Higher order geometrical distortion in serial MR brain imaging

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Introduction

Geometrical distortion leads to inter-acquisition spatial change. This impedes the detection of clinically interesting anatomical change that can occur during serial MR imaging studies. Geometrical distortion mainly arises from B0 inhomogeneities, errors in the imaging gradients and errors due to object susceptibility changes. Susceptibility effects can be reduced by increasing the readout gradient strength. Previous work on geometrical distortion for serial MR studies has focussed on scaling error [Lemieux, Holden]. Here we study more general orders such as shears and higher order polynomial terms. Our aim is to identify the factors that lead to distortion change so that we may accurately correct distortion in serial MR brain images. Accordingly we have designed a set of experiments to quantify measurement precision; impact of readout gradient strength (G_r), sequence parameters (TR/TE/flip angle) and shim settings on distortion; and distortion change over time.

Methods

To detect geometrical distortion we used a specially designed phantom with 427 accurately manufactured (error=0.02mm) spherical reference structures and a high order polynomial distortion detection algorithm [Breeuwer]. We measured distortion either relative to physical space or relative to another phantom scan. Linear distortion is described by: scale (s_x, s_y, s_z) and shear (s_{xy}, s_{xz}, s_{yz}) components and higher order distortion by polynomial coefficients, where x is anterior/posterior (A/P), y is left/right (L/R) and z is head/foot (H/F). The amount of distortion is estimated by calculating the mean distance (residual) between the locations of two sets of reference structures, denoted as dp. We used dp to design another measure, dp_4 , describing the amount of distortion for each polynomial order. dp_4 is a 4-tuple, the first component indicates the amount of first order (linear) distortion, the second how much second order etc... We acquired n>30 standard 3D gradient echo (FFE) and multi-slice spin echo (SE) image sets of the phantom with a Philips Gyroscan ACS2 1.5T MR scanner at two resolutions. Sequence details were as follows. FFE1: voxel size 1x1x1.8mm, 256mm FOV, 124 slices, G_r=2.55mT/m. FFE2: voxel size 2x2x2mm, 256mm FOV, 110 slices, G_r=1.275mT/m. For both FFE1 and FFE2, TR/TE/flip angle were 30/4.5/30. SE: voxel size 2x2x2mm, 256mm FOV, 110 slices, G_r=1.275mT/m, TR/TE = 500/20ms. For all scans the readout gradient was in the A/P (x) direction. To estimate measurement precision we acquired six consecutive FFE1 scans with repositioning of the phantom and calculated the standard deviation of the 6 components of linear distortion. The impact of the readout gradient strength, G_r , was investigated with six FFE2 scans with G_r ranging from 0.64 to 1.75mT/m. The influence of the sequence parameters was studied by varying TR, TE, flip angle and the slice gap to produce five FFE2 and five SE scans that differed by one parameter from the baseline. Shim settings were investigated with three FFE1 and three FFE2 scans that differed only in shim setting: default shim (DS), auto shim (AS) and manual shim (MS). DS refers to the shim that was set at installation and optimised over the scanner's imaging volume; AS refers to automatic shimming immediately prior to scanning and is optimised over the FOV; and MS to volume-localised shimming over a 1cm3 volume at the center of the phantom, performed using the spectroscopy package. Distortion change over time was measured relative to the first of a series of 11 weekly FFE1 scans.

Results

The precision (stdev) of the linear distortion terms for the six FFE2 scans was: (s_x, s_y, s_z) <=0.03% and (s_{xy}, s_{xz}, s_{yz}) <=0.04°. For distortion change as a function of G_r , the standard deviation of the (s_x, s_y, s_z, s_{xy}, s_{xz}, s_{yz}) components was (0.27%, 0.06%, 0.03%, 0.11°, 0.37°, 0.05°) showing most change in the readout dependent directions (s_x, s_{xy}, s_{xz}). The coefficient of linear correlation, r, for (s_x, s_{xy}, s_{xz}) with decreasing, G_r , was (0.93, 0.87, 0.94) showing a high inverse linear correlation with G_r (see Fig 1). The dp_4 residual was (32.94%, 39.61%, 5.60%, 1.88%) indicating that almost all the distortion change was either first or second order. For the various sequence parameters the largest components of linear distortion were also (s_x, s_{xy}, s_{xz}). The mean (stdev) for (s_x, s_{xy}, s_{xz}) for both sequences was - FFE2: s_x -1.53 (0.28), s_{xy} 0.60 (0.07), s_{xz} 0.92 (0.21); SE: s_x -1.35 (0.82), s_{xy} 0.40 (0.21), s_{xz} -2.41 (0.92). The sagittal shear, s_{xz} , was significantly higher for SE than for FFE2 ($p<0.01$). The largest distortion change for the FFE2 scans was for the AS and DS shim settings (dp = 1.2mm). The largest components for these settings were s_x=0.08%, s_{xz} =-1.09° for FFE1 which increased to s_x=0.09%, s_{xz} =-2.13° for FFE2 (see Fig 2). There was a similar pattern of increase for the MS to DS correction: s_x=0.25%, s_{xz}=-0.43° for FFE1 s_x=0.78%,s_{xz}=-1.11° for FFE2. Shim changes introduced a near linear distortion change: dp_4 = (71.93%, 0.00%, 0.00%, 0.00%) (FFE1, AS to DS); dp_4 = (54.29%, 0.00%, 0.00%, 2.86%) (FFE1, MS to DS). For the time series of 11 weekly scans, mean (stdev) 7 (1) days, the standard deviation of the distortion components (s_x, s_y, s_z, s_{xy}, s_{xz}, s_{yz}) was (0.09%, 0.04%, 0.06%, 0.02°, 0.05°, 0.03°). For the set of 33 FFE1, FFE2 and SE scans, corrected to physical space, the mean residual, dp, decreased as a function of the order of correction (r>0.9, n=33). The mean (n=33) dp_4 measure was (44.83%, 30.16%, 9.85%, 0.9%) indicating that 75% of the distortion was first or second order.

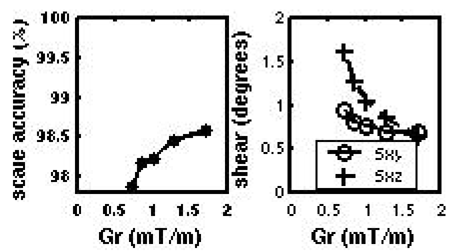

Fig1: s_x, s_{xy}, s_{xz} as a function of the readout gradient strength G_r.

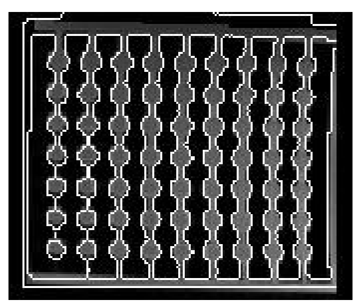

Fig2: sagittal shear (s_{xz}) distortion change for DS (grey scale) and rigidly registered AS (white outline) shimmed scans.

Discussion

We can measure linear distortion to high precision (scale <= 0.03%, shear <=0.04°). Linear distortion in the readout dependent directions increased with decreased readout strength (r>0.93) which is consistent with theory. Changes in G_r led to first and second order distortion changes, but not third and fourth order ones. Object independent distortion may be smaller for the FFE scans than SE ones possibly because of distortion introduced by slice selection. Changes in distortion over 11 weeks was: scale < 0.1%, shear<= 0.05° and are negligible for clinical serial MR. Different shims produced only linear distortion changes. The largest observed distortion change was for AS and DS (FFE1) shims and gave a shear change > 1° .

References

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