N-SPAMM for efficient displacement-encoded acquisition in myocardial tagging

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Introduction The development of HARP [1] and DENSE [2] has significantly facilitated cardiac motion analysis for assessing myocardial function. To improve the accuracy of displacement measurement, these methods have been combined with CSPAMM [3], which eliminates the static signals from T_1 recovery [4-5]. Recently, this approach has been extended to additionally separate the echo and anti-echo signals so that the pure displacement-encoded signals can be recovered without (or with only mild) additional filtering [6-7]. In that approach, the idea is to acquire two 1-1 CSPAMM scans with the sinusoidal tag pattern shifted by half the tag distance between the two scans. As a result, one scan acquires the sine tagging pattern ($\sin(2\pi\, x\, k_{tag})$), while the other scan acquires the cosine tagging pattern ($\cos(2\pi\, x\, k_{tag})$). These two patterns can then be combined by Euler's formula to yield a pure displacement-encoded complex sinusoid: ($\sin(2\pi\, x\, k_{tag}) + i{*}\cos(2\pi\, x\, k_{tag}) = \exp(i\, 2\pi\, x\, k_{tag})$). By eliminating the anti-echo signals (i.e. the $\exp(-i\, 2\pi\, x\, k_{tag})$ component), the tagging distance can be reduced, thereby minimizing intra-voxel dephasing [6-7]. However, the disadvantage of that approach is that at least 4 scans need to be acquired (2 for each of the 2 CSPAMM). In this work, we describe the principle of N-SPAMM, where N denotes the number of scans. We show that the signals can be separated with only N=3 scans, thereby reducing scan time by 25%. The same principle can also be applied to resolve higher-order harmonic peaks by using additional scans. Furthermore, the approach can be extended to higher spatial dimensions (e.g. 2D and 3D tags), with concomitant increases in time saving.

Theory When a 1-1 sinusoidal tagging pattern is applied, the *k*-space signal is convolved with a *k*-space point spread function containing 3 peaks. The 2 outer harmonic peaks will carry the displacement-encoded information, while the central DC (direct-current) peak does not. In N-SPAMM, we impart a linear phase shift to the other 2 peaks by shifting the position of the tagging pattern (Fig. 1 bottom). To resolve the outer harmonic peaks, we repeat the scan with the tagging pattern shifted by different amounts. In this way, each peak will be modulated by a different phase factor, as determined by the shift. This process, in effect, encodes the peaks, which can be separated subsequently by inverting the encoding. In the case of a 1D line tag, there are 2 harmonic peaks and 1 DC peak, so there are 3 unknowns, which can be resolved using $N \geq 3$ scans. In fact, any shift amounts can be used for peak encoding, provided that the encoding matrix is non-singular. The optimal encoding requiring the fewest scan is dubbed 3-SPAMM, since it involves acquiring 3 scans (i.e. N=3) and shifting the tagging pattern by 1/3 the tag distance in each scan. The harmonic and DC peaks are then modulated by phase factors as determined by a 3x3 Fourier matrix. As a result, the peaks can be separated (i.e. decoded) by Fourier transformation (Fig. 1), in a similar fashion to reconstructing phase-encoded signals in conventional MRI. By utilizing 1/5 shifts and 5 scans, one can additionally resolve the 2nd-order harmonic peaks. Extension of this concept to 2 and 3 dimensions allows pure displacement-encoded signals to be recovered from 2D and 3D grid tag patterns using 5 and 7 scans respectively.

Methods To validate the method, *in vivo* cardiac tagging images were acquired from a rat. 1-1 SPAMM tagging was used to generate sinusoidal tagging patterns with shifts as described above. Images were acquired with EKG triggering on a Bruker 4.7T PharmaScan MRI (Bruker BioSpin, Ettlingen, Germany) using a gradient-echo sequence (TE/TR/flip = 1.34ms/15ms/30deg) and a birdcage volume coil.

Results Fig. 2 shows exemplary results for 3-SPAMM line tagging. The 3-SPAMM encoded images (top) show tagging patterns shifted by 1/3 the tagging distance in each image. 3-SPAMM decoding involves applying a Fourier transform across the scans. The DC image (middle row, center) contains only background phase, and can be used to phase-correct the displacement-encoded images (bottom row).

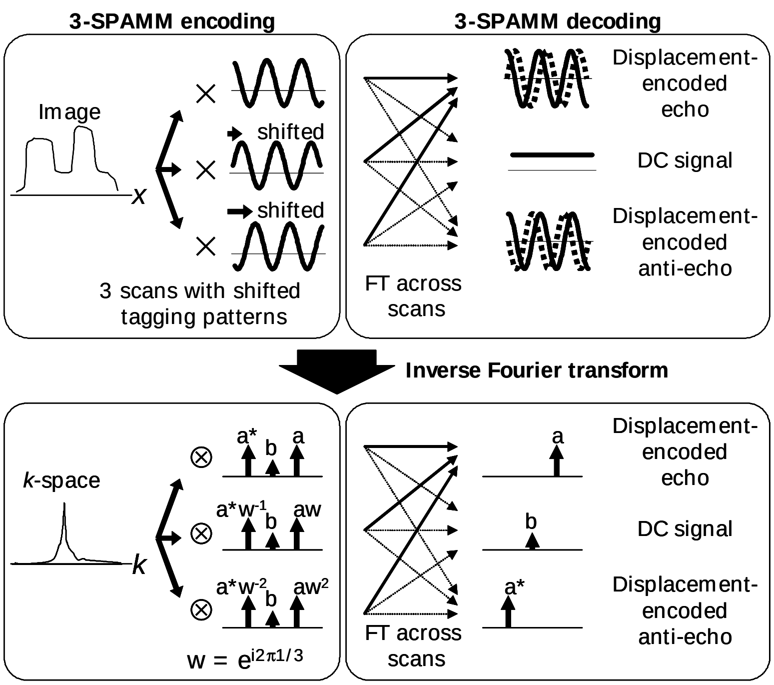

Fig. 1 Theory of N-SPAMM for N=3 in image space (top) and *k*-space (bottom)

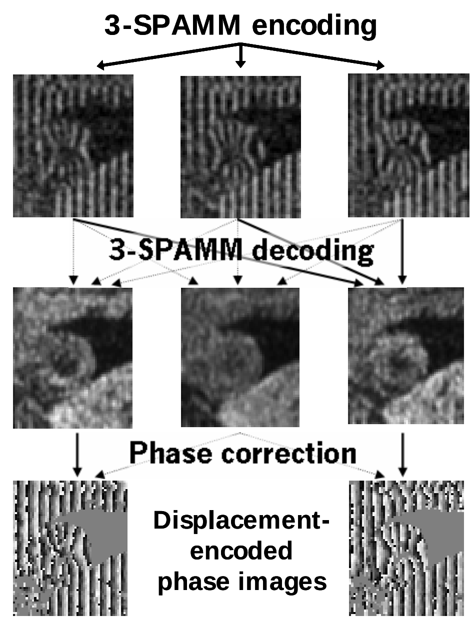

Fig. 2 Cardiac tagged images of rat heart acquired with 3-SPAMM encoding and the decoded displacement-encoded phase images from the echo (right) and anti-echo (left) signals, respectively

Discussion Displacement-encoded signals can be separated from one another and from the DC signal by shifting the tagging patterns. Optimal shifts can be designed such that the signals are encoded according to an orthogonal matrix, thereby allowing least-squares optimal reconstruction. With this approach, it is possible to separate signals in 1D line tags, 2D and 3D grid tags using as few as 3, 5 and 7 scans, respectively.

References [1] Osman NF, et al. MRM 1999;42(6):1048-1060. [2] Aletras AH, et al. JMR 1999;137(1):247-252. [3] Fischer SE, et al. MRM 1993;30(2):191-200. [4] Kuijer JP, et al. MRM 2001;46(5):993-999. [5] Gilson WD, et al. MRM 2004;51(4):744-752. [6] Epstein FH, et al. MRM 2004;52(4):774-781. [7] Aletras AH, et al. JMR 2004;169(2):246-249.