Extended Kalman Filtering for Continuous volumetric MR-Temperature Imaging

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Introduction

For the continuous monitoring of High Intensity Focused Ultrasound (HIFU) interventions using real-time Magnetic Resonance (MR) thermometry [1], a volumetric observation of the temperature in the near- and far-field would be preferable.

Recently, we proposed to obtain a continuous volumetric MR-temperature monitoring as follows [2]: 1) The targeted area is continuously scanned during the heating process by a multi-slice sequence ; 2) Measured data and a priori knowledge of 3D data derived from a forecast based on a physical model are combined using an Adapted Extended Kalman Filter (AEKF) [3], whereby the purpose of the AEKF is two-fold: Measurement noise reduction and an increase of the temporal resolution due a model based interpolation. In order to full-fill this role, the applied model has to be a sufficiently accurate description of the observed heating process. Here we present a quantitative analysis of the accuracy of the method when applied to different temperature increases and when applied with different spatial resolutions.

Materials and Methods

Volumetric MR-thermometry: The proposed approach combines temperature measurements obtained from a spatio-temporally under-sampled multi-slice acquisition with a physical model of temperature distribution for the reconstruction of 4D MR-thermometry. The bio-heat transfer equation (BHTE) was employed as the physical model for 3D temperature prediction, which includes the applied acoustic power (the spatial distribution of the acoustic pressure field was determined using an acoustic field simulation based on Rayleigh integration over the active transducer surface), a-priory knowledge of the absorption rate, the heat diffusion coefficient and the perfusion value [4]. The temperature modelling with the BHTE was performed using a model resolution matching the reconstructed MR measurements: An integration of the analytic distribution of the acoustic pressure field was individually performed over each voxel in the field of view to obtain temperature prediction matching the sampling of the MR measures. The measurement noise was determined before the heating process by evaluating the temperature variance in the targeted area on a thermometric dataset in absence of any heating. The process noise covariance was automatically adjusted over time based on a dynamic evaluation of the temperature bias over a temporal window of 10s.

Experimental setup: MRI guided HIFU heating was performed using a Philips Sonalleve system (Philips Healthcare, Finland) on a phantom using a PRF sequence which acquires one slice placed in the coronal direction, sweeping continuously through ten positions within the desired observation area (T_{acq}=0.17s per position). 1000 slices were acquired using a single-shot EPI sequence (TR=24ms, TE=11ms, flip angle=10°, FOV=76×100×30mm^3, images were reconstructed to a voxel size of 0.5×0.5×3mm^3 to mitigate partial volume effects) and compared to thermocouple measurements (T-type).

The method was tested for the following application scenarios:

1) Moderate heating: voxel size=1.5×1.5×3mm^3, 50W of HIFU heating during 30s (**Fig. 2**).
2) Increased spatial resolution: voxel size=1×1×3mm^3, 50W during a 60s (**Fig. 3**).
3) Increased heating power: voxel size=1.5×1.5×3 mm^3, 75W during a 30s (**Fig. 4**).

Results and Discussion

Fig. 1 shows three orthogonal temperature maps extracted from a volume reconstructed at the end of the heating process. A significant reduction in measurement noise can be visually observed between the original measured MR-temperature data and the volumetric AEKF reconstructed temperature data. **Fig. 2-4** shows that, using the reference measurement obtained with the thermocouple probe (indicated by the white arrow in **Fig. 1**), the precision of the measurement (i.e the standard deviation of the difference between the red and the black curve) was found to be improved by a factor 40-50 % using the proposed AEKF reconstruction. It can be observed however that the accuracy occasionally decreased up to 5°C off the true value with the AEKF reconstruction due to model mismatch.

Conclusion

This study shows that the reconstruction delivers accurate measurements for heating rates of ~1°C/s (**Fig. 2-3**) as well as ~2°C/s (**Fig. 4**). The method provided significant noise reduction, in particular when a high spatial resolution leads to a low SNR, while having a minimal impact on accuracy. Since the method is suitable for real-time guidance (processing-time per 3D volume < 0.17s, image production latency < 60ms in the presented implementation) it is a step towards more precise volumetric MR-temperature monitoring with a high spatial and temporal resolution.

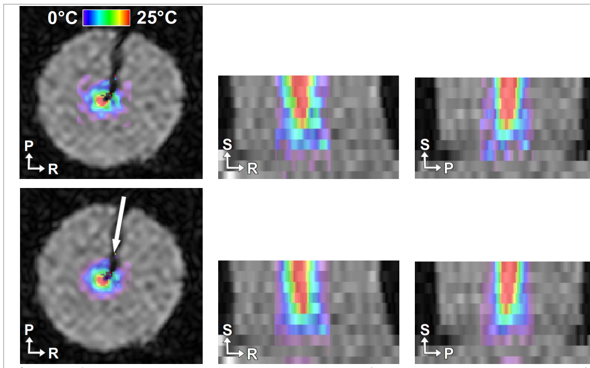

Figure 1. MR-Thermometry results obtained on a phantom heating experiment with HIFU, after 30s of "moderate" heating. **Top row:** original spatio-temporally under-sampled measured temperature (reconstructed using a sliding window). **Bottom row:** AEKF reconstructed temperature data. Read (R), Phase (P) and Slice (S) directions are reported on the bottom left of each image.

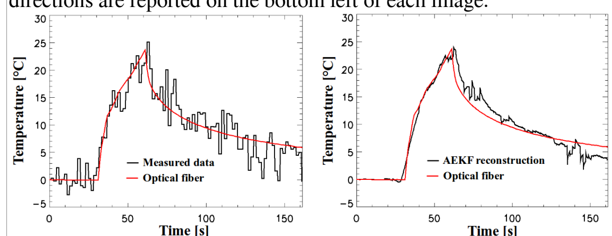

Figure 2. Comparison between the PRF-based MR-thermometry with a voxel size of 1.5×1.5×3mm^3 (black line) and the reference temperature measured with the thermocouple probe (red line). Heating was performed using 50W of electrical power during a period of 30s.

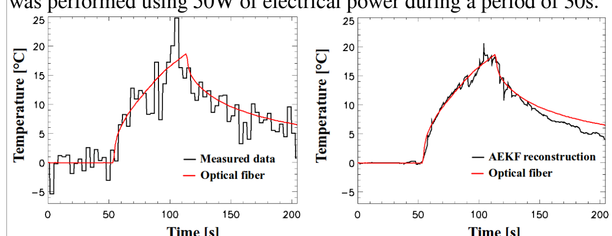

Figure 3. Comparison between the PRF-based MR-thermometry with a voxel size of 1×1×3mm^3 (black line) and the reference temperature measured with the thermocouple probe (red line). Heating was performed using 50W of electrical power during a period of 60s.

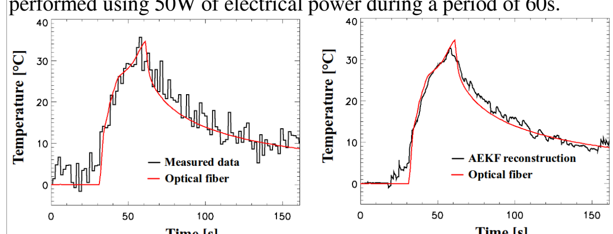

Figure 4. Comparison between the PRF-based MR-thermometry with a voxel size of 1.5×1.5×3mm^3 (black line) and the reference temperature measured with the thermocouple probe (red line). Heating was performed using 75W of electrical power during a period of 30s.

References

[1] Cline HE et al; J Comput Assist Tomogr, 1992; 16(6): 956-965.
[2] Denis de Senneville et al; ISMRM 20th Annual Meeting, 2012;#1558.
[3] Kalman, R.E., Journal of Basic Engineering 1960;82 (1):35–45.
[4] Pennes H. et al., Journal of applied physiology, 1948;1(2):93–122.