Simultaneous 3D tracking of multiple 19F labeled capsules using a 3D Golden Angle sampling scheme

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Introduction: Tracking of small fluorine (19F) labeled capsules bears great potential for clinical applications. Tracking of single 19F labeled markers has previously been performed for gastrointestinal applications [1,2] and for catheter tracking [3] using projection imaging along three orthogonal directions. For these applications, simultaneous fast tracking of multiple capsules or marker points is highly desirable: The assessment of local intestinal motor function and of variations and dynamics in intestinal content distribution and gastrointestinal transit time is greatly facilitated by the application and tracking of multiple capsules. Likewise, simultaneous *in vivo* monitoring of multiple and/or different oral drug delivery systems would be of interest for pharmaceutical industry. Similarly, multiple markers along a catheter are required to reliably detect and track its moving bend shape. Proceeding from the tracking of only one to two or more capsules in 3D space, three orthogonal projections are not sufficient anymore for unambiguous detection of capsule positions. Instead, multiple non orthogonal projections along different directions can be acquired, which is inherently fulfilled for radial sampling. The 3D Golden Angle (3DGA) radial projection scheme [4] shows particular favorable characteristics for multiple capsule tracking and has advantages over other 3D radial sampling schemes. 3DGA allows for relatively uniform "quasi-random" k-space coverage at any time and for any number of used projections and allows for the reconstruction of 3D images. Moreover, the reconstruction window size (numbers of profiles) used for image production can be (dynamically) adapted for optimal SNR performance. Therefore, in this study the use of the 3DGA method for tracking of multiple 19F labeled capsules is studied with regard to SNR efficacy and achievable temporal resolution.

Methods and Materials: ***Data acquisition:*** Experiments were performed on a 3T whole-body Achieva MR system (Philips Healthcare, Best, The Netherlands) equipped with a dual-channel 19F transmit-receive surface coil (PulseTeq Ltd, UK, 20cm diameter). A modified balanced FFE 3D radial sequence with 3D Golden Angle projections [4] was used (Figure 1). Scan parameters were: FOV 32x32x32 cm^3, TR/TE (ms) 6.8/3.1, spatial resolution 4 mm, sinc-Gaussian RF pulse with a bandwidth of 1823 Hz, pulse length of 3.29ms and peak amplitude of 4.92µT. ***In vitro experiments:*** 140µl of Perfluoro-15-crown-5-ether (15C5, Exfluor Research, USA) was chosen as 19F marker and filled inside capsules designed and validated for in vivo application [2]. A total of 6400 projections (total scan time = 44s) was acquired for each scan. In a first experiment, 4 capsules were fixed onto a cylinder with radius 2.2cm at heights $0, 3, 6, 9$ cm and angles $0°, 90°, 180°, 360°$, respectively. The cylinder was rotated with different velocities v using abdominal (anteroright) configuration of the 19F coils. In a second experiment, the signal leakage from 19F signal sources in images reconstructed from undersampled k-space data was studied on one capsule at a fixed location. During 4 scans, the SNR for this capsule was measured with only this capsule in place and with 1, 2 or 3 additional capsules positioned next to the first capsule. ***Data processing:*** The temporal resolution of the tracking (ΔT) was set by choosing different reconstruction window sizes of N = 30, 60, 90, 120 and 150 k-space lines. The combined k-space data was gridded and 3D images were then reconstructed using FFT of the k-space data. An iterative search algorithm was used to detect capsule positions: In a first step, the 3D coordinate corresponding to the signal intensity maximum in the reconstructed 3D image was determined, defining the position of one capsule. Subsequently, this detected capsule was cut out from the 3D image and the algorithm was repeated from step 1 to find the next capsule. An SNR of 27 was chosen as the cut-off value for correctly identified capsule positions. To study the dependence of the reconstruction window size on the success rate for correct capsule position detection, the fraction of correctly identified capsule positions for different reconstruction window sizes was calculated.

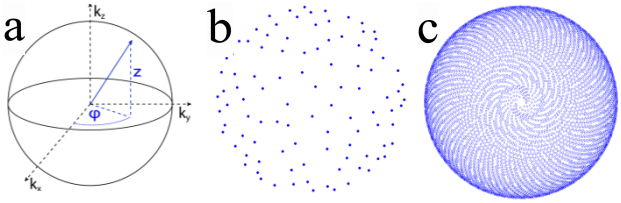

Figure 1 (a) 3DGA projection scheme. Projection m is defined by $\varphi = 2\pi mA$, $z = mB$ with constants A = 0.6823 and B = 0.4656. (b-c) Simulated positions of the projection direction vector tips for a 3D Golden Angle projection scheme using 100 (b) and 6400 (c) projections, showing relatively uniform k-space coverage.

SNR>27	ΔT =204ms	ΔT =408ms	ΔT =612ms	ΔT =816ms	ΔT =1020ms
$\overline{v1}$ =3.1 mm/s	78.7%	85.7%	90.2%	92.0%	91.8%
$\overline{v2}$ =7.5 mm/s	73.9%	86.2%	89.8%	91.6%	90.6%
$\overline{v3}$ =13.4 mm/s	65.8%	73.8%	76.1%	78.9%	79.5%

Table 1 Fraction of capsule positions detected with SNR>27 for 4 capsule tracking. $\overline{v1}$, $\overline{v2}$ and $\overline{v3}$ are mean capsule velocities. Cells are shaded gray if the travelled distance of the capsule per reconstruction window exceeds the spatial resolution of 4mm, leading to partial volume effect. Reconstruction window sizes were N = 30, 60, 90, 120, 150 k-space lines.

Results: Tracking of four capsules using 3DGA was successfully performed (Figure 2) for mean capsule velocities ≤13.5 mm/s. The velocity and reconstruction window size dependence on the success rate for correct capsule position detection is displayed in Table 1. SNR values for a single capsule and when adding 1 to 3 more capsules into the FOV were 65.3, 57.2, 43.2 and 37.5, respectively (N = 30).

Discussion: 3DGA allows for reliable and fast simultaneous tracking of multiple capsules. Due to the continuous optimized radial sampling scheme, 3DGA allows for SNR dependent (dynamic) adaption of image reconstruction for capsule position detection by means of using different reconstruction window sizes. The measured SNR decrease for multiple capsules indicates that iterative Compressed Sensing methods [5] could be used to increase SNR in multiple capsule tracking. Furthermore, tracking algorithms that take past capsule positions into account should be applied.

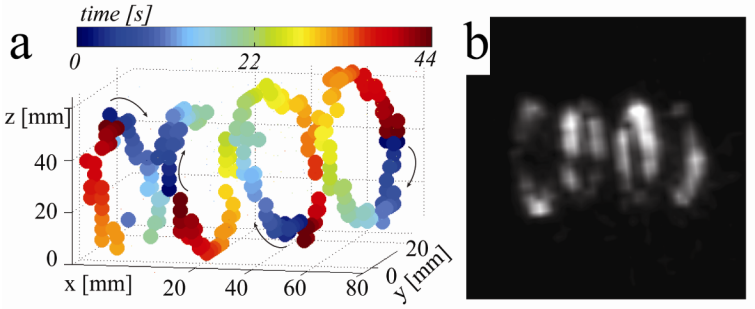

Figure 2 (a) Determined capsule positions of four capsules fixed onto a cylinder and rotated with mean velocity 3.1 mm/s. The reconstruction window size is 30 k-space lines with a corresponding temporal resolution of 204ms. Arrows denote the motion direction of the four capsules. (b) Reconstructed 3D image from 6400 k-space lines.

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References: [1] Schwarz et al. MRM 48:255-61 (2002) ; [2] Hahn et al. 4662, ISMRM 2010 ; [3] Kozerke et al. MRM 52:693–697 (2004) [4] Chan et al MRM 61: 354-363 (2009); [5] Lustig et al., MRM 58:1182-1195