PCA-based image registration for on-line MR temperature monitoring of moving tissues

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Purpose/Introduction

Real-time MR-thermometry provides continuous temperature mapping inside the human body and is therefore a promising tool to monitor and control interventional therapies based on thermal ablation carried out with help of radio-frequency, laser, cryogenics or focused ultrasound (FUS). The Proton Resonance Frequency (PRF) technique gives the temperature changes by comparing phase differences between dynamically acquired images and reference data sets [1]. The temperature evolution allows on-line thermal dose evaluation during the intervention, which in turn permits an accurate prediction of tissue necrosis. In order to use such methods on moving organs such as liver and kidney, two basic problems have to be solved:

- Motion related phase artifacts (due to susceptibility effects) in temperature maps must be corrected in real-time.
- Temperature information must be mapped to a reference position in order to allow thermal dose computation, as the history of temperature is required for each pixel.

Although the latter can in principle be addressed by any established 2D image registration method, the complexity of the periodical motion patterns in the abdomen are poorly described with global six parameters affine models. More sophisticated approaches, like optical-flow based image registration, obtain the complex displacement of image components on a pixel-by-pixel basis [2]. However, optical-flow based algorithms rely on the assumption that the total image energy remains conserved. This condition can be violated during thermotherapy. Since tissue is heated, several MR relevant tissue properties such as T_1 and T_2 relaxation times can change during imaging. This leads to local intensity variations, which in turn can be interpreted by optical-flow based algorithms as "false" motion. This makes optical-flow based image registration less robust compared to affine models which rely on a global fit of the image content and are thus less susceptible to local intensity variations. In this feasibility study, the multi-baseline approach proposed for periodic motion [3] is extended by blending optical-flow based image registration during an uncritical preparation step with a principal-component analysis (PCA) based motion correction during the therapy step [4], in order to detect and correct for regional displacement patterns.

Material and Methods

MRI imaging: Dynamic MR temperature imaging was performed on a Philips Achieva 1.5 Tesla with a dual-shot gradient recalled EPI sequence (TE=13ms, TR=70ms, Matrix: 128x96, FOV=240mm, RFOV=70%, single slice) with six element-head coil.
Thermal treatment: For heating an in-house developed Radio-Frequency ablator was used. After a preparation phase of 50 dynamic scans, 20 Watts of RF-power was applied for 50s (350 dynamic scans).
Ex-vivo phantom: 600g of calf liver was mounted on a motorized platform to simulate periodic organ displacement (23mm peak-to-peak, period 3.8s).
Image processing/correction strategy: Fourier reconstruction was performed on the MR-system, motion correction and thermometry off-line using an in-House C++/IDL image processing library. The entire intervention is divided in three steps (figure 1). In the learning step, 50 images were acquired to sample a full period of the motion cycle. A complete set of reference magnitude and phase images is established and organ displacement relative to the first image is estimated using optical flow based 2D image registration. Subsequently, a PCA is performed on the ensemble of the 50 displacement vector fields, which results in a ranked (by contribution to the total variance) set of principal motion patterns. This parameter space is reduced by selecting only a subset of the highest ranked components which accounts for more than 95% of the motion (for kidney/liver imaging, typically two to six components).

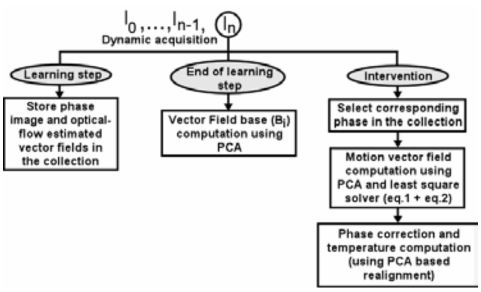


Figure 1. Data processing sequence

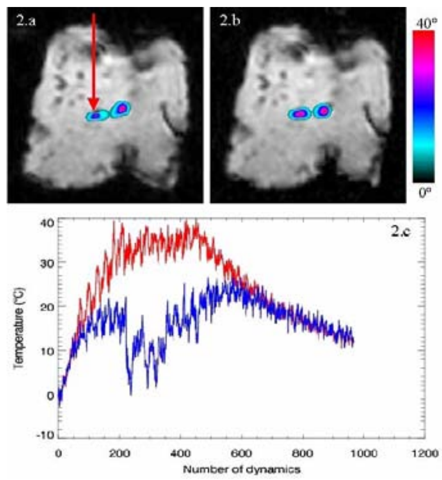
During the therapy step, each new magnitude image is registered to the reference image with help of the linear combination of this reduced set of principal components (1) by minimizing the least-square difference (2) with a Marquardt-Levenberg least square solver :

$$T_n = \sum_{i=0}^{k-1} C_i B_i \quad (1) \qquad\qquad LS = (I_R - T_n(I_n))^2 \quad (2)$$

I_R represents reference magnitude image, I_n current magnitude image, C_i the i^{th} coefficient corresponding to the B_i^{th} principal component. Instead of using optical flow to realign temperature map (e.g. in [3]), we used PCA-based realignment for increased robustness and temperature accuracy.

Results and discussion

Figure 2.a and **2.b** show a snapshot of the temperature distribution after 40 seconds of radiofrequency heating. In figure **2.a**, the temperature image registration is performed by the optical flow based method during heating. Note the deformation of the left heated area. Figure **2.b**, shows the same data registered with the proposed PCA-based approach which uses optical flow only during the preparation phase. The distortion artefact is absent here. **Figure 2.c** shows the temperature evolution of the area indicated by the red arrow in fig. **2.a**. In blue the temperature is depicted as obtained with optical flow based realignment, in red the temperature for the same data realigned with PCA.
The distortion of the hotspot in figure **2.a** demonstrates the effect of local intensity variations due to heating on the optical-flow based image registration. Since the condition of conserved image intensity is violated, miss-registration occurs. This miss-registration can lead to incorrect readings of the temperature evolution if a fixed point of interest is observed, as shown in figure **2.c**. Furthermore, the condition of conserved image intensity also leads to a decreased robustness against interference artifacts (not shown), which occur frequently on magnitude images during high power RF or FUS-ablation. This can bias the normalisation of the image and thus lead to a complete failure of image registration. The proposed PCA-based method performs well even on images with local intensity variations or image artefacts since it requires neither a conserved image intensity nor a normalized magnitude image, but rather relies on a global fit of the principal components. The obtained temperature accuracy was evaluated in a ROI placed in a non-heated area and found to be comparable to the optical flow based thermometry (1.1°C of temperature uncertainty is measured in both methods).



Conclusion

Motion compensated MR-thermometry for thermal therapy has to cope with RF-artifacts and relaxation-time changes of the monitored tissue. While purely optical-flow-based realignment may lead to temperature map computation errors for the case of local or global intensity changes, PCA-based realignment gives accurately registered temperature maps, since it relies on a global fit of the principal components. Furthermore, for applications which require real-time image registration, PCA-based image realignment has computational advantages, since the reduction of complex periodic motion patterns to the most significant principle components reduces the degrees of freedom for the registration without a priori assumptions of the form of the motion.

References

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