropic blades, this procedure only varies slightly and is also described in Refs. [11,12]. The rotation motion correction with anisotropic blades uses the largest circular region in k -space that overlaps between all the blades which has a radius of

$$k_r = L \min(\Delta k[n]) = \frac{L}{\max(\text{FOV}(\alpha))} \quad (17)$$

It is different from the largest overlapping region, which will be noncircular for anisotropic blades and has anisotropic resolution. This resolution anisotropy varies with the object rotation angle and would interfere with the rotation registration. However, the region described in Eq. (17) is the same size as the region used for isotropic blades that support an FOV of $\max(\text{FOV}(\alpha))$.

The translational motion can be corrected using a 2D correlation to estimate the shift, and this method is tolerant of resolution anisotropy. Therefore, a larger circular k -space region without the requirement that each blade cover it completely can be used for increased accuracy. The rotation correction begins with gridding the magnitude k -space data, weighted by the k -space radius squared [1], for each blade onto a polar grid. We used the Lucas-Kanade method [14] to align this data and find the estimated rotation of each blade. The translation correction used a 2D correlation of the rotation-corrected, gridded k -space data for each blade to find the approximate shift values. Reconstructions were performed using the gridding algorithm with a minimal oversampling ratio [15]. An iterative algorithm was used to compute the density for all k -space points [16]. Nonuniform k -space sampling results in a coloring of the image noise and a reduction in the signal-to-noise ratio (SNR) efficiency, as described in [17]. This is inherent to PROPELLER, and anisotropic FOV trajectories will result in further coloring and efficiency loss.

7. Simulations

Simulated k -space data were created by inversely gridding images onto the PROPELLER trajectories using the non-uniform FFT (nuFFT) [18]. A normal Shepp-Logan phantom of 175×233 pixels is used to demonstrate the reconstruction accuracy. The constant L reconstructions used trajectories with $L=12$ and 310 samples per line. In the PROPELLER EPI trajectory, L varied between 12 and 16, and N_r between 192 to 256, with a maximum of 3072 samples per blade.

A skinny Shepp-Logan phantom of 88×233 pixels was used with motion to demonstrate the value of adding space for rotation into the FOV. Elliptical FOVs of 91×242 pixels with 19 blades and 128×242 pixels with 23 blades with $\delta_\alpha=0^\circ$ were used, as well as an elliptical FOV of 91×242 with $\delta_\alpha=17.2^\circ$ and 23 blades. $L=12$ and $N_r=280$ were used for all the trajectories. The k -space blade data were simulated with $\pm 16.33^\circ$ of rotation applied to individual blades. The exact rotation angles were used in the reconstructions.

The motion correction results used simulated k -space data from an axial slice of a T_1 -weighted brain image. The trajectories used 300 samples per line. Rotational motion was simulated by rotating individual blades up to $\pm 20.5^\circ$ before the nuFFT operation. Translational motion was simulated by adding a random linear phase to the k -space data of each blade after the nuFFT, resulting in shifts of up to eight pixels. All images were reconstructed on a 256×256 grid.

8. MATLAB design functions

The design algorithms are available in MATLAB (The Mathworks Inc., Natick, MA) format as part of the “Radial FOVs” package, which the most recent version can be downloaded at http://www-mrsrl.stanford.edu/~peder/radial_fovs/.

9. Results

9.1 PSFs

Fig. 4 compares trajectories and PSFs from both the primary and variable L design algorithms to an isotropic PROPELLER acquisition. Both algorithms precisely match the desired rectangular FOV shape, and also require a reduced number of blades. Using the primary design algorithm with constant L (Fig. 4B) has a 17.6% reduction from the isotropic acquisition, and the variable L design for PROPELLER EPI (Fig. 4C) has a 41.6% reduction, which translates into scan time reductions.

Various PSFs with and without room for anticipated motion of the object are shown in Fig. 5. The long-dashed lines indicated the desired FOV shapes, including their maximum rotation angles. The shapes are matched precisely. Allowing room for motion increases the number of blades required but will also improve the reconstruction in the presence of motion. Each trajectory shown requires less blades than an isotropic FOV with the same maximum radius.

9.2 Simulations

Fig. 6 shows reconstructed images and a cross-section of the Shepp-Logan phantom using constant L designs and a variable L design. Both the fully sampled circular and elliptical FOVs produce excellent reconstructions with no artifacts (Fig. 6A, C and D), but the undersampled circular FOV has noticeable contrast variations due to aliasing (arrows in Fig. 6B). The aliasing in Fig. 6A–C is primarily a result of the pseudoangular sampling, and the aliasing magnitude is increased in Fig. 6D because it contains significant contributions from both the pseudoangular and pseudoradial sampling. Fig. 6B and C used 12.9% fewer blades than Fig. 6A, and the variable L design (Fig. 6D) required 22.6% fewer blades. These results demonstrate

that shaping the FOV can be used to reduce either the number of blades required or the aliasing artifacts.

When the FOV is tightly tailored to the object shape as in Fig. 6C and D, any rotation puts part of the object outside of this FOV. This will result in aliasing artifacts even with perfect knowledge of the motion, which is demonstrated in Fig. 7A. Enlarging this elliptical FOV can reduce these artifacts, but as shown in Fig. 7B, there are still regions of signal dropout due to aliasing when the rotations put the object outside of the FOV. The motion estimation may also suffer from this aliasing when the object is rotated outside of the FOV. The most efficient solution to allow for rotation is shown in Fig. 7C, for which Eq. (10) has been used with $\delta_{\alpha}=17.2^{\circ}$ to put room in the design for motion. In this case, which requires the same number of blades as the enlarged elliptical FOV in Fig. 7B, the aliasing artifacts are eliminated. There are still some small imperfections because of gaps in k -space when the blades are additionally rotated in the reconstruction process.

The modified PROPELLER rotational and translational motion correction reconstruction schemes described in the Reconstruction section were used for correction of artificially induced motion, the results of which are shown in Fig. 8. When the FOV is undersampled isotropically (Fig. 8C), the reconstructed image quality suffers, as shown by the degradation of the features in the zoomed portion of the image. Also, when an elliptical FOV is used that does not leave any room for motion (Fig. 8D), the quality also suffers. Both the enlarged elliptical FOV (Fig. 8E) and the elliptical FOV with room for motion (Fig. 8F) yielded reconstructed image quality similar to the fully sampled isotropic FOV in Fig. 8C while using 4.8% fewer blades, which would result in an equivalently shortened acquisition time. This reduction in acquisition time will also reduce the SNR of the exam. Although aliasing artifacts from the enlarged elliptical FOV are not visible in this case, they may exist and can degrade image quality as shown in Fig. 7.

10. Discussion

We have presented algorithms that design PROPELLER trajectories for anisotropic FOVs and demonstrated their performance through PSFs and reconstructions of simulated data. This performance should readily extend into in vivo acquisitions because the PSFs precisely describe the effects of the anisotropic sampling, and this has been demonstrated in Refs. [11, 12]. Also, the motion correction is only slightly different from the current PROPELLER algorithms, and the simulations presented used substantial motion with randomization on approximately real data. It should be noted that the scan time reductions obtained with this and other anisotropic FOV techniques comes at the expense of reduced SNR.

This algorithmic method and the analytic method in Refs. [11,12] present slightly different solutions to the same problem, each of which has its own advantages. The analytic method is very simple to compute because a closed-form approximate solution is obtained while the algorithmic method will be slower. The reduction to an elliptical FOV in the analytic method requires less parameters, which simplifies the exam prescription. As demonstrated, our algorithmic method is very precise and can exactly match both the object shape and the anticipated rotation regions. The exam prescription is more complicated, although an automated procedure (outlined below) would alleviate this problem. The PROPELLER EPI algorithm presented here has no comparable solutions. We have also demonstrated that with motion, an elliptical FOV can have aliasing artifacts, and these can also be caused by irregular shapes. In these cases, using our method with a tailored FOV will ensure no aliasing is introduced, as shown in Fig. 7. However, in some acquisitions, the additional aliasing from an elliptical FOV without room for motion will not be noticeable, as shown in Fig. 8. This aliasing will be more noticeable for larger rotations and skinnier FOV shapes.

The repetition of the design, described by Step 5 in Fig. 3, is very important because it insures there are no significant FOV shape distortions. These distortions are the result of enforcing circular symmetry using the scaling factor, S , that has an approximate range from $1 - \frac{1}{N}$ to 1 for N blades. Since N is on the order of 10, the shape distortion can be substantial if repetitions are not performed. Repetition is not necessary in the 2D PR algorithm [10] where N is on the order of 100 so the shape distortions are very small. Both the primary design and the variable L design algorithms are simple and relatively quick algorithms. The low number of blades keeps each design repetition relatively fast, and on the order of 10 design repetitions is sufficient. This allows for on-the-fly computation of the trajectory for each individual scan. As dictated by Eq. (10), the anisotropic FOV should be slightly different from the object to allow for rotational motion. For larger anticipated rotations, there is less gain by using anisotropic FOVs, and there is no gain when $\delta_\alpha \geq 90^\circ$. However, many cases probably have less than 20° of rotation, especially since patients are generally situated to minimize motion, making anisotropic FOVs advantageous. Prescription of the FOV could be done automatically based on a scout image and using image processing methods. After a given slice location is chosen, the shape and size of the anatomy could be detected using methods such as thresholding and morphological processing. $\text{FOV}(\alpha)$ can then be directly determined by applying the Radon transform to a binary image of the detected region. The amplitude of this transform data is proportional to the diameter of the object and, thus, can be used to directly determine $\text{FOV}(\alpha)$. This resulting $\text{FOV}(\alpha)$ could be placed on the scout image and modified by the operator if necessary. A simpler but slightly less efficient alternative would be to offer several standard shapes (ellipse, oval, etc.) that can be adjusted to different sizes on a graphical prescription.

In PROPELLER reconstruction, blades may be discarded based on the data integrity [1]. The penalty is that the discarded blade's k -space that is not covered by other blades, which is in the high frequencies, is now lost. For anisotropic objects, the amount of information in k -space varies angularly, which is the basis for the algorithms presented. For isotropic blade sampling with these objects, the information lost from discarding an individual blade will vary by blade, even though the same amount of k -space is lost. For anisotropic sampling tailored to the object, the information lost from an individual blade will be approximately the same for all blades because their size varies based on the information density in k -space.

There are some relatively simple modifications to this algorithm that may be useful. One such modification would be to design the trajectory based on a desired number of blades, as has been done in Refs. [11,12]. Short-axis PROPELLER EPI acquisitions [13] could also be designed by modifying the geometry constraints, both in the primary and variable L design algorithms. Another set of modified geometry constraints would support undersampled PROPELLER acquisitions [19] for further reducing the total acquisition time including using parallel imaging [7].

The PROPELLER EPI algorithm with variable L uses a varying gradient amplitude in the readout direction with a constant sampling bandwidth to vary the pseudoradial sample spacing according to the desired FOV shape. The implementation described keeps either the EPI gradient duration constant, allowing for an identical TE across blades for the same T_2 or T_2^* contrast or keeps the number of acquisition points constant, resulting in the same duty cycle for each blade. A potential issue that may affect the in vivo image quality are eddy currents, which are often a problem in EPI acquisitions. Using anisotropic blades may require varying eddy current compensation for the different gradient waveforms.

11. Conclusion

The algorithms presented enable more efficient PROPELLER imaging by tailoring the FOV to the object of interest for any shape, size, and maximum rotation. They are more flexible than

previous methods and, by including space for rotation, they allow for motion correction without introducing aliasing artifacts. They are fast enough to be computed on-the-fly, allowing for maximum efficiency in each individual scan. The variable number of lines design further improves the imaging efficiency in PROPELLER EPI acquisitions.

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References

1. Pipe JG. Motion correction with PROPELLER MRI: application to head motion and free-breathing cardiac imaging. *Magn Reson Med* 1999;42:963–9.
2. Pipe JG, Zwart N. Turboprop: improved PROPELLER imaging. *Magn Reson Med* 2006;55:380–5.
3. Forbes KP, Pipe JG, Karis JP, Farthing V, Heiserman JE. Brain imaging in the unsedated pediatric patient: Comparison of periodically rotated overlapping parallel lines with enhanced reconstruction and single-shot fast spin-echo sequences. *Am J Neuroradiol* 2003;24:794–8.
4. Pipe JG, Farthing VG, Forbes KP. Multishot diffusion-weighted FSE using PROPELLER MRI. *Magn Reson Med* 2002;47:42–52. [PubMed: 11754441]
5. Forbes KP, Pipe JG, Karis JP, Heiserman JE. Improved image quality and detection of acute cerebral infarction with PROPELLER diffusion-weighted MR imaging. *Radiology* 2002;224:551–5.
6. Wang FN, Huang TY, Lin FH, Chuang TC, Chen NK, Chung HW, Chen CY, Kwong KK. PROPELLER EPI: an MRI technique suitable for diffusion tensor imaging at high field strength with reduced geometric distortions. *Magn Reson Med* 2005;54:1232–40.
7. Chuang TC, Huang TY, Lin FH, Wang FN, Juan CJ, Chung HW, Chen CY, Kwong KK. PROPELLER EPI with parallel imaging using a circularly symmetric phased-array RF coil at 3.0 T: application to high-resolution diffusion tensor imaging. *Magn Reson Med* 2006;56:1352–8.
8. King KF. Spiral scanning with anisotropic field of view. *Magn Reson Med* 1998;39:448–56.
9. Scheffler K. Tomographic imaging with nonuniform angular sampling. *J Comput Assist Tomogr* 1999;23:162–6. [PubMed: 10050828]
10. Larson PEZ, Gurney PT, Nishimura DG. Anisotropic field-of-views in radial imaging. *IEEE Trans Med Imaging* 2008;27:47–57. [PubMed: 18270061]
11. Devaraj, A.; Pipe, JG. Elliptical field of view in PROPELLER MRI. Proceedings of the 15th Annual Meeting of ISMRM; Berlin, Germany. 2007. p. 1665
12. Devaraj A, Pipe JG. Anisotropic field-of-view PROPELLER imaging. *Magn Reson Med*. 2008 [Accepted].
13. Skare S, Newbould RD, Clayton DB, Bammer R. PROPELLER EPI in the other direction. *Magn Reson Med* 2006;55:1298–307.
14. Lucas, BD.; Kanade, T. Iterative image registration technique with an application to stereo vision. Proceedings of the 7th International Joint Conference on Artificial Intelligence; Vancouver, BC, Canada. 1981. p. 674-9.
15. Beatty PJ, Nishimura DG, Pauly JM. Rapid gridding reconstruction with a minimal oversampling ratio. *IEEE Trans Med Imaging* 2005;24:799–808.
16. Pipe JG, Menon P. Sampling density compensation in MRI: rationale and an iterative numerical solution. *Magn Reson Med* 1999;41:179–86.
17. Tsai CM, Nishimura D. Reduced aliasing artifacts using variable-density k-space sampling trajectories. *Magn Reson Med* 2000;43:452–8.
18. Fessler JA, Sutton BP. Nonuniform fast Fourier transforms using min-max interpolation. *IEEE Trans Signal Proc* 2003;51:560–74.
19. Arfanakis K, Tamhane AA, Pipe JG, Anastasio MA. *k*-space undersampling in PROPELLER imaging. *Magn Reson Med* 2005;53:675–83. [PubMed: 15723398]

Fig. 1. PROPELLER sampling. Sampling within a blade is separable in (A) pseudoangular and (B) pseudoradial directions, each of which results in PSF lobes that will cause aliasing and restrict the FOV. The gray lines show the approximate spatial variations derived in Eqs. (2) and (4). The PSF lobes from the combined sampling are illustrated in (C). Rotating the blades in k -space results in an equivalent rotation in the PSF. All of the illustrations on the right are exaggerated for demonstration of the sampling principles.

Fig. 2.

Adjacent blade geometry. The adjacent blades in the design are chosen such that the appropriate spacing between them matches the desired FOV. The extended blade widths ($L\Delta k_{\alpha}[n]$) correspond to the blade angles ($\alpha[n]$) as described in Eq. 9.

(1) Initialization.

(2) Calculate next blade parameters by solving the non-linear system in Eqs. (8) and (9).

(3) Repeat previous setup until a complete set of blades is created

(4) Calculate a scaling factor, S , to make blades flush.

(5) If the scaling factor is too large, repeat the design with a slightly increased FOV size. If this results in an increase in the number of blades, the previous design is used.

(6) Scale the blade angles and line spacings.

(7) Remove the repeated blade $\alpha[N] = \alpha_0 + \pi$ (equivalent to $\alpha[0] = \alpha_0$). The total number of blades is N .

Fig. 3.

PROPELLER trajectory design algorithm with a constant $L[n]=L$.

Fig. 4.

Examples of PROPELLER sampling patterns (top row) and PSFs (bottom row). The PSF images are shown with logarithmic intensities. (A) Isotropic FOV with $L=12$ and 12 blades. (B) Rectangular FOV using the primary design algorithm with $L=12$ and 10 blades. (C) Rectangular FOV using the variable L design algorithm for PROPELLER EPI with L varying between 12 and 21, $N_{\text{blade}}=1140$, and 7 blades.

Fig. 5.

PROPELLER PSFs without and with room for motion, with zoomed images of the main lobe region. The long-dashed yellow lines indicate the desired FOV shape, including rotation. The rotated shapes are shown at several angles with the short-dashed blue lines in (B), (D)–(F). The PSF images are on a logarithmic scale. Ellipse ($L=12$): (A) $\delta_\alpha=0^\circ$, 9 blades, and (B) $\delta_\alpha=35^\circ$, 11 blades. Oval ($L=12$): (C) $\delta_\alpha=0^\circ$, 9 blades, and (D) $\delta_\alpha=15^\circ$, 10 blades. Rectangles identical to Fig. 4B,C but with $\delta_\alpha=15^\circ$: (E) $L=12$, 11 blades, and (F) variable L from 12 to 20, 9 blades.

Fig. 6.

Phantom reconstructions with different PROPELLER FOVs. (A) Circular FOV with 31 blades with $L=12$. (B) Circular FOV with 27 blades with $L=12$. (C) Elliptical FOV with 27 blades with $L=12$. (D) Elliptical FOV with 24 blades using PROPELLER EPI with L from 12 to 16. The undersampled circular FOV has streaking artifacts and contrast variation inside the phantom (arrows).

Fig. 7.

Phantom reconstructions in the presence of rotational motion, the extent of which is indicated by the thin dashed lines. The thick, dashed lines show the supported FOV. (A) Using a tight elliptical FOV with 19 blades results in significant aliasing artifacts. (B) A larger elliptical FOV with 23 blades reduces these aliasing artifacts, but there are still some regions of signal dropout (arrows). (C) Aliasing artifacts are eliminated when using a tight elliptical FOV with room for motion that requires 23 blades. The smallest ellipse that includes room for all of the rotational motion would require 25 blades.

Fig. 8.

Correction of simulated rotational and translational motion. (A) Sample image without motion correction. Motion corrected results using (B) a fully sampled circular FOV with 21 blades (C) an undersampled circular FOV with 20 blades (D) an anatomically matched elliptical FOV without room for motion and 19 blades (E) an enlarged elliptical FOV with $\delta_\alpha=0^\circ$ and 20 blades and (F) an anatomically-matched elliptical FOV with $\delta_\alpha=21^\circ$ and 20 blades.