A Frobenius norm based motion detection method

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Introduction: MR imaging takes relative long acquisition time therefore is prone to motion artifacts. Motion artifacts are only observed after the entire scan is finished in normal MR imaging, at the cost of having lots of time wasted. To mitigate the problems above, a sampling strategy was proposed[1], which uses internal motion detection to judge whether object moves or not, and stops the acquisition immediately when unacceptable motion is detected. In the sampling strategy, motion detection plays a critical role. In this work, we present a novel motion detection method, which quantifies the motion caused change, and provides a clear threshold for determining whether a motion is acceptable or not without any training process.

Method: 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 slices are perpendicular to each other and also perpendicular to the readout direction of the imaging acquisition. In first 2 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 through the method detailed below: After inverse Fourier transform, the reference profile is 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 denotes the number of pixels selected from the profile; R and I represent the real and imaginary part of the pixels. The new 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 condition of no motion occurring 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[2], with the probability density function $P_{\|D\|_F}(x) = \frac{1}{\Gamma(nK)(\sqrt{2}\sigma)^2}\left(\frac{x}{2(\sqrt{2}\sigma)^2}\right)^{nK-1} x^{nK} \exp\left(\frac{-x^2}{2(\sqrt{2}\sigma)^2}\right)$; the mean value $m_{\|D\|_F} = \frac{1\cdot3\cdot5\cdot(2nK-1)}{2^{nK-1}(nK-1)!}\sqrt{\frac{\pi}{2}}\sqrt{2}\sigma$; 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, $Chi(x) \cong Norm\left(m_{\|D\|_F}, (s_{\|D\|_F})^2\right)$. In probability, one could claim that motion happens in case of $\|D\|_F$ exceeding the threshold of $m_{\|D\|_F} + 4.0 * s_{\|D\|_F}$. However this threshold might be too sensitive to local muscle contraction, blood pulsation, small displacements etc., which just slightly degrades the quality of reconstructed image. A buffer is needed to avoid unwanted stop of the scan. To simplify the estimation of the buffer, local and tiny movements of the object are modeled by the displacement of the acquired profile reference. Given the reference profile is shifted by t pixels ($0 \le t \le 1.0$), the calculated buffer $buff = (m_T + f * s_T) - (m_{\|D\|_F} + f * s_{\|D\|_F})$, where $m_T = \frac{1\cdot3\cdot5\cdot(2nK-1)}{2^{nK-1}(nK-1)!}\sqrt{\frac{\pi}{2}}\sqrt{2}\sigma\ {}_1F_1\left(-0.5, nK, \frac{-(tS)^2}{4\sigma^2}\right)$, $s_T = \sqrt{2nK(\sqrt{2}\sigma)^2 + (tS)^2 - m_T{}^2}$, $t = \frac{\Delta d}{\Delta x}$. 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 a slightly greater value than 4.0 (typically 8.0 in our experiments) in practice to tolerate the inaccuracy in the estimation of mean and standard deviation. Δx is the readout resolution of the navigator echoes. Δd is the tolerable displacement of the objects (typically set to the readout resolution of image acquisition). The final threshold, which is used to judge if voluntary motion exists, is $TH = (m_{\|D\|_F} + f * s_{\|D\|_F}) + buff$. Experiments The proposed motion detection method has been implemented into the SPACE sequence, and tested on clinical MR scanners. First, volunteer experiments were conducted to evaluate the performance of the Frobenius norm base motion detection method by comparing it with an optical motion tracking system[3]. Next, a group of volunteer datasets were acquired. The sampling strategy in Ref 1 was applied. Navigators were acquired only for tracking purpose, and didn't interrupt the scanning. Images were reconstructed with all acquired data and evaluated by experienced technicians (Table 1).

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). Fig2 shows that the Frobenius norm based method is superior to the edge shift based motion detection. 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.

References:

1. Li et al, ISMRM 2013: 2590; 2. Olaf Dietrich et al, Magnetic Resonance Imaging, Volume 26, Issue 6, July 2008,754-762; 3. Maclaren J et al, PLoS ONE 2012; 7 (11): e48088.

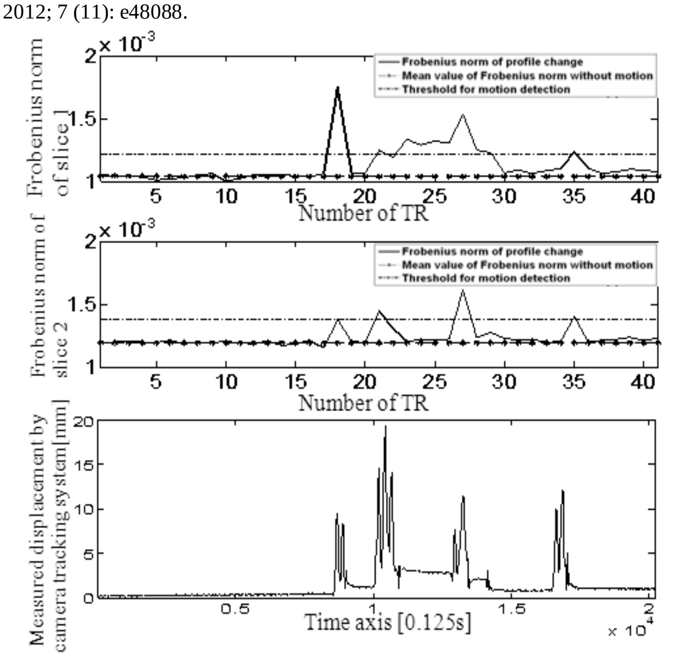

Fig1. Comparison of the Frobenius norm of the profile change with the measured displacement of the object by camera tracking system

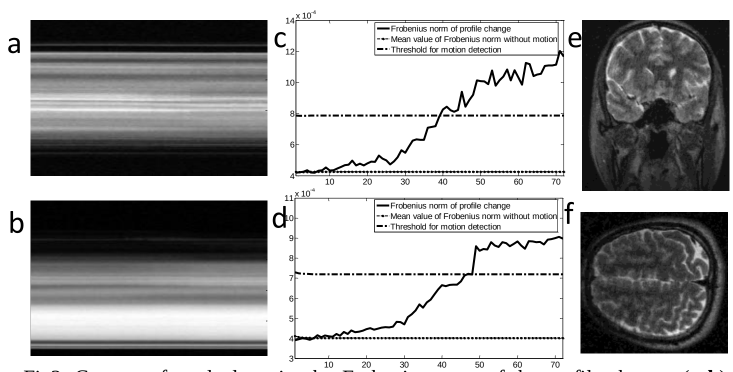

Fig2. Capture of gradual motion by Frobenius norm of the profile change. (**a-b**) are the profiles of two slices with perpendicular readout directions; (**c-d**) show the calculated Frobenius norm of the corresponding profile differences and the threshold for motion detection; (**e-f**) are the reconstructed images with all acquired data. It shows that the gradual motion is nearly invisible in the measured profiles, but successfully detected by Frobenius norm. The strong motion artifacts in the reconstructed images proved the 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.