Reference-less PRFS MR thermometry using a thin open border and the harmonic functions theory: 2D experimental validation

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Introduction. PRFS MR thermometry (MRT) is the generally preferred method for monitoring thermal ablation. Standard implementation with reference phase subtraction is highly sensitive to tissue motion and to external perturbation of the magnetic field. Previously described reference-less MRT (1) used polynomial interpolation from a closed and thick border towards the inner ROI.

Theory. Unlike "black box" polynomial interpolation, we used here the fundamental theoretical frame of harmonic functions. Based on equations from ref (2) we demonstrated that the unwrapped phase in GRE image is a harmonic function in 3D within a homogeneous medium. The problem was restricted to 2D with residual terms in the phase's Laplacian of zero and first order. A thin and unheated open border (filling factor ≥ 60%) was re-filled to a closed border by harmonic interpolation which intrinsically excluded temperature-induced phase shift. Further, the closed-border information was used to solve the inner 2D Dirichelet problem for the background phase to be subtracted from the acquired phase map. A single time point acquisition is therefore sufficient to provide MRT maps. The calculation algorithm does not use matrix inversion hence no singularity problem can occur.

Material and Methods. All experiments were performed on a 3T whole body MRI scanner (Magnetom Trio @ Tim system, Siemens AG, Germany). The method was tested in various configurations. HIFU sonication (256 element phased array @974kHz) was performed in degassed meat samples and *in vivo* rabbit thigh (IEB approved protocol) under PRFS MRT using a 5-slices GRE-EPI sequence with echo train length 9, TE = 8.9 ms , TR=161 ms, FA 10°, BW= 500Hz/pixel, voxel 1 x 1 x 5 mm^3, spectral lipid saturation, 0.2 to 0.4 ºC STD. To assess for the method robustness, one-step motion of large amplitude (3.5 cm) was deliberately applied to an *ex vivo* sample while continuing volumetric sonication along a 2D disk pattern of 16 mm diameter. Baseline acquisition was performed on two healthy volunteers with untriggered, GRAPPA=2 accelerated GRE-EPI,TE/TR/TA= 9ms/28.91ms/300ms, BW=930Hz/px, FOV=310mm, resolution= 2.7x2.4x8mm, FA=15°, 121 water selective pulse, flow compensation of the central echo, echo train length=7, 15 coil element, 300 ms/slice.

Results and Discussion. In static tissues under moderate heating the reference-less method provided identical results to the standard reference subtraction (± noise) even for large ROI (4-6 cm) Fig 1.f. Major improvement was obtained in moving tissues Fig.4. Accuracy as good as 0.5°C was obtained in volunteers liver under free breathing with ultra-fast acquisition (0.3s/slice), Fig 2.d. The temperature was correctly calculated along the HIFU beam due to the "aperture" provided by the open border. Following cases can be managed by the current method but not with atlas-based multi-reference MRT: tissue expansion/contraction during thermo-ablation Fig.3, liver drift (3), peristaltic-induced motion of kidney, external magnetic perturbation (interventional device) simultaneous to breathing.

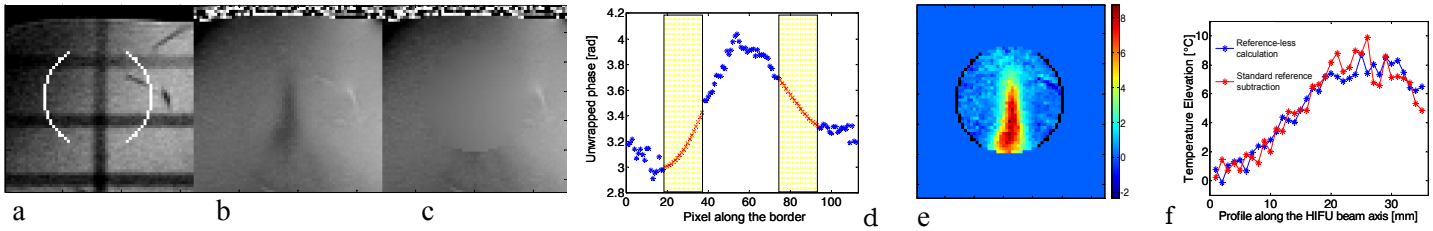


Fig.1 Illustration of the open-border reference-less PRFS MRT based on near-harmonic property of unwrapped phase map. **a).** GRE magnitude with overlaid open border (filling factor 65%) of 40 voxel diameter; **b).** unwrapped phase map as acquired; **c).** reconstructed background phase by solving the inner 2D Dirichelet problem; **d).** harmonic interpolation for the missing part of the background phase border (colored region); **e).** reference-less temperature map from a HIFU sonication, and **e).** comparison between standard subtraction and reference-less PRFS MRT in static tissue.

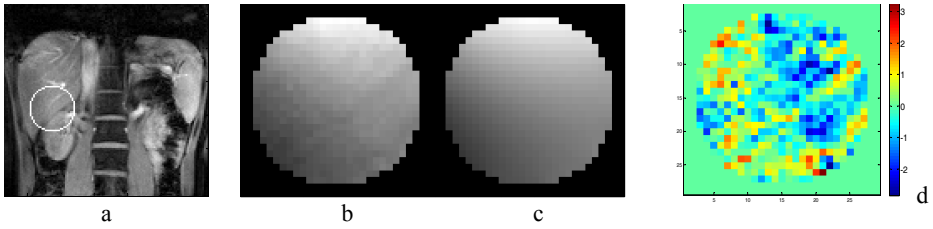


Fig.2 Accuracy of the method in healthy volunteer abdomen. **a).** Magnitude image with 65 mm diameter contour (see white circle lower liver/right kidney); **b).** Acquired phase map (unwrapped); **c).** Dirichelet-reconstructed background phase; **d).** Residual temperature error after background subtraction (i.e. baseline accuracy). Color code ±3°C. Standard deviation over the ROI is 0.51°C.

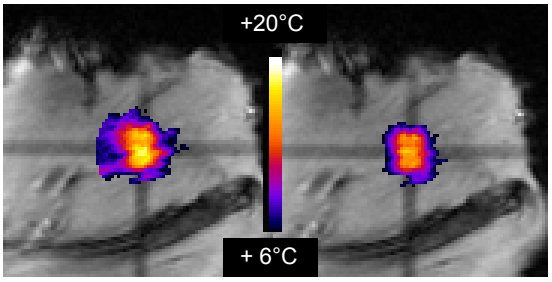
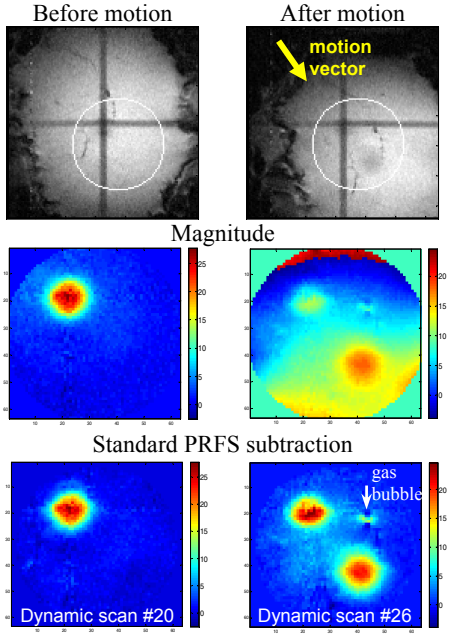


Fig 3. *In vivo* map of temperature elevation during volumetric sonication under automatic feedback control (3 x 2 interleaved HIFU foci, 4 mm gap) in rabbit thigh. Shown FOV=100 mm. **Left:** using standard PRFS subtraction, B_o offset corrected. Muscular fibers contraction produces MRT errors. **Right:** using the new reference-less method (insensitive to tissue drift)

Fig.4. Motion-robustness of the method



References. (1) Rieke V, 2004, Mag Res Med, 51, 1223-31 (2) Salomir R, 2003, Concepts Mag Res (MRE) B, 19B, 26-34, (3) von Siebenthal 2007, Med Phys 34:3620-9