Improved shim method for balanced SSFP

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Introduction

Balanced SSFP (bSSFP) has been used for various applications such as cardiac, muscular-skeletal, and functional imaging [1-3]. The sequence has a unique magnetization profile that contains signal drop-out for off-resonance frequencies around ±1/(2TR) (Fig.1c shows the magnitude profile). This signal drop-out results in dark areas in the image and therefore limits the spatial coverage of bSSFP (Fig. 1a). To remove this artifact, a very short TR (~5 ms) is commonly used. However, using a short TR is not always favorable: it decreases the data acquisition time within a TR (the readout duty cycle), and, more importantly, it decreases the level of contrast in SSFP fMRI where the relative signal change is linearly dependent on TR [4].

One way to increase the spatial coverage is by changing the spatial distribution of the off-resonance frequency. This can be achieved to some degree by changing the shim values. The most common approach for a shim method is to find the shim values that minimize the least square errors of the residual field (least-square shim). However, this method does not provide spatially maximal coverage for bSSFP since the signal is rather uniform within the central portion of the profile while significant signal drop-out exists only around ±1/(2TR) (Hz); there exists a tolerance range for off-resonance frequency and a better shim algorithm can be designed to utilize this tolerance range (see Fig. 1 for a simple f_0 correction [5], other shim components can be incorporated for a better result). Here we propose a new algorithm, minimizing maximum off-resonance frequency or simply "min-max shim" that improves the off-resonance coverage in bSSFP imaging and SSFP fMRI.

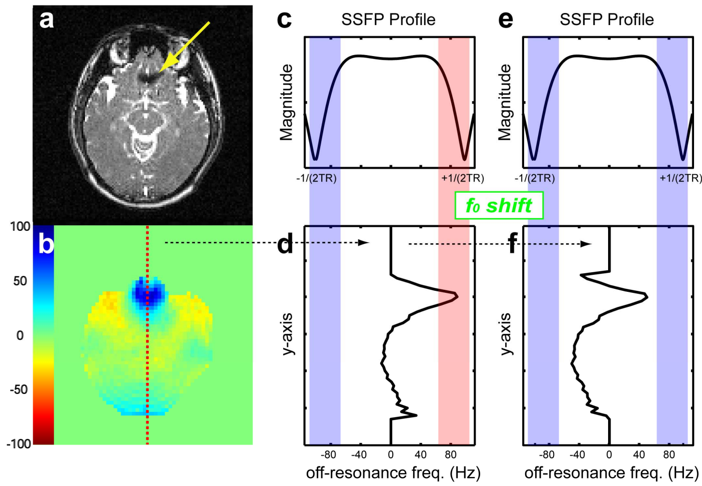

Fig.1: conceptual illustration for bSSFP shim. (a) bSSFP image (b) field map (Hz), (c, and e) bSSFP magnitude profile (d) least-square error shim result along the dotted red-line in (b). Artifact is expected in the pink strip (f) f_0 can be shifted to remove the artifact. *Note that a better result is achievable by including linear and higher-order shims*

Theory

One approach to achieve better spatial coverage in bSSFP is to iteratively minimize the maximum absolute off-resonance frequency of the field map by adjusting the shim values. This formula can be described as follows:

$$\underset{s_0,\, s_x,\, s_y,\, \ldots}{\operatorname{argmin}} \max(|\, \text{Field\_map} - F_0 s_0 - F_x s_x - F_y s_y - F_z s_z - F_{xy} s_{xy} - \text{and other higher order shims} \,|) ,$$

where F_0, F_x, F_y, … represent the center frequency, x-shim, y-shim, … induced field basis vector (or matrix), and s_0, s_x, s_y,… represent the variable shim values. This can be reformulated as a linear program and be solved very efficiently [6]. The resulting field map will have the minimum off-resonance peaks with the positive and negative peaks the same. Based on the shim result, one can use a longer TR or choose the necessary TR that ensures artifact free images.

Experiment and Results

To demonstrate the efficacy of this min-max shim method, bSSFP imaging was performed on human brains using a 1.5 T GE scanner. Field maps were acquired using an 18-shot spiral sequence (FOV = 24 x 24 cm^2 and resolution = 4 x 4 mm^2) with two different echo times (TE = 2 ms and 6ms). Both the min-max shim and the least-square shim were implemented and the shim values were changed based on the results. Only linear terms (x-, y-, and z-shim) and f_0 were corrected since the system was not equipped with higher-order shims. The imaging sequence for bSSFP was a 3D Cartesian trajectory with TR = 7 -10 ms, TE = TR/2, FOV = 24 x 24 cm^2, matrix size = 128 x 128, Slab size = 40 mm, and slice thickness = 2.5 mm.

Figure 2 shows the improvement of the min-max shim over the least-square shim. The artifacts (yellow arrows) observable in the least-square shim results (above the ear canal in the upper figure and above the sinus area in the lower figure) disappeared when the min-max shim was used. The off-resonance range was changed from [-74, +33] Hz to [-51, 51] Hz. In another experiment, when a TR was changed from 7 ms to 10 ms, similar artifacts were observed with TR = 8 ms for the least-square shim and with TR = 10 ms for the min-max shim (results not shown).

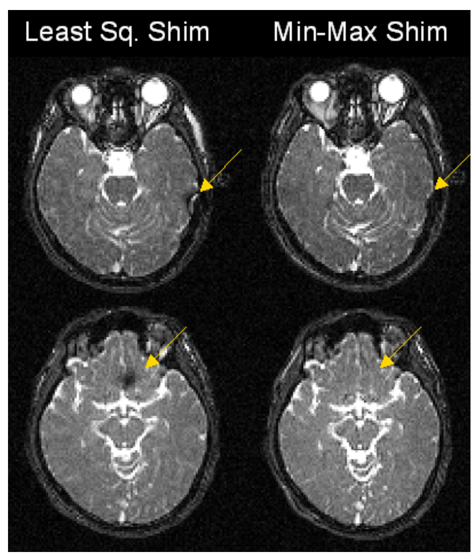

Fig.2: Two different shim results. The least-square shim results show artifacts (arrows, left figures) that disappeared in the min-max shim results (right figures)

Discussion and Conclusion

In bSSFP, the spatial coverage can be improved (or a longer TR can be used) using the proposed min-max shim. This result also indicates that the min-max shim can be used to increase the readout duty cycle in bSSFP imaging or the level of functional contrast in SSFP fMRI.

If the maximum off-resonance is still too large for the minimum TR, a region-growing algorithm could be incorporated with the min-max shim to minimize the areas in which the signal drops out. The min-max shim method will be useful for other applications including fat saturation using spectral-spatial pulses, and water/fat suppression in spectroscopy.

References [1] Scheffler, Euro.Rad., 2003, 13:2409 [2] Miller, MRM, 2003, 50:675 [3] Bowen, ISMRM, 2005, 119 [4] Kim, ISMRM, 2007, 696 [5] Deshpande, MRM, 2003, 49:803 [6] Boyd, Convex optimization, Cambridge Press