Robust 3D SPACE imaging freely stopped by patient motion

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Introduction: 3D turbo spin echo requires long acquisition time, therefore is prone to motion artifacts. Existing methods to address this problem[1,2] are either restricted to small or rigid motion or require additional hardware for motion tracking. However, the intolerable motion, especially from patients' voluntary movements, is often dramatic or non-rigid. Another disturbing fact is that in conventional MR imaging, the corruption of the image by motion artifacts becomes visible only after the entire scan is finished, but much time is wasted. To mitigate this problem, two features were introduced into a prototype SPACE[3]: a) integrated motion detection, which makes an assessment on the level of the motion, and stops the acquisition immediately when unacceptable motion is detected; b) a sampling strategy, optimized for the image reconstruction in cases that an acquisition is interrupted. In this work, we extended the sampling strategy from radial reordering to linear reordering, and proposed a more robust method for motion detection. Comprehensive in vivo experiments have been conducted to evaluate the performance of the method.

Method: <u>Sampling strategy</u> Details of the sampling strategy with radial reordering are given in Ref 3. It is extended to linear reordering by sorting the echo trains by their distance to the k-space center and dividing them into multiple sections. <u>Motion detection</u> Navigators are acquired at the end of each TR. Two thin slices perpendicular to the readout direction of the imaging acquisition are excited. A gradient echo with only frequency encoding is acquired for each slice. The frequency encoding directions in the two navigator slices are perpendicular to each other and also perpendicular to the readout direction of the imaging acquisition. Over the initial TRs, navigators without RF pulses are acquired to estimate the statistics of the noise. The first acquired navigator with an RF pulse is taken as reference. The acquired navigators in the following TRs are compared to the reference for motion detection as follows: After inverse Fourier transform, the Frobenius norm of the difference between the reference profile A and the actual profile B is taken as a measure of motion, with $A = \begin{bmatrix} a_{R11}, a_{I11} & \cdots & a_{R1n}, a_{I1n} \\ \vdots & \ddots & \vdots \\ a_{RK1}, a_{IK1} & \cdots & a_{RKn}, a_{IKn} \end{bmatrix}$, where, n denotes the number of channels; K the number of pixels selected from the profile; R and I the real and imaginary part of the pixels. The newly acquired profile is $B = \begin{bmatrix} b_{R11}, b_{I11} & \cdots & b_{R1n}, b_{I1n} \\ \vdots & \ddots & \vdots \\ b_{RK1}, b_{IK1} & \cdots & b_{RKn}, b_{IKn} \end{bmatrix}$. The Frobenius norm of their difference D is $\|D\|_F = \sqrt{\sum_i^K \sum_j^n (a_{Rij} - b_{Rij})^2 + (a_{Iij} - b_{Iij})^2}$. In the absence of motion between A and B, the elements in D are normally distributed with zero mean and variance $2\sigma^2$. It can be inferred that $\|D\|_F$ is associated with Chi distribution[4], with the mean value $m_{\|D\|_F} = \frac{1 \cdot 3 \cdot 5 \cdot (2nK-1)}{2^{nK-1}(nK-1)!} \sqrt{\frac{\pi}{2}} \sqrt{2}\sigma$; and the standard deviation $s_{\|D\|_F} = \sqrt{2nK(\sqrt{2}\sigma)^2 - m_{\|D\|_F}^2}$. Since nK is in the order of thousands, $Chi(\|D\|_F) \cong Norm\left(m_{\|D\|_F}, (s_{\|D\|_F})^2\right)$. If $\|D\|_F$ exceeds the threshold given by $m_{\|D\|_F} + 4.0 * s_{\|D\|_F}$, motion is assumed to occur. However in practice this threshold might be too sensitive to local muscle contraction, blood pulsation etc., and therefore a buffer is needed to avoid unwanted interruption of the scan. To simplify the estimation of the buffer, slight movements of the object are modeled by the displacement of the acquired profile reference. Given the reference profile is shifted by t pixels ($0 \leq t \leq 1.0$), the calculated buffer $buff = (m_T + f * s_T) - (m_{\|D\|_F} + f * s_{\|D\|_F})$, where $m_T = \frac{1 \cdot 3 \cdot 5 \cdot (2nK-1)}{2^{nK-1}(nK-1)!} \sqrt{\frac{\pi}{2}} \sqrt{2}\sigma \, _1F_1\left(-0.5, nK, \frac{-(tS)^2}{4\sigma^2}\right)$, $s_T = \sqrt{2nK(\sqrt{2}\sigma)^2 + (tS)^2 - m_T^2}$, $t = \frac{\Delta d}{\Delta x}$. S is the intensity of the signal in the Frobenius norm of the profile gradient, $_1F_1(a, b, z)$ is the confluent hypergeometric function. f is a scaling factor, set to 8.0 in our experiments to account for the inaccuracy in the estimation of mean and standard deviation. Δx is the readout resolution of the navigators. Δd is the tolerable displacement of the objects (set to the readout resolution of image acquisition). The final threshold, which is used to judge if motion exists, is $TH = (m_{\|D\|_F} + f * s_{\|D\|_F}) + buff$. <u>Experiments</u> the proposed sampling strategy and the motion detection method has been implemented into a prototype SPACE, and tested on clinical MR scanners. First, volunteer experiments were conducted to evaluate the performance of the Frobenius norm based motion detection by comparing it with an optical motion tracking system[5]. Next, 47 volunteer datasets were acquired. The proposed sampling strategy was applied. Navigators were acquired for tracking purpose, and didn't interrupt the scanning. Images were reconstructed in two ways: a) reconstruction with all acquired data; b) reconstruction with only the data before the first detected motion; Image quality was evaluated by experienced technicians (Table 1 and Table 2).

Results & Discussion: The dual thin slice projection and the Frobenius norm of the profile change enable the monitoring of motion in all dimensions. Experiments showed its consistency with the optical tracking system (Fig1). Statistical results in Table1 show that the motion detection method can properly detect most of the unacceptable movements. Exceptions were corresponding to the cases that subjects moved at the very beginning or the end of the scan, but kept static for the rest of the time. Statistical results in Table2 show that the sampling strategy successfully recovered about 50% of the scans when motion happened at a late phase of the acquisition. An example is given in Fig2. Due to the early stop of the motion corrupted scans, and the recovery of the images, the output of the SPACE imaging was substantially increased with the proposed technique. The proposed motion detection method is superior to the similarity based method[3] because it provides clear threshold but does not need a training process.

References:
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3. Li et al, ISMRM 2013: 2590;
4. Olaf Dietrich et al, Magnetic Resonance Imaging, Volume 26, Issue 6, July 2008, 7 54 -762;
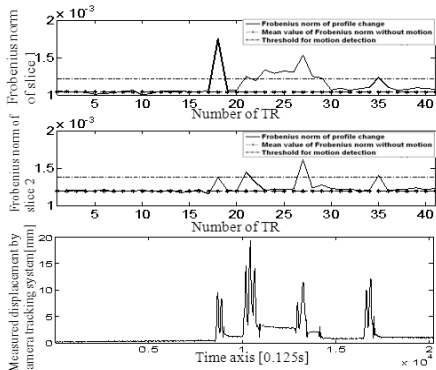5. Maclaren J et al, PLoS ONE 2012; 7 (11): e48088.

Fig1. Comparison of the Frobenius norm of the profile change with the measured displacement of the object by camera tracking system
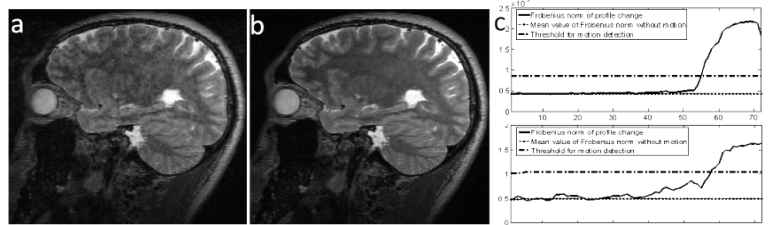

Fig2. A T2 weighted SPACE imaging, reconstructed **a)** with all acquired data; **b)** with only the data acquired before the first detected motion; **c)** the Frobenius norm of the profile change of two slices, and the threshold for motion detection.

Motion detected	Image quality acceptable	Image quality unacceptable
25	6	19
No motion detected	Image quality acceptable	Image quality unacceptable
22	22	0

Table1. Evaluation of the appropriateness of the threshold setting in motion detection; Image were reconstructed with all acquired data.

Recon with freely stopped acquisition	Image quality acceptable	Image quality unacceptable
14 (out of 19)	9	5

Table2. Evaluation of the reconstruction with only the data acquired before the first detected motion in the proposed SPACE imaging. The datasets were taken from the cases with detected motion (completion rate > **35%**), but unacceptable image quality in table 1.