Automatic In-Plane Rotation for Doubly Oblique Cardiac Imaging

Peter Kellman, J. Andrew Derbyshire, Elliot R. McVeigh,
Laboratory of Cardiac Energetics, National Heart Lung and Blood Institute, NIH, DHHS, Bethesda Maryland 20892 USA

INTRODUCTION

A method for automatically calculating the in-plane rotation for doubly oblique slice geometry is proposed. Doubly oblique slice orientation is commonly used in applications such cardiac imaging, and results in an in-plane rotation of the body cross-section. For torso imaging with oblique geometry, the body cross-section is approximately elliptical, with major and minor axes and ellipticity in the approximate range 1.5 – 2.5. It is often desirable to adjust the in-plane orientation for frequency encoding (readout) along the major axis and phase encoding along the minor axis to ensure a minimum alias free field-of-view (FOV) in the phase-encode direction. In other words, with the proper in-plane rotation, the FOV in the phase encode direction may be reduced to the minor axis dimension. This is particularly important for reduced FOV imaging such as UNFOLD [1] or parallel MR methods, SENSE [2] or SMASH [3], as well as general imaging with an asymmetric FOV.

METHODS

Description and Theory

A doubly oblique imaging plane is generally specified by its normal vector **n**=$[n_x,n_y,n_z]^T$ (superscript ^{T} denotes transpose) or rotation matrix (**M**), and is typically prescribed graphically. Consider the body to be a cylindrical ellipsoid. The intersection of an oblique plane, defined by the equation:

$$\mathbf{r}^T \bullet \mathbf{n} = [x \quad y \quad z]\begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} = 0 \qquad [1]$$

where **r**= $[x, y, z]^T$, and a cylindrical ellipsoid defined by the equation:

$$\alpha x^2 + \beta y^2 = \frac{x^2}{(L/2)^2} + \frac{y^2}{(S/2)^2} = 1 \qquad [2]$$

with major and minor axes defined by L and S, respectively, is an ellipse in the oblique plane. Without loss of generality, a centered ellipse is considered in this formulation. The angle of rotation for an off-centered ellipse will be the same as a centered ellipse, although there will be a translation. The derivation of the in-plane rotation angle ϑ follows. Let (x, y, z) be the body coordinate system and (x_1, y_1, z_1) be an arbitrary coordinate system such that z_1=0 for all points in the scan plane. If the oblique plane coordinates are transformed from the body coordinates (x, y, z) into (x_1, y_1, z_1), then the ellipse parameters in (x_1, y_1) may be derived as follows. Let the coordinate transformation from **r**=$[x, y, z]^T$ into $\mathbf{r}_1=[x_1, y_1, z_1]^T$ be defined by the matrix rotation

$$\mathbf{r} = \mathbf{M} \bullet \mathbf{r}_1 \qquad [3]$$

Then the ellipse in (x_1, y_1) may be found by substituting into Eq. (2) as:

$$\alpha x^2 + \beta y^2 = \alpha(m_{11}x_1 + m_{12}y_1)^2 + \beta(m_{21}x_1 + m_{22}y_1)^2 = Ax_1^2 + Bx_1y_1 + Cy_1^2 = 1 \qquad [4]$$

with z_1=0, m_{ij} elements of rotation matrix **M**, and with the coefficients, A, B, and C, derived as:

$$\begin{aligned} A &= \alpha m_{11}^2 + \beta m_{21}^2 \\ B &= 2\left(\alpha m_{11}m_{12} + \beta m_{21}m_{22}\right) \\ C &= \alpha m_{12}^2 + \beta m_{22}^2 \end{aligned} \qquad [5]$$

The ellipse in (x_1, y_1) is rotated by the angle ϑ and has major and minor axes defined as L′ and S′. A new coordinate system (x_2, y_2, z_2), for which the in-plane ellipse rotation has been optimized, is defined by:

$$\begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} = \begin{bmatrix} \cos(\vartheta) & -\sin(\vartheta) & 0 \\ \sin(\vartheta) & \cos(\vartheta) & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix} \qquad [6]$$

Then substituting Eq. (6) into Eq. (4) for the ellipse in (x_1, y_1) yields the ellipse in (x_2, y_2):

$$ax_2^2 + bx_2y_2 + cy_2^2 = 1 \qquad [7]$$

where the coefficients may be derived as:

$$\begin{aligned} a &= A\cos^2(\vartheta) + B\cos(\vartheta)\sin(\vartheta) + C\sin^2(\vartheta) \\ b &= B\cos^2(\vartheta) - 2(A-C)\cos(\vartheta)\sin(\vartheta) - B\sin^2(\vartheta) \\ c &= A\sin^2(\vartheta) - B\cos(\vartheta)\sin(\vartheta) + C\cos^2(\vartheta) \end{aligned} \qquad [8]$$

with ellipse parameters calculated as (by setting the cross-term coefficient *b*=0):

$$\begin{aligned} \cot(2\vartheta) &= \frac{A-C}{B} \\ L' &= 2\big/\sqrt{a} \\ S' &= 2\big/\sqrt{c} \end{aligned} \qquad [9]$$

Thus the in-plane rotation angle ϑ is calculated in terms of the body major and minor axis dimensions (L and S). It is further shown by substitution that the angle ϑ is determined solely by the ellipticity (ratio) e = L/S and rotation matrix **M**.

Figure 1 illustrates an example of a body ellipse with e=2 intersected by a doubly oblique plane with normal [1 1 1] resulting in the ellipse in bold which has an in-plane rotation of ϑ=23º in the plane defined by the box labeled **A**. After in-plane rotation the box labeled **B** with the same dimensions is aligned with the body ellipse and will not have wrap for phase encode along minor axis direction. For e>2, the rotation angle shown in Figure 2 for **n**=$[1\ 1\ 1]^T$ is very insensitive to the ellipticity (e) for a wide range of normal vector directions. Thus a good approximation to the in-plane rotation angle may be calculated automatically from the normal vector using a default value for e=2.0 which will be within several degrees for a wide range of interest.

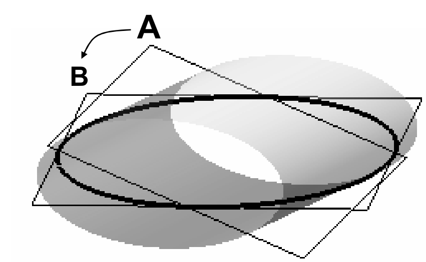

Figure 1. Illustration of doubly oblique imaging plane intersecting an ellipsoidal cylinder resulting in an ellipse (bold) with in-plane rotation (plane **A**) which may be rotated for minimum alias free FOV (plane **B**) with phase encode direction along minor axis dimension.

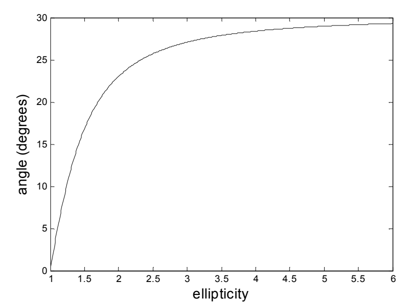

Figure 2. In-plane rotation angle versus ellipticity for doubly oblique plane with normal with normal [1 1 1] illustrating insensitivity of angle for e>2.

Experiments were conducted using a GE Signa CV/*i* 1.5T MR imaging system. A standard pulse sequence was modified to incorporate the automatic in-plane rotation as a user enabled option. The value for body ellipticity was set by default to e=2.0, and could be easily modified by the user as a research control variable. Short axis cardiac imaging was performed using a gated-segmented FGRE sequence with 320x240 mm² FOV. The doubly oblique short axis cardiac imaging plane was determined by a localization procedure as follows. A singly oblique long axis image was graphically prescribed from sagital images which contained the heart. The doubly oblique short axis view was then prescribed from the resultant long axis image. Doubly oblique images were acquired with and without the automatic in-plane rotation.

RESULTS

Figure 3 shows example images of a single short axis doubly oblique cardiac image (a) before and (b) after in-plane rotation has been applied. In this example, the body ellipticity was approximately e= 2.0, and the normal vector was [-0.48 0.69 -0.55], and the rotation angle was calculated to be 34º.

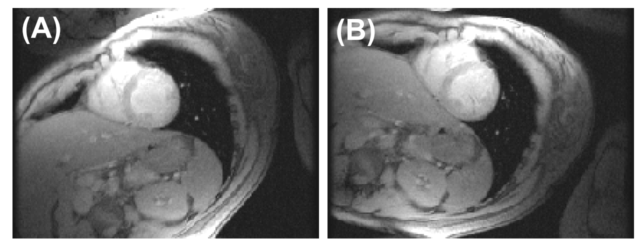

Figure 3. Example doubly oblique SAX cardiac images (a) before and (b) after automatic in-plane rotation.

CONCLUSIONS

In-plane rotation is desirable for doubly oblique imaging, e.g., cardiac applications, particularly for reduced FOV accelerated imaging such as SENSE. The proposed method provides an approximate solution automatically eliminating the requirement for additional measurements. Another benefit is the elimination of alias artifacts including wrap of arms and shoulders due to the fact that these features may be placed in the frequency readout direction. It should be noted that in-plane rotation will, in general, affect the minimally achievable TR for a given gradient performance (slew rate and maximum gradient).

REFERENCES

1. Madore B, Glover GH, Pelc NJ. Unaliasing by Fourier encoding the overlaps using the temporal dimension (UNFOLD), applied to cardiac imaging and fMRI. *Magn Reson Med* 1999;42:813–828.
2. Pruessmann P, Weiger M, Scheidegger MB, Boesiger P, SENSE: Sensitivity Encoding for Fast MRI. *Magn. Reson. Med.*, 42(5), 952–62, 1999.
3. Sodickson DK, Manning WJ. Simultaneous acquisition of spatial harmonics (SMASH): fast imaging with radiofrequency coil arrays. *Magn Reson Med* 1997;38(4):591-603.