Active Frequency Stabilisation for Prolonged bSSFP Imaging: Application to Neonatal Cardiac MRI

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Introduction: Balanced-Steady State Free Precession (bSSFP) has become a core tool for cardiac MR (CMR) imaging, because it provides excellent blood-myocardium contrast and has high SNR efficiency. However, the sequence exhibits banding artefacts if variations in the B0 field are greater than the primary pass bandwidth. These artefacts are characterised by rapid local amplitude and phase changes, which cause signal instability if they intersect regions of flowing blood [2, 3]. The resulting flow related artefacts can render cardiac bSSFP images unusable. There are two requirements for successfully controlling this problem: i) precise shimming so that in the region of the heart $\gamma B0 < 1/TR$, and ii) sufficient frequency stability throughout the acquisition to ensure the bands do not drift into the blood pool. Neither is a major problem for adult CMR using breath-holds, since adequate shimming can be readily achieved using commonly available automated volume shim procedures and acquisition times are limited to a few tens of seconds. Performing successful CMR in the newborn population requires a distinctive approach to that of conventional adult scanning [1] and both the above requirements for successful bSSFP tend to fail. In addition to the more rapid heart rates and the lack of ability to perform breath-holds, the increased resolution required for the smallest preterm infants means that longer multiple-average scans and high demand on gradients are typically required. Since the likely underlying cause of scanner frequency drift is suspected to be thermal in origin and associated with prolonged heavy gradient demand, the problem is particularly acute in neonatal CMR. In this work we have implemented frequency stabilised scanning and combined this with image based shimming to achieve stable bSSFP imaging over prolonged periods: we then applied this to the study of the neonatal heart. The proposed methods are likely to have wide application where longer acquisition times are required, such as 3D coronary MRA performed under free breathing.

Methods: Frequency stabilisation was implemented on the scanner by modification of the code to perform frequency drift measurements by exciting a reference slab in a chosen region of interest, processing the FID to determine the current centre frequency and then updating of the spectrometer frequency. This discrete module was integrated into a multi-2D bSSFP sequence to control the frequency prior to each increment of slice position in the stack. For cardiac applications the reference slab was orientated and centred parallel to the mid short axis plane, so as to cover the whole heart. The technique was tested in phantoms using a bSSFP protocol optimised for neonates (detailed below). Prolonged scanning of a phantom with multiple averaging of the slice stack was compared to a single phase, and single averaged, reference stack (Time for Acquisition (TA) ~8s). Band artefacts were deliberately introduced by applying a linear y-shim offset of 0.1mT/m (creating ~4Hz/mm ramp across the sample), so that any instability in the centre frequency resulted in displacement of bSSFP bands relative to the reference image.
B0 mapping and shimming was implemented using an RF spoiled ECG gated (dual in-phase TE) gradient echo sequence with resolution: 1.56 x 1.56 mm, and 10x4mm slices designed to cover the heart in the short axis plane (FA/TE1/TE2/TR=10/2.3/4.6/10). Optimum second order shim values were calculated offline in Matlab using a least squares minimisation fit of manually masked heart ROIs drawn on B0 magnitude images; phase unwrapping was performed where necessary.
Cardiac MRI was performed on a Philips (Best, Netherlands) 3T Achieva MR scanner using an 8-element paediatric receive-coil to study 10 infants (Gestational ages: 25^{+5} to 40^{+3} weeks, weight: 755 to 3120g) using a retrospectively gated bSSFP sequence acquiring 20 cardiac phases at 1x1 mm resolution in-plane, 4mm slices with 8 (serial) averages. 2- and 4- chamber views were acquired followed by a 10-slice (-1mm gap) short axis stack covering the left ventricle, starting at the apex: total stack TA~10mins (FA/TE/TR=35/1.9/3.8ms). Infants were scanned with ear protection, routine monitoring and without sedation or anaesthesia; informed parental consent and full ethics approval was obtained.

Results and discussion: Figure 1 reveals a significant scanner frequency drift during the acquisition of the bSSFP cine stack (TA~10mins). The profile plots show band locations have drifted by ~28mm by the time the last slice has been acquired - corresponding to ~112Hz. This level of drift is significant considering the primary pass bandwidth of bSSFP (TR=3.8ms) is only ± 132 Hz. Slice-by-slice active frequency determination and spectrometer updating (Fig. 1c) stabilises bands from slice 3 onwards. The initial drift of < 36 Hz is due to a one slice lag between acquisition, and processing and updating of the scanner frequency in this implementation. The degree of drift observed, particularly in the initial phase of a scan, does not follow any reproducible pattern and depends primarily on the scanning activity immediately proceeding. Therefore, it is not adequate to implement a predetermined fixed increment of the frequency per slice, and as such a dynamic active frequency stabilisation method is required to allow scans of arbitrary length to be performed. The requirement for image based shimming in neonatal CMR is illustrated in figure 2, where automated volume shimming failed to remove bands from the blood pool, whereas reliable starting conditions were achieved in every neonate using the image based approach. Combining accurate shimming with frequency stabilisation resulted in successful multi-average whole heart cine stacks on all infants. A typical example is shown in figure 3. Two slices from the stack – one early, one late on – are shown acquired with and without the dynamic frequency stabilisation. The initial slices (towards the apex) of the stack are free of artefacts in both, but by slice 7 without frequency drift correction dark bands have crossed into the blood pool deteriorating the upper half of the stack significantly. The frequency drift correction applied during all stacks acquired on neonates averaged a total of 163±20 Hz. This higher value observed *in vivo* compared to the phantom data may be due to the more intense scanning load typical of routine neonatal CMR examination. An additional point of interest is that the drift in B0 is relatively spatially invariant over this field of view - apparent by a shift rather than a distortion in the bands.

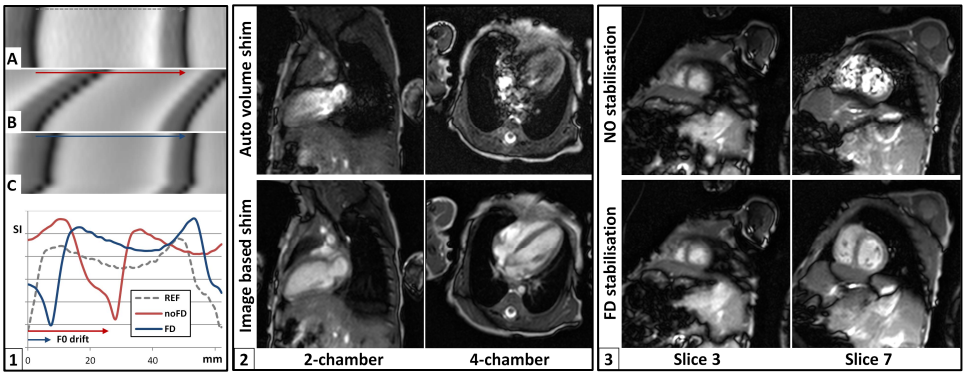

Fig. 1: Frequency drift determined in phantoms and effect of frequency stabilisation. Multi-planar reformats in y-z plane show location of bands in (a) the rapidly acquired stack (no drift), (b) full bSSFP stack without stabilisation, and (c) a stack using the proposed slice-by-slice active frequency drift stabilisation. Profile plots reveal the extent of drift in bands for the last (top) slice acquired in each stack. **Fig. 2:** bSSFP images acquired following (top row) automated volume, and (bottom row) image based-shimming for two cardiac views. **Fig. 3:** bSSFP short axis images of a late-diastolic cardiac phase, showing slices 3 and 7 taken from a 10-slice stack acquisition: without frequency correction (top row) and with active frequency stabilisation (bottom row).

Conclusion: We have implemented two methods which combine to deliver reliable sustained scanning using bSSFP under conditions where shimming is a challenge; the benefits of which have been demonstrated on neonatal CMR to allow more accurate assessment of cardiac function. Fine adjustment of B0 combined with active frequency control can ensure bSSFP sequences operate in a stable fashion for as long as required. An interesting side feature of the frequency stabilisation is that small fluctuations due to respiration can also be picked up and this might in future be utilised for an additional level of consistency in performance.

References: [1]: Price et al. Proc. ISMRM 19 #1178 (2011). [2]: Schär et al. Magn Reson Med 51:799–806 (2004). [3] Markl et al. JMRI 20:697-705 (2004).