Frequency Filtered SENSE Shimming for B0 inhomogeneity detection

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Introduction: The SENSE Shimming (SSH) technique [1] is a novel method for detecting relative in-plane B0 inhomogeneities. The approach is based on explaining variations of the slope of a Free Induction Decay (FID), seen by the elements of a coil array, using a 2D reference image. Recently an extension was presented that uses the full temporal evolution of the FID, adjusting a model taking into account relaxation in a non-linear fit [2]. This new approach is capable of estimating quantitative B0 inhomogeneity information instead of only relative values. Due to the nature of the FID data the SSH methods presented so far are restricted to cases where the object lays completely within the FOV, i.e. where the same magnetisation density is seen by the reference image and the FID. Here we present a further extension, which takes into account the readout filtering properties of the data acquisition pipeline on a scanner, yielding a concept of frequency filtered FID data. This new approach is capable of detecting in-plane quantitative B0 inhomogeneities not only in the transversal but also in the coronal and sagittal planes.

Concepts: Before the raw data of an MR experiment can be Fourier transformed they have to be converted to the rotating frame of reference. This is usually done in two steps: first the signal is demodulated by multiplication with a reference signal, yielding a complex output, where the frequency content is shifted from B0*γ to a range that can be digitised, usually in the order of several MHz. The digitised data are then filtered using a decimation filter, which restricts sampling rate and frequency content to the frequency content of the desired FOV. It is during this process where aliasing in the readout direction is prevented, if the desired FOV is smaller than the extent of the magnetisation (e.g. Figure 1): one approach is to decimate with a filter such that the passband lays on the desired FOV and the transition region to the stopband on FOV/4 in either direction (depending on the filter). The data can then be sampled with a multiple of the FOV frequency (usually a factor of two is chosen) out of which only the central part is relevant after the Fourier transform of the raw data. While the mechanism is of great importance for imaging, it restricts the usage of the SSH method as presented so far [1,2] to cases where the FOV of the reference image contains the full magnetisation seen by the coils, since in the FID data no gradient induced spatial frequency dependency is generated, which could be filtered. On the other hand it has to be kept in mind that conceptually the centre of k-space corresponds to the integral of the magnetisation without any gradient encoding, i.e. to a point on an FID. We therefore suggest to acquire frequency filtered data with a very limited k-space extent, out of which only the k-space centre is taken, in order to simulate an FID (Figure 2). The k-space extent needs to be sufficient in order for the filter support for the central k-space point not to reach into times of gradient switching. If this is respected the data can be acquired with a very low gradient amplitude and the non-linear fitting as from approach [2] can be applied on the k-space centres. In order to avoid eddy current effects only data with the same polarity as the reference image readouts are used.

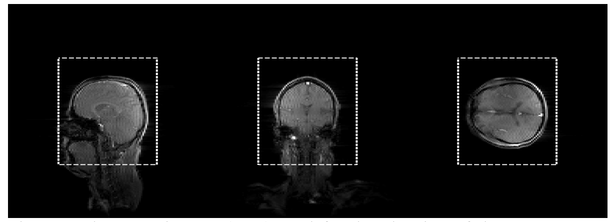

Figure 1: the scout images (SOS) used for the planning of the measurement (FOV: 0.5x0.5m²) show clearly the large area seen by the coil sensitivities of the used head array. For imaging a FOV of about 0.25x0.25m² is usually chosen (white boxes). A regular FID would see signal from the neck and shoulders.

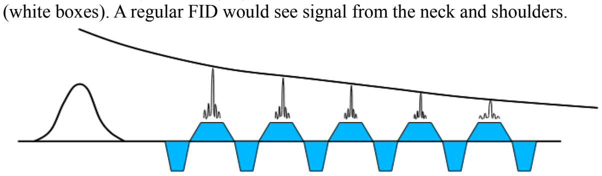

Figure 2: the concept of frequency filtered FIDs used in the method. The flat top time of the gradients is only a few samples long. Only the k-space centres are taken into account.

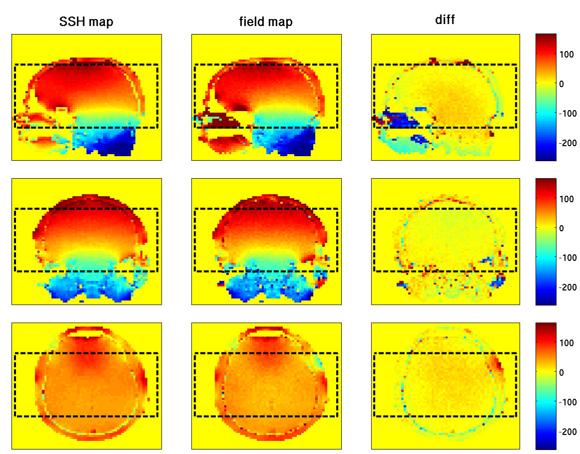

Figure 3: a comparison of the B0 inhomogeneity maps obtained with the proposed method and field maps. On the right hand side the differences between SSH maps and field maps are shown. Values are given in Hertz. The images are shown with twice the desired FOV in readout direction, the dashed box indicate the area after removal of the oversampling.

Methods: In vivo measurements were performed in a healthy volunteer on a 3T TIM Trio (Siemens Healthcare, Erlangen, Germany), using a twelve channel head array. The sequence used was a modified FLASH sequence which allowed for acquiring the k-space of the reference image first, with TE_1=4.92ms, followed by a second reference image at TE_2= TE_1+2.46ms and the frequency filtered FID; TR was set to 40ms. The second reference image was only used as a gold standard for comparing the performance of the suggested method. In order to confirm the filtering effect in the readout direction the readout FOV was set to 0.128m in the sagittal view and 0.112m in the coronal and transversal view. The phase FOV was always set to twice the readout FOV, with a matrix of 64x32. The real dwell time for the imaging was set to 7.5µs and 10µs for the filtered FID, with a total acquisition time of 20ms for the FID. The flat top time of a single FID k-space was chosen to be 120µs, which was confirmed enough for the k-space centre and its surrounding points to be sampled reliably. No fat suppression and no subject specific shim were performed. For unwrapping of the field maps an algorithm from Zhou et al. [3] was used.

For the processing a non-linear fit was performed based on a signal model taking into account relaxation and field inhomogeneities [2]. For the inhomogeneities an initial phase estimate was used, along with a set of six solid harmonics. For relaxation masks were calculated from the reference image. The non-linear fit was performed in a simulated annealing fashion, where in three iterations of ten repetitions each the start values were randomly varied with decreasing probability; if the residuals were less than a given threshold the iterations were stopped, otherwise the overall best result was taken. The initial guess was obtained using the linear SSH method [1].

Results & Discussion: Figure 1 shows the magnetisation density seen by the coil array in a scout image. Unless for the transversal plane the magnetisation extends way outside the usual FOV; a regular FID will receive signal from the whole area, whereas the filtering suggested here restricts the signal to the same region as for the imaging. Figure 3 compares the B0 inhomogeneity maps obtained with the suggested method and field maps calculated from the two images. The images show the real FOV in phase encoding direction (left-right) and the oversampled FOV in readout direction (up-down). The desired FOV is indicated by the dashed boxes.

As can be seen the calculated maps correspond very well to the field maps, except for regions of low signal where the phase unwrap failed sometimes even for the field maps (c.f. the sagittal view). The processing time for the iterations varied from 10s to 90s, depending on the speed of convergence, with the transversal view being the fastest. In our experiments at 3T the method was stable, which will need to be confirmed in a more detailed study. The new approach forms a conceptual bridge between the SSH methods presented so far and projection based approaches (e.g. [4,5]): if the flat top time for the frequency encoded FID is extended such that Fourier transfoms can be performed then the non-linear SSH method could be applied on a pixel basis; the time between projections would have to be short enough to avoid undersampling artifacts. In a conclusion, the frequency filtered FID can indeed be used for estimating B0 field inhomogeneities as suggested in [2], even in cases where the magnetisation extends outside the FOV.

References: [1] Splitthoff and Zaitsev, MRM 62, 1319-1325, 2009; [2] Splitthoff and Zaitsev, ISMRM Stockholm 2010, #144; [3] Zhou et al., MRM 62, 1085-1090, 2009; [4] Ward et al. MRM 48, 771-780, 2002; [5] Splitthoff et al., ISMRM Berlin 2007, #985.

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