MR-guided thermotherapy of abdominal organs using a robust PCA-based motion descriptor

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Introduction

Thermotherapies can now be guided in real-time using magnetic resonance imaging (MRI) [1]. This technique is gaining importance in interventional therapies for abdominal organs such as liver and kidney. An accurate on-line estimation and characterization of organ displacement is mandatory to prevent misregistration and correct for motion related thermometry artifacts [2]. Here we describe the use of a Principal Component Analysis (PCA) to detect spatio-temporal coherences in the physiological organ motion and to characterize in real-time the complex organ deformation: During hyperthermia, incoherent motion patterns could be discarded, which enabled improvements in the compensation of motion related errors in thermal maps, as well as in the motion estimation robustness.

Materials and Methods

Preparative learning step: Motion patterns were learned during a preparative learning step performed before hyperthermia. A training set of N motion vector fields (N=200) relating the current target position in each image was obtained using an optical-flow based image registration algorithm [3]. Due to the oversampling of the physiological motion cycle, the N vector fields are sparse and a reduced parameterized motion flow model D_i was constructed using a PCA [4]: The spatial transformation T_t at instant t between the actual anatomical image (M_t) and the reference (M_{ref}) could be expressed as a linear combination of the computed basis vector fields B_i (**Eq. (1)**). The threshold value for K, which separates eigenvectors representing physiological motion from eigenvectors coding for noise contribution was determined as follows: Since the respiratory and the cardiac activities are periodic, D_i were analyzed in the Fourier domain. Typical periods of the respiratory and cardiac activities are, in the general case, in the range of 0.15-0.3Hz and 0.5-2Hz, respectively. A threshold of 4Hz was used to separate contributions from physiological motion from noise. The reduced set of parameters D_i, which gives a representation of the organ deformation only due to physiological motion, can be computed by minimizing **Eq. (2)** over D_i using a Marquardt-Levenberg least square (LS) solver.

$$T_t(x,y) = \sum_{i=0}^{M-1} D_i^t B_i(x,y) \qquad (1)$$

$$LS = \left(M_{ref} - T_t^{-1}(M_t)\right)^2 \qquad (2)$$

Thermometry processing: To address susceptibility related phase changes with motion, a linear relation between motion and registered phase variations was evaluated during the preparative learning step individually for each voxel [4]. During hyperthermia, the estimated motion descriptors D_i were used to obtain on-line a synthetic reference phase map. This phase map was subtracted to the acquired motion registered phase image to suppress the background phase information prior to temperature calculation.

In-vivo study: Dynamic MR temperature imaging was performed on a Philips Achieva 1.5 T with a single-shot gradient recalled echo-planar sequence. The precision of the thermometry was evaluated under real-time conditions on both kidney and liver of 12 healthy volunteers under free breathing. The employed sequence was designed as follows: 3000 dynamic sagittal images, one slice, TR=100ms, TE=26ms, flip angle=35°, FOV=256×168×6mm^3, matrix=128×84.

Ex-vivo heating study: A porcine muscle was positioned on a motorized platform, which generated a periodic translational displacement (amplitude=10 pixels, frequency=0.5 Hz). RF heating was performed using a clinical MR-compatible bipolar RF device (Radionics, Burlington, MA) with 8 W of RF-power during 75 seconds. The employed sequence was designed as follows: 3000 dynamic coronal images, dual-shot, gradient recalled echo-planar acquisition sequence, TR=30ms, TE=15ms, flip angle=20°, FOV=256×104×5mm^3, matrix=128×58. For an independent assessment of the object displacement, an additional navigator echo, which provided a one dimensional displacement information.

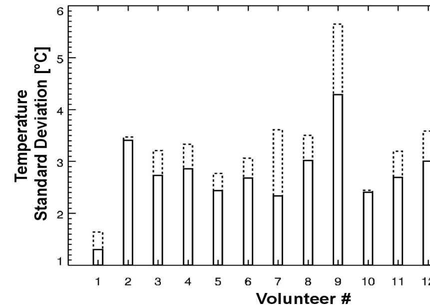

Figure 1. Histogram of the temperature precision obtained in the liver of the twelve volunteers when the temperature maps were computed using an affine motion model (dash line) and the proposed PCA-description, which gives a representation of the organ deformation only due to physiological motions and discard noise contributions (solid line).

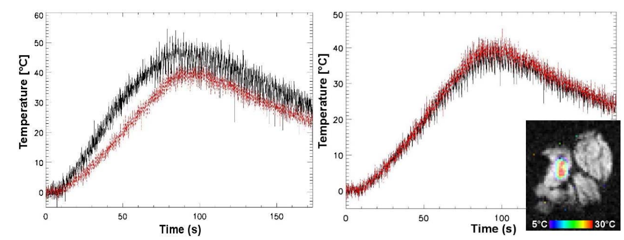

Figure 2. Thermometry results obtained for the ex-vivo RF heating experiment in a pixel located in the heated area. The reference temperature obtained with navigator echo based displacements is shown by the red line.

Left: Temporal temperature evolution obtained with phase images registered using the optical-flow algorithm: Optical-flow based algorithms rely on the assumption of conservation of local intensity along the trajectory which can be violated during thermotherapy because rapid MR-imaging is in general associated with low Signal-To-Noise ratio. In addition, since the tissue is heated, several MR relevant tissue properties such as $T1$, $T2$ and $T2*$ relaxation times are subject to change during imaging. This leads to local intensity variations, which in turn can be misinterpreted by optical-flow based algorithms as “motion”.

Right: Temporal temperature evolution obtained with phase images registered using the PCA-based motion. The temperature map computed after 50 seconds of heating is shown in the insert.

Results and Discussion

The proposed approach addresses both motion compensated MR thermometry and target tracking by applying high frame rate MRI coupled with a real-time motion estimation and characterization obtained from all incoming images. The PCA was used to detect spatio-temporal coherences of the periodic organ motion in a preparative learning step. During hyperthermia, incoherent motion patterns could be discarded, which allowed the following improvements: 1) The PCA-based motion descriptor was used to model the magnetic field variation with the target displacement, which improved the correction of motion related errors in temperature maps (**Figure 1**) ; 2) The PCA-based motion descriptor was used to provide a flow field that was consistent with the learned model and robust under the assumption of global brightness constancy but allowed local intensity variations (**Figure 2**).

The method allowed achieving a sub-second temporal resolution with very short image latencies (<80 ms) over sustained imaging periods of several minutes. During the intervention both, the target location and the target temperature were continuously available with a high temporal resolution and precision. This renders the method well suitable for the MR-guidance of a heating intervention on abdominal organs in vivo under free-breathing over sustained periods of several minutes and presents therefore a step towards clinical non-invasive HIFU therapies of kidney and liver tumors.

References

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