Super-resolution for real-time volumetric MR temperature imaging

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Recently, real time magnetic resonance (MR) thermometry has evolved into the method of choice for the guidance of non-invasive ablation modalities such as high-intensity focused ultrasound (HIFU). For this role MR-thermometry should preferably have a high temporal and spatial resolution and allow observing the temperature over the entire target area with a high precision. This is in practice difficult to achieve, in particular if the target area is subject to physiological motion, such as in the liver or the kidney. The requirement to avoid intra scan artefacts due to target motion prohibits the use of 3D acquisitions without gating and limits for multi-slice imaging generally both the achievable in-plane resolution and the slice thickness. Furthermore, the motion introduces additional undesired inter-scan artefacts across the acquired slice stack. Here, an alternative approach is proposed in which the targeted area is continuously scanned by a multi-slice sequence. Compared to the in-plane resolution, the slice thickness is deliberately chosen relatively large. This leads firstly to a high SNR and thus allows registering all obtained slices to a common reference position using an image based motion registration. Secondly, it allows discarding undesired fat signal with spectrally selective excitation pulses. Subsequently, the realigned image stack is subjected to a super-resolution (SR) algorithm, which provides an increased spatial resolution in the slice encoding direction. This approach allows removing the effect of physiological motion from the observed target volume and enables isotropic sampling of high spatial resolution.

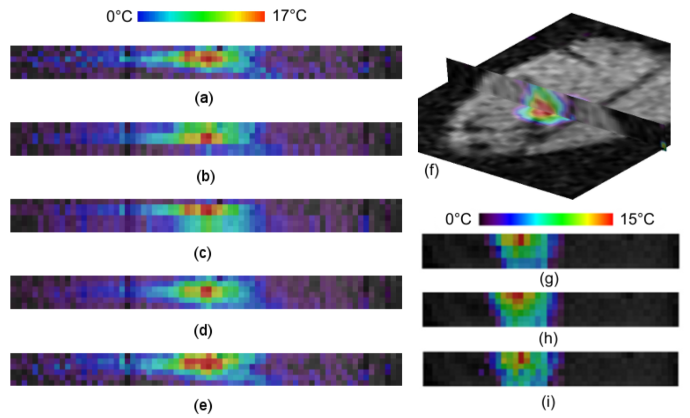

Figure 1. The image column on the left allows a direct comparison of the temperature distribution at peak temperature between the different reconstruction methods in slice direction: (a) true high-resolution (2.5mm), (b) low-resolution (5 mm), (d) trilinear gridding and (e) super-resolution. Note the high degree of similarity between the true high-resolution and the SR images. The images to the right display the results of the heating experiment under periodical motion: The native resolution of 5mm in slice direction (g), trilinear gridding only (h) and super-resolution (i). The 3D cut-out (f) of the temperature overlayed over the T_2^* weighted image illustrates the isotropic resolution when reconstructed using super-resolution.

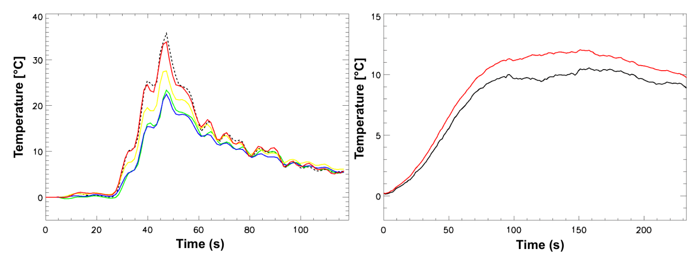

Figure 2. On the left a comparison of the temperature evolution in the hottest voxel during the static heating experiment. The results from the true high-resolution image (dashed) and the super-resolution (red) are very similar, while the low-resolution (blue, yellow) are due to the partial volume effect in slice direction substantially biased. Note that trilinear gridding (green) of the low-resolution images did not lead to a substantial improvement. The graph on the right shows similar results for the volumetric ablation experiment under periodic motion: The smaller slice thickness achieved with super-resolution leads to systematically higher temperature readings compared to the low-resolution data.

Materials and Methods

MR-imaging: A gradient recalled multi-shot EPI sequence (25 lines per readout, TE=19ms, TR=125ms, 121 spectral spatial excitation pulse with α=35º, in-plane resolution 2.5×2.5 mm^3) was employed on a 1.5T Philips Achieva MR-scanner to perform two experiments: A HIFU heating experiment in absence of motion with 14 slices and a slice thickness of 2.5 mm (as a reference), which was subsequently down-sampled to 5 mm for the SR algorithm. The second heating experiment was performed under periodical motion (2 cm ptp, 0.3Hz) obtaining 7 slices of 5 mm and reconstructed using SR on the fly. For both experiments the slice offset was increased dynamically by 2.5 mm until the entire target volume was sampled ("slice sweep").

Image processing: In the first step of the processing chain a positional dependent phase correction is performed similar to the approach presented by de Denis de Senneville et al [1], which removes the background phase. Then, each imaging slice is registered to a common reference position using an optical-flow based image registration algorithm [2]. Subsequently, an iterative back-projection method originally proposed by Irani and Peleg [3] is used grid the realigned slices into an isotropic sampling grid. This method is based on the minimization of differences between the original low-resolution images, and the low-resolution images generated (back-projected) from down-sampling the current best guess of the high-resolution image. For comparison, all slices were in addition also gridded into a higher slice resolution using a trilinear gridding.

Heating experiment: Heating was performed for 60s with 60W acoustic power with a Philips Sonalleve HIFU system, which is integrated into the patient bed of the MR-system. The target object was a piece of calf liver mounted on a motorized phantom performing a periodic movement of 20mm amplitude and a periodicity of 3s. Target tracking and real time corrections were applied similar to the methods described by Ries et al [4].

Results and Discussion

The results are summarized in figure 1 and 2. The static reference experiment shows that a slice sweep in conjunction with super-resolution leads to similar results than a native high resolution in slice direction. Low resolution imaging and trilinear gridding lead to systematically lower values due to the increased partial volume effect. These findings are in accordance with the conclusions of Todd et al. [5] who investigated this effect in detail. Similar results were obtained when the target was subject to periodic motion and active beam steering / real time motion stabilization was employed. A more detailed analysis of the influence of the precision of the in-plane realignment on the super-resolution algorithm in slice direction is currently under way.

Conclusions

It is important to see the proposed approach in the appropriate context: Super-resolution has generally limited merit in MR-imaging as shown by Scheffler et al [6]. However, in this particular context of performing quantitative volumetric imaging on moving targets, it allows to deal with in-plane motion in image space first and to subsequently reduce the slice thickness towards an isotropic resolution. This is important, since the accuracy of MR-thermometry is biased by partial volume effects and thus by the voxel size.

References

[1] Denis de Senneville B. et al., Magn Reson Med. , 2007. Vol 57, 319 – 330.
[2] Roujol S et al; Magn Reson Med. 2010 Apr;63(4):1080-7.
[3] Irani M et al. J Vision Comm Image Rep, 1993;4:324-335
[4] Ries M et al; Magn Reson Med. 2010 Sep 27 n/a. doi: 10.1002/mrm.22548
[5] Todd N. et al. , MRM online September 2010, 10.1002/mrm.22636
[6] K. Scheffler et al., Magn Reson Med., vol. 48, pp. 408, 2002.