Multi-planar reference-less PRFS thermometry using a linear spectral decomposition of the background phase on a base of spatial spherical harmonics

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Introduction. PRFS MR thermometry (MRT) is the generally preferred method for MR monitoring of the 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 (1,2,3) was systematically applied on slice-per-slice basis, as a two dimensional problem. The purpose of the current work was to develop and validate a novel method for multi-planar reference-less PRFS thermometry using a linear spectral decomposition (LSD) of the background phase on a base of spatial (3D) spherical harmonics.

Theory. It has been demonstrated (3) that the unheated spatially unwrapped phase in GRE image ($\emptyset_{bk}$) is a harmonic function in 3D within a homogeneous medium $\nabla^2\emptyset_{bk} = 0$. The problem was restricted to 2D (3) for slice-per-slice calculations with residual terms in the phase's Laplacian of zero and first order, so called "near-harmonic" reference-less PRFS MRT. Here, the 3D formulation of the problem motivated by the underlying Maxwell's equations no longer requires any approximation for non-zero residual terms in the phase's Laplacian. Hence, a true single pixel border can be used. The shell spherical harmonics are written here using the real functions formalism:

$$C_l^m(\theta,\varphi) = N_{lm} \cdot P_l^m(\cos\theta) \cdot cos(m\varphi)$$

$$S_l^m(\theta,\varphi) = N_{lm} \cdot P_l^m(\cos\theta) \cdot sin(m\varphi)$$

where $P_l^m(\theta)$ are the associated Legendre polynomials and $m = 0,1,\ldots l$ and $N_{lm} = \sqrt{\frac{2l+1}{4\pi}\cdot\frac{(l-m)!}{(l+m)!}}$. The background GRE phase is approximated on a spherical shell of radius R_0 as the finite summation of shell spherical harmonics :

$$\emptyset_{bk}(r = R_0, \theta, \varphi) \approx \sum_{l=0,1,2,\ldots} \sum_{m=0}^{l} [a_{lm}C_l^m(\theta,\varphi) + b_{lm}S_l^m(\theta,\varphi)]$$

The LSD coefficients a_{lm} and b_{lm} were determined by solving a linear system of l_{max}^2 equations, corresponding to the magnitude-weighted minimum sum of phase difference squares relative to the experimentally measured phase (see Fig. 2) along the three perpendicular circles that are shown in Fig.1. The background phase was afterwards reconstructed within the **entire volume of the sphere** as :

$$\emptyset_{bk}(r, \theta, \varphi) \approx \sum_{l=0,1,2,\ldots} \left(\frac{r}{R_0}\right)^l \sum_{m=0}^{l} [a_{lm}C_l^m(\theta,\varphi) + b_{lm}S_l^m(\theta,\varphi)]$$

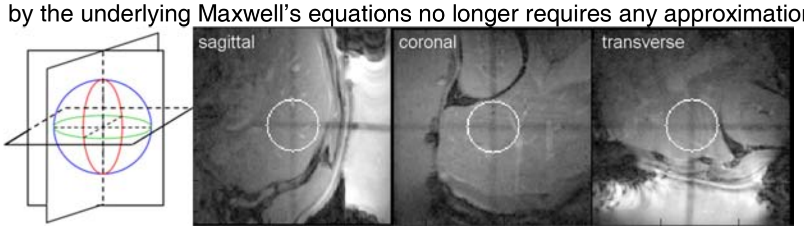

Fig.1. Left: intersection between a sphere of radius R_0 and three perpendicular slices resulting in three orthogonal circles. Right: in vivo GRE magnitude data shown for sheep liver MRgHIFU setup (FOV = 128 mm square).

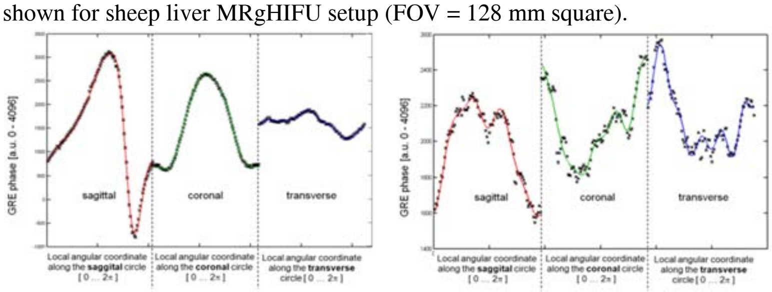

Fig.2. Approximation of the GRE experimental phase acquired along the three perpendicular circles by a finite series summation of spherical harmonics up to the order 6 (one colored segment per slice). **Left**: ex vivo tissue sample. **Right**: in vivo sheep liver, same setup as in Fig. 1.

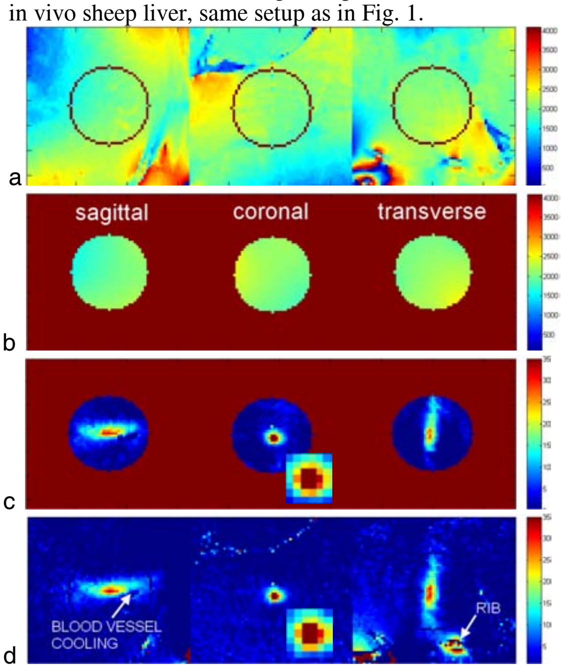

Fig.3. In vivo results (sheep liver), FOV = 64 x 64mm **a).** Native GRE phase maps measured in three perpendicular slices (no heating); **b).** The reconstructed background phase using the new method; **c).** PRFS multi-planar reference-less MRT elevation for fixed focus HIFU sonication [0 .. 35°C] scale; **d).** The corresponding respiratory gated time-referenced PRFS MRT. Note the coronal zoom-in inset.

Material and Methods. Experiments were performed on a 3T whole body MRI scanner. MRgHIFU sonication (256 element phased array f=1MHz) was performed in degassed meat samples and *in vivo* sheep liver (IRB approved protocol) under PRFS MRT using a 3 slices segmented GRE-EPI sequence (interleaved excitation) with echo train length 9, TE = 10.5 ms , TR=161 ms, FA=10°, BW= 500Hz/pixel, voxel 1 x 1 x 5 mm^3, spectral water selective 121 pulse, 0.5ºC inherent STD, temporal resolution=2.4s. The new method was confronted to the standard reference subtraction that is expected to work accurately 1) in static *ex vivo* tissues and 2) with respiratory gating in sheep liver under general anesthesia and regular forced breathing.

Results and Discussion. The new reference-less method provided very similar results to the standard reference subtraction (within ± 1°C SD) even for large ROI (>4 cm). The conditioning number of the matrix to be inversed when computing the LSD coefficients was on the order of 10^5, that is many orders of magnitude below the inverse of the floating precision of the computer (typically 10^{-15} for data type "double"). Hence, no risk of numerical singularity exists. As the spherical harmonics are inherently orthogonal, the LSD uses the minimum possible number of terms, for instance 36 terms for the series of order 6. Conversely, writing a 6th order polynomial of 3 independent spatial coordinates would yield hundreds of terms, impossible to fit because of ill-conditioned numerical problem. The computing time linearly increased with the radius of the sphere (R_0) and was typically 100ms for 12 pixels radius under Matlab running on a standard PC, demonstrating real time capability. The concept was illustrated with three orthogonal MRT slices, but it can be adapted to other multi-planar slice geometries. The method may also be used in reference-free flow measurements, or in accelerated shimming of a volume, or in quantifying the local geometrical distortion when the LSD spherical harmonics appear rotated.

References. [1] Rieke V, MRM, 2004,51:1223-31. [2] Grissom WA, MRM, 2010, 64:1068-77 [3] Salomir R, IEEE TMI, 2012, 31:287-301.