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J_ID: Z3T Customer A_ID: MRM22514 Cadmus Art: MRMT22514 Ed. Ref. No.: 10-11438.R1 Date: 21-June-10 Stage: Page: 1

Magnetic Resonance in Medicine 000:000–000 (2010)

Motion Correction in MR Thermometry of Abdominal Organs: a Comparison of the Referenceless Vs. the Multibaseline Approach

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Reliable temperature and thermal-dose measurements using AQ2 proton resonance frequency shift-based MR-thermometry for MR-guided ablation of abdominal organs require a robust correction of artefacts induced by the target displacement through an inhomogeneous and time-variant magnetic field. Two correction approaches emerged recently as promising candidates to allow continuous real-time MR-thermometry under free-breathing conditions: The multibaseline correction method, which relies on a pre-recorded correction table allowing to correct for periodic phase changes, and the referenceless method, which depends on a background phase estimation in the target area based on the assumption of a smooth spatial variation of the phase across the organ. This study combines both methods with real-time in-plane motion correction to permit both temperature and thermal-dose calculations on the fly. Subsequently, the practical aspects of both methods are compared in two application scenarios, a radio frequency-ablation and a high-intensity focused ultrasound ablation. A hybrid approach is presented that exploits the strong points of both methods, allowing accurate and precise proton resonance frequency-thermometry measurements during periodical displacement, even in the presence of spontaneous motion and strong sus-AQ3 ceptibility variations in the target area. Magn Reson Med 000:000–000, 2010. ©2010 Wiley-Liss, Inc.

Key words: artifacts; technique development; technical research; correction; susceptibility

INTRODUCTION

MR-thermometry based on the proton resonance frequency shift (PRF) of moving targets, such as the abdominal organs, is complicated by the continuous target motion through an inhomogeneous and time-variant magnetic field. This causes thermometry artifacts, for which several correction strategies have been proposed in the past, such as respiratory gating (1), navigator echoes (2), multibaseline acquisition to sample periodic changes (3,4), and referenceless phase corrections (5). In particular, the latter two approaches emerged recently as promising candidates to allow continuous MR-thermometry of abdominal organs under free-breathing conditions.

As both methods represent a valid solution to the problem, this article highlights the particular limitations and strong points of both methods for the two typical application scenarios of a minimally invasive radio-frequency (RF) ablation and a noninvasive high-intensitive focused ultrasound (HIFU) ablation. Subsequently, a hybrid approach is suggested which exploits the advantages of each method and circumvents their particular limitations. This is achieved by extending a previously proposed processing pipeline for motion stabilized PRF-based MR-Thermometry (6), which was based on a multibaseline correction only, with an additional processing module permitting referenceless MR-thermometry as suggested by Rieke et al. (5). All three methods are subsequently used to assess the temperature evolution of an ex vivo RF-ablation in calf liver and an in vivo ultrasound ablation on a porcine kidney, and compared with respect to their methodological advantages and limitations.

MATERIALS AND METHODS

General Strategy

Rapid single shot, single slice gradient recalled EPI imaging was used to avoid intrascan artifacts and obtain high temporal resolution. The scan slice is aligned parallel to the main direction of displacement to reduce the effect of motion to a 2D in-plane displacement. The incoming images are first coregistered on a voxel-by-voxel basis to a common reference position and then subjected to either a multibaseline phase correction, a referenceless phase correction or the hybrid correction.

The temperature maps for all three methods are calculated on-the-fly (i.e., before the calculation of the next temperature image). Subsequently, a temporal filtering based on an infinite impulse-response filter is applied to the temperature maps to increase the signal-to-noise ratio (SNR), and finally the thermal dose is calculated.

In-Plane Motion Compensation

As the employed image registration algorithm is described in detail by Roujol et al. (6), only a short summary is given here.

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Grant sponsor: Diagnostic Molecular Imaging (EC-FP6-project); Grant number: LSHB-CT-2005-512146; Grant sponsors: Ligue Nationale Contre le Cancer, Conseil Régional d'Aquitaine, Agence National de Recherche (project MRgHIFU-ALKT), Fondation InNaBioSanté (project ULTRAFIT), AQ9 Philips Medical System.

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Received 12 February 2010; revised 25 March 2010; accepted 27 April 2010.
DOI 10.1002/mrm.22514
Published online in Wiley InterScience (www.interscience.wiley.com).

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The target area is preselected in a preparative step by a user defined region-of-interest (ROI) on a chosen reference image. During real-time imaging, the target area of each incoming image is coregistered to the reference image using a principal displacement component (PDC) estimation of six free parameters (two translations, a rotation, a scale and two shears) (7). This serves as a preconditioning for a second hierarchical multiresolution optical flow based image registration algorithm which provides 2D displacement vector fields on a voxel by voxel basis (8). Note that all corrections are estimated on the T_2* weighted magnitude images but applied to the complex MR-images to avoid interpolation problems with spatial phase wraps.

Multibaseline MR-Thermometry

This approach requires a preparation step before the actual intervention, in which *N* magnitude together with the coregistered phase images and the corresponding displacement vector fields are collected in a look-up table. Subsequently, the table is ordered according to the PDC amplitude derived from the displacement vector fields and phase-unwrapped on a pixel-by-pixel basis across the table. Finally, the coefficients of a system of *N* equations expressing the unwrapped registered phase (ϕ_t) of each individual voxel as a linear combination of the six PDCs are solved using a singular value decomposition (SVD), as described in detail by Roujol et al. (6). This step can be seen as the adaptation of a linear model of the magnetic field change dependent on the individual displacement of each voxel.

This model is used in the interventional phase to resynthesize a corresponding background phase image from the displacement vector field of each newly arriving image.

Although, recent MRI designs have excellent spatial magnetic field homogeneity, their field is not entirely stable over time when sustained high frame-rate imaging is applied (9). Therefore, the subtraction of phase images acquired at different times can be affected with a different bias for each pixel (10). In this study, this perturbation is corrected by subtracting a global temperature offset [a magnitude-weighted average is used to give less importance in low SNR areas (11)] obtained from a ROI which is chosen in the moving organ, adjacent to the ablation area.

Referenceless MR-Thermometry

In this approach, a background phase estimate is obtained by fitting a polynomial function to the measured phase obtained from a ROI outside the treatment area, which is assumed to remain at body temperature as described by (12). To avoid fitting problems due to spatial phase wraps, phase-unwrapping is applied in the ROI before fitting (13,14). The appropriate size and location of the ROI as well as the optimal polynomial order for the phase fit are determined before heating. In the presented experiments a polynome of fifth order adapted by a signal-magnitude weighted least-squares fit was found sufficient to represent the phase function outside the heated region.

Combined Multibaseline and Referenceless MR-Thermometry

The hybrid approach employs initially the multibaseline algorithm to continuously provide temperature maps across the entire field of view. In addition, these temperature maps are also used to dynamically update the preparation parameters of the referenceless algorithm:

1. The fitting ROI is continuously adjusted: For this, the multibaseline temperature map is thresholded (all values above 2.0°C are discarded) and subsequently eroded by one voxel.
2. This ROI is used to calculate a referenceless temperature estimate. The difference between the temperature estimate obtained with multibaseline and with referenceless is retained as an offset correction.

Should a spontaneous movement occur during the intervention, for which no reference phase is prerecorded, the processing pipeline switches dynamically from multibaseline to referenceless MR-Thermometry using the most recent fitting ROI and correction. The criteria used to detect spontaneous motion is based on the observed two translations and the rotation of the PDC-estimation: Any currently detected translation or rotation exceeding the value range observed during the preparation phase by more than 0.5 voxel (translation) or 0.5° (rotation) is considered a spontaneous movement and leads to the algorithm transition.

Experimental Set-Up

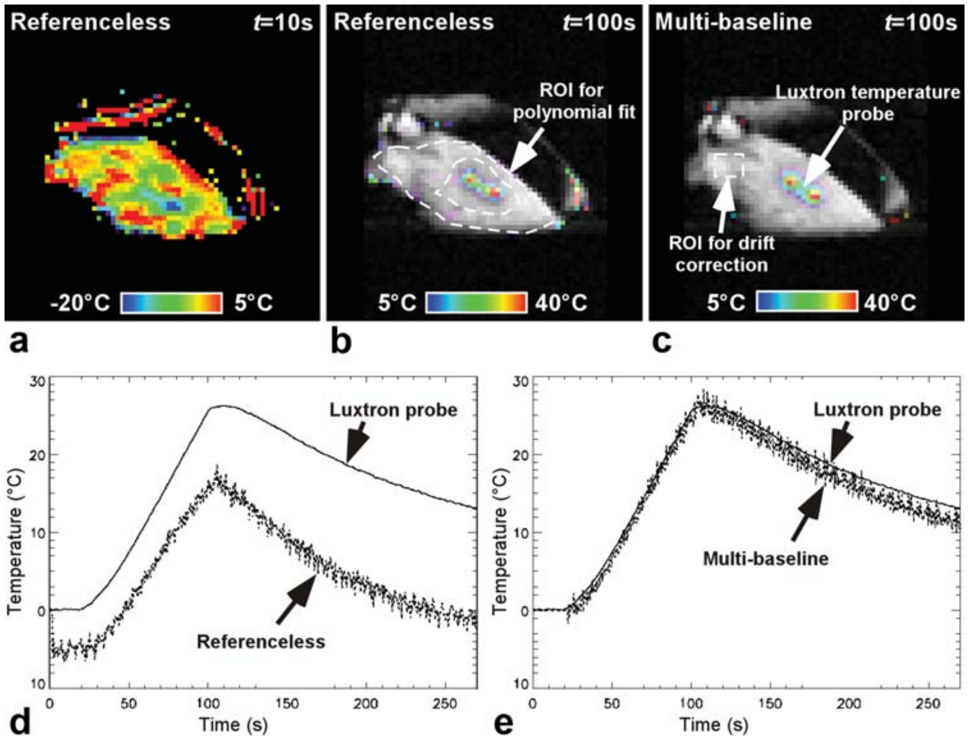
MRI Imaging

All imaging was performed on a 1.5 T Philips Achieva scanner, using either the integrated phased array coil of the HIFU system or for RF-heating a loop-shaped surface coil (20 cm diameter) for signal reception. Dynamic MRI was performed with a gradient recalled EPI sequence using a 121-binomial water-selective excitation pulse.

Phantom Heating Study Using RF

Physiological motion, with a periodic purely in-plane displacement in read-out (frequency encoding) direction, of an amplitude of 22 mm and a period of 6 secs, was simulated by mounting a calf liver on a motorized platform. The following acquisition parameters were used: 3000 dynamic coronal images, single slice, TR = 18 msec, TE = 8.8 msec, 14 images/sec, FOV = 256 × 88 × 6 mm^3, matrix 128 × 44, multishot acquisition with 11 lines per excitation, Band-width per pixel = 1.7 kHz. Three-hundred images were acquired before hyperthermia to allow precise sampling of the periodical displacement for the multibaseline method. Subsequently, the tissue was heated with 8 W of RF-power during 85 secs using bipolar electrodes, placed 1.2 cm apart.

The accuracy of the MR thermometry was evaluated using the readings of a fiber optic probe as a gold standard. The fiber optic probe (Luxtron STB Medical, LumaSense, France) was placed between both electrodes, and



C O L O R

FIG. 1. MR-Thermometry results obtained on the phantom heating with RF. **a**: Temperature map obtained using the referenceless approach before heating. Two hot spots are observable around the two electrodes although no heating is performed. **b**,**c**: Temperature maps obtained after 80 secs of heating using the referenceless (b) (the ROI used for the polynomial fit is reported in dashed lines) and the multibaseline approach (c). **d**,**e**: The comparison between the PRF-based MR thermometry (dashed line) and the reference temperature measured with the optical fiber thermometer (solid line) (white arrow in (c)) with the referenceless (d) (the ROI used for the polynomial fit is reported in the dashed plot) and with the multibaseline approach (e) (the ROI used for drift correction is reported in the dashed plot).

its position identified by additional high-resolution spin-echo (SE) imaging. The precision of the MR thermometry was quantified during the cool-down period (time interval 120–250 s) using the standard deviation between MR measurements and a fitted exponential decay curve.

To evaluate the influence of spontaneous motions, the experiment was repeated under periodical motion and a singular lateral displacement of 1 cm amplitude and 1 sec duration was introduced after 50 sec of MR-thermometry, whereby the sample did not return to its original position.

In Vivo Heating Study Using HIFU

MRI guided HIFU was performed in vivo in the kidney of a pig under general anesthesia. The following acquisition parameters were used: 1500 dynamic sagittal images, single slice, TR = 100 msec, TE = 41 msec, single-shot EPI sequence, bandwidth per pixel = 2085 Hz, flip angle = 35°, FOV = 320 × 140 × 6 mm^3, matrix = 128 × 56, using the integrated phased array coil of the HIFU system. One-hundred images were acquired before the beginning of the sonication, allowing a precise sampling of the motion pattern for the multibaseline method. Heating was then performed for 60 secs with an acoustic power of 100 W using a Philips HIFU-platform (Philips Healthcare, Helsinki, Finland), consisting of a 256 element phased-array transducer integrated in the MR-bed. The transducer radius and aperture were 120 mm and 126 mm, respectively, and the focal point size 1 × 1 × 7 mm^3. The animal was placed in right lateral decubitus position so that the right kidney was accessible through an unobstructed beam-path directly below the rib-cage. The focal point position was dynamically adjusted with respect to target displacements using the method described in (15).

RESULTS

Phantom Heating Study Using RF

Figure 1 shows the temperature maps of the RF-heating experiment at peak temperature for the referenceless (a,b) and the multibaseline method (c). The two hot spots observable in 1b,c represent the temperature rise in the proximity of the two RF electrodes. The precision of the temperature, when no correction is applied, was evaluated in the heated region before hyperthermia. Apparent temperature fluctuations of up to 40°C (peak-to-peak) were measured although no heating was performed. F1

The multibaseline method provided artifact-free temperature maps over the entire object and allowed to follow the induced temperature change during the entire duration of the experiment, as shown in Fig. 1c. Compared to the reference measurement obtained with the fiber optical probe, the accuracy of the measurement was found to be below 0.9°C off the true value for the first 150 sec of the

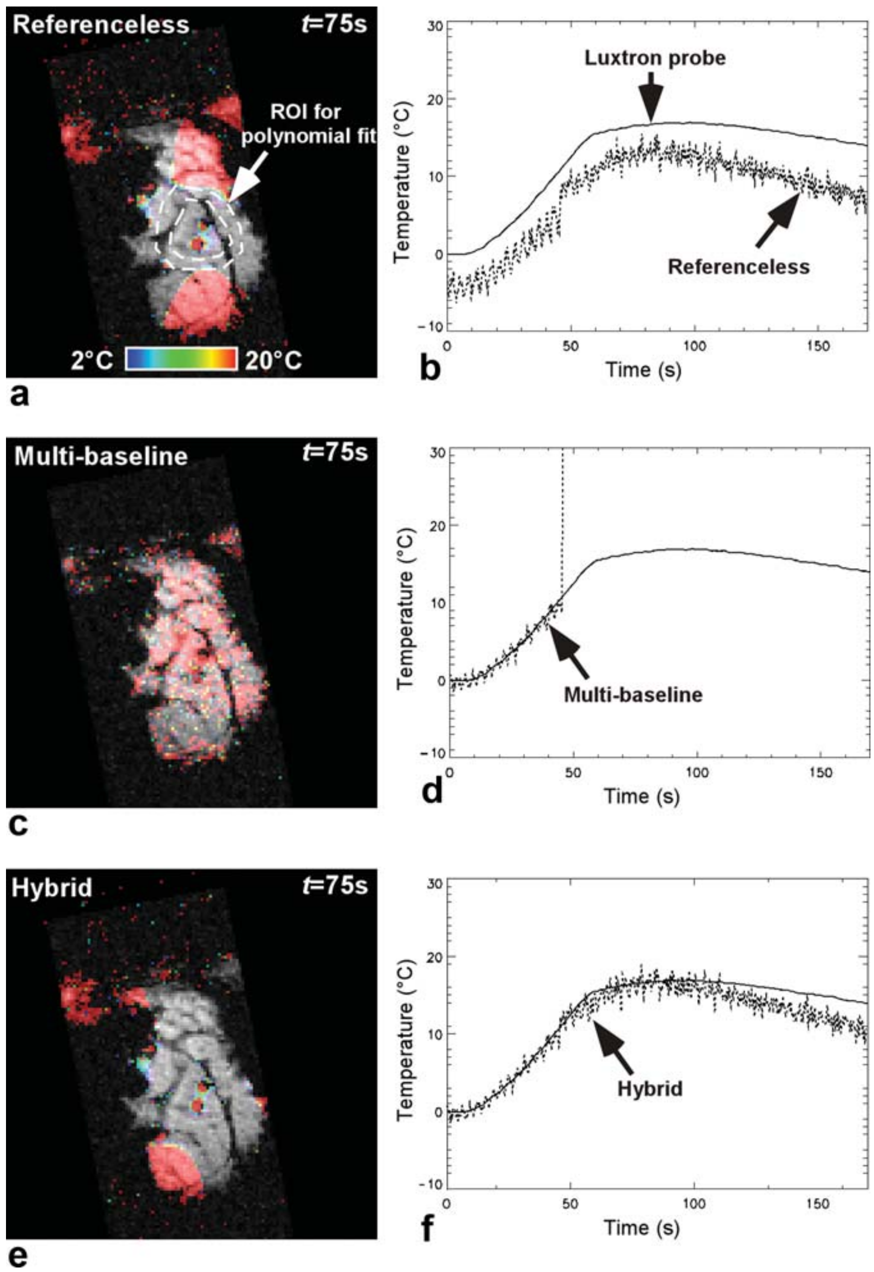


FIG. 2. MR-Thermometry maps obtained 25 sec after the occurrence of a spontaneous motion event (at $t = 50$ sec) of the referenceless (**a**), the multibaseline (**c**) and the hybrid (**e**) approach and the corresponding temporal evolution at the position of the Luxtron probe (**b,d,f**). The accuracy of the referenceless approach is limited by its ability to cope with the local magnetic field variations in the vicinity of the RF-electrodes which leads to an offset (b). Furthermore, the static ROI choice leads to a discontinuity at the point of the motion event. As the multibaseline approach can not cope with this type of motion, it is not able to provide meaningful temperature readings after the event (artifact >50°C). Note that the hybrid approach follows closely the true temperature evolution.

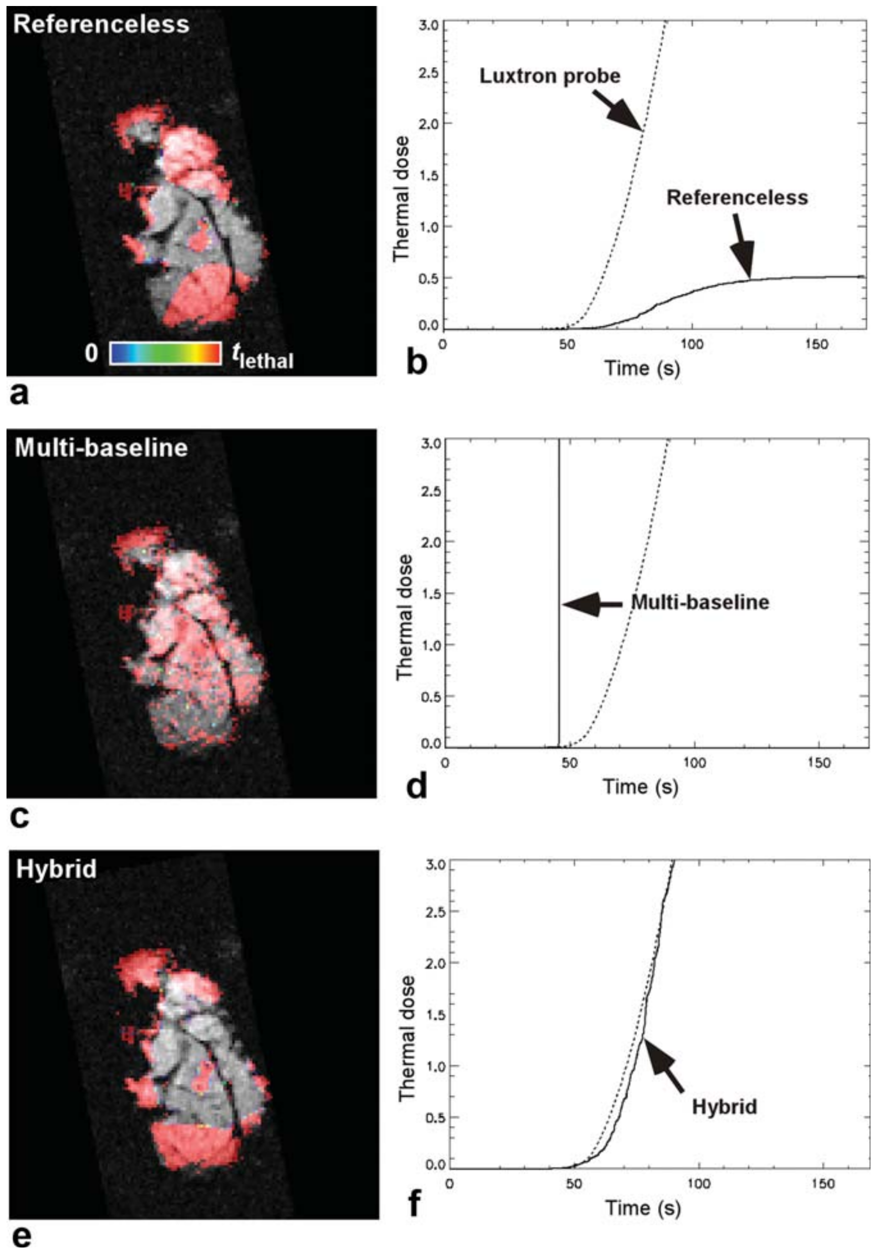
experiment and degrading subsequently to a systematic offset of −2°C towards the end of the experiment. The precision of the measurement was determined as ±0.75°C. Similarly, the estimated thermal dose in the control point was found in close correspondence with the values calculated from the probe readings: Both methods estimate the absorption of the lethal dose after 80 sec.

In comparison, the temperature measurements obtained with the referenceless-method showed temperature variations even before the application of RF-power. This effect was found to be induced by the susceptibility variations of the RF-electrodes which cause local distortions of the magnetic field. As these field modifications do not extend into the ROI, the fit results in a poor representation of the true background phase. As a result, the distortion pattern of the electrodes impairs the accuracy by offsetting the temperature readings by −20°C in the direct vicinity of each electrode and by up to +8°C in the intermediate area, as shown in Fig. 1a.

Furthermore, this offset was found to change progressively during the experiment as shown in Fig. 1d: The offset evolves from the initial −6 to −15°C towards the end of the experiment whereby the measurement noise of ±0.69°C remained constant. As a consequence, the calculated thermal dose estimated the absorption of the lethal dose 25 sec later than the estimation based on the fiber-optic readings.

Spontaneous Motion Study Using RF

Similar to the previous experiment, the temperature measurements using the referenceless approach were



COLOR

FIG. 3. Thermal dose maps (25 sec after spontaneous motion event) and temporal evolution of the thermal dose at the location of the Luxtron probe for all three methods. Dosimetry based on the referenceless approach systematically underestimates the true thermal dose in this example, but is not affected by the motion event. In comparison, the multibaseline approach is not able to provide meaningful thermal dose estimates after the spontaneous displacement. Note that only the hybrid approach provides a high degree of accuracy during the entire intervention.

found biased by local magnetic field variations, which are not correctly reproduced by the polynomial fit as
F2 shown in Fig. 2a,b. As a result of this offset, the calculated thermal dose values also underestimate the true thermal dose at the location of the probe position. However, besides a small discontinuity of ~4°C, the referenceless method is well able to provide precise temperature readings despite the singular occurrence of spontaneous motion (periodical motion is present during the entire experiment).

Although the multibaseline method was initially able to provide accurate temperature readings during the presence of periodical motion only, the method was found unable to cope with spontaneous motion. Since the induced motion event de-validated the prerecorded correction data, all subsequent temperature measurements showed large fluctuations of up to 50°C as shown in Fig. 2c,d. Consequently, the calculation of the thermal dose did not provide meaningful values as shown in Fig. 3c,d. F3

Contrary to the previous two methods, the hybrid approach provided accurate temperature and thermal-dose estimates over the entire duration of the experiment. The transition between "multibaseline mode" and "referenceless mode" was triggered by the automatic detection of the motion event and did not introduce any apparent degradation of MR-thermometry except a change in measurement precision, as shown in Fig. 2f.

On-Line In Vivo Study Using HIFU

Figure 4 shows the temperature maps of each method obtained after 55 secs of sonication (t = 75 sec) with the corresponding temperature evolution at the focal point F4

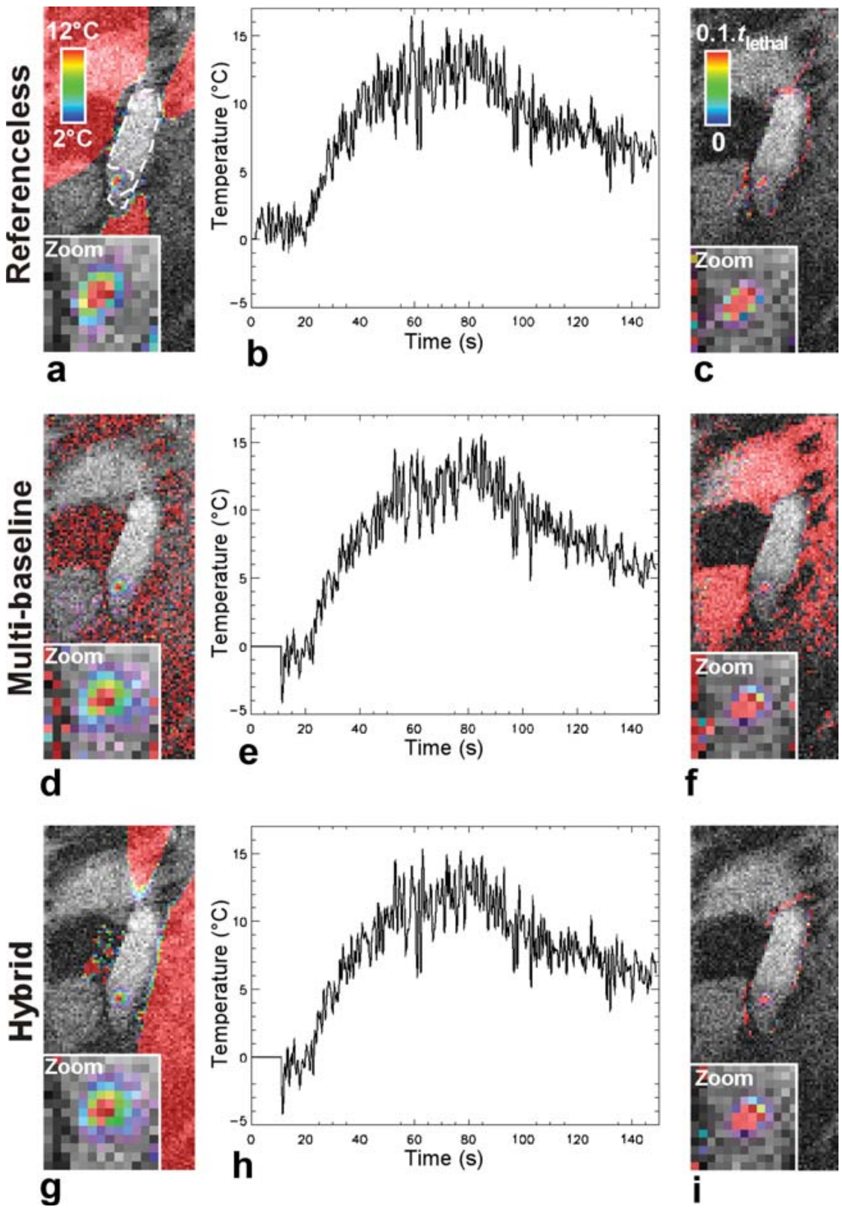


FIG. 4. MR-Thermometry results obtained on a pig kidney during HIFU ablation. Images (**a**), (**d**), (**g**) show the temperature maps after 55 secs of sonication for the referenceless, the multibaseline and the hybrid approach, respectively. The corresponding temporal evolution of the temperature at the position of the focal point is shown in the graphs (**b**), (**e**), (**h**). Note that for the hybrid the correction method was switched 10 secs before the end of the sonication ($t = 50$ sec) from "multibaseline" to "referenceless". The corresponding thermal dose estimations obtained at the end of the experiment are displayed in the images (**c**), (**f**), (**i**). Note that the referenceless appears slightly elongated in the direction of the boundary of the organ. This effect can be attributed to the asymmetry of the fitting ROI.

position. In absence of any phase correction strategy, apparent temperature fluctuations of up to 8°C (peak-to-peak) were observed in the target area. All three correction approaches lead to a comparable observation of the temperature evolution (+12°C peak temperature at $t = 80$ sec), which leads to a final thermal dose of 45% (referenceless), 33% (multibaseline), and 28% (hybrid) of the lethal dose (which is taken as 43°C during 240 min). The higher thermal dose value of the referenceless correction can be attributed to a ~1°C residual offset compared to the other two correction approaches.

As a noninvasive heating device was used, no strong susceptibility variations were observed in the heating region, and only 1°C of temperature baseline offset was measured using the referenceless approach at the focal point position. However, since the ablation area is located in the vicinity of the organ boundary, an optimal placement of the ROI was found essential to achieve consistent results. Compared to the multibaseline approach, the temperature and thermal dose maps are slightly elongated in the direction of the organ boundary, which was found to be a consequence of the asymmetry of the fitting ROI.

Although in this experiment no spontaneous motion event occurred, the feasibility of the hybrid correction for in vivo experimentation was evaluated by triggering a transition from "multibaseline mode" to "referenceless mode" 50 sec after the start of the experiment, as shown in Fig. 6. Besides a change in measurement noise, no additional thermometry artifacts were observed. AQ4

DISCUSSION

Multibaseline MR-Thermometry

As shown in Figs. 1, 2, and 4, PRF-thermometry based on the model correction allows an accurate correction of susceptibility related phase changes even in regions with complex susceptibility distributions or signal discontinuities, such as organ boundaries or in the vicinity of laser or RF probes.

However, the model correction for susceptibility related phase changes is designed to correct MR-thermometry artifacts in abdominal organs which are subject to a periodic displacement due to the respiratory cycle. As phase variations are "learned" in a preceding learning step and subsequently applied to correct the MR-thermometry during the intervention, the method can intrinsically not correct for MR-thermometry artifacts associated with spontaneous motion, as shown in Fig. 2c. Although the correction is not entirely constrained to positions present in the collection, as it can also interpolate intermediate positions, the observation of a significant deviation of the pre-recorded motion pattern requires to discard the image data and, for the case that the change is not reversible, leads to the necessity of a complete recalibration of the phase correction data. This is a disadvantage compared to the referenceless method which is not restricted to periodical motion, as shown in Fig. 2a. The impact of this disadvantage depends in practice on the frame-rate of the employed imaging sequence. In the presented example of subsecond sampling, a recalibration can be completed in the relatively short time of two to five respiratory cycles. However, for the case of low frame-rate imaging a complete recalibration leads to long interruptions of the temperature measurements and thus to potentially unacceptable interruptions of the intervention.

Another drawback of MR-thermometry using a phase reference compared to the reference-less methods is that magnetic field drifts are not inherently corrected. MR-thermometry for interventional applications requires in general sustained high frame-rate imaging which may lead to spatio-temporal fluctuations of the external magnetic field (9). These fluctuations have been observed due to frequency drifts of the exciter/receiver system (16), or by temperature changes in the shimming material of the scanner due to the high load on the gradient coils (9). Since referenced methods compare the image phase at the beginning of the intervention to a later phase, these fluctuations or drifts are interpreted incorrectly as part of the temperature evolution. This effect can in general be addressed with a 1st order temporal drift correction based on an offset obtained from an adjacent ROI. The ROI has to be chosen sufficiently far to be unaffected by hyperthermia, but close enough to display a similar temporal evolution of the field drift than the target area. Whether both conditions remain fulfilled during the entire experiment, is in practice a priori hard to evaluate, as it can be seen in Fig. 1e: The indicated ROI, which is used for the drift correction, was chosen sufficiently far from the ablation area to avoid contamination through thermal diffusion, but shows over time a different temporal drift behavior than the ablation area, which in turn leads to a systematic underestimation of the target temperature towards the end of the experiment.

Referenceless MR-Thermometry

In comparison, problems associated with a apriori choice of a ROI are even more pronounced for the referenceless approach: Since the required phase reference used for the PRF-calculations is derived from a polynomial fit, its quality depends largely on optimal ROI placement, size, and shape. Ideally, the fitting ROI should encompass the ablation area, should be sufficiently close to allow a precise estimation of the background phase in the target area, but at the same time also be sufficiently far to avoid contamination of the fit due to heat diffusion/conduction, and not encompass areas displaying strong local susceptibility variations.

In general, all four required conditions can be well fulfilled when the ablation is carried out using a noninvasive heating modality in areas showing a uniform susceptibility distribution. An example of such an application are HIFU ablations in the center of the liver, where the referenceless approach has been shown to lead to reliable and precise results (17).

The limitations of the referenceless approach compared to multibaseline approaches become evident when application scenarios are considered that do not permit to fulfill all four conditions simultaneously, such as minimally invasive ablations, or interventions at the boundary of organs:

In the first presented example, strong local B_0 variations, which are typically present in the ablation area when invasive ablation devices such as RF-electrodes, laser-fibers or cryo-ablators are employed, have a strong influence on the local phase. These local variations can not be modeled by a polynomial fit based on far field data. This in turn leads to incorrect estimates of the background phase and consequently to temperature offsets in the vicinity of the device as shown in Figs. 1a,d, and 2b. Therefore, due to the exponential dependence of the thermal dose on the temperature, these systematic offsets have a large impact on the accuracy of the time estimate when the necrosis occurred, as shown in Fig. 3b.

Furthermore, the presented experimental data also displays the problems associated with underestimating the extent of heat conduction/diffusion when placing the fitting ROI before the ablation. After the application of a background phase correction (i.e., $T_n - T_0$), the relative temperature change of the referenceless approach shows an increasing bias of up to 9°C compared to the implanted temperature probe. This is probably due to the fact that heat diffusion towards the end of the experiment contaminates the phase in the fitting ROI, which in turn leads to a systematic underestimation of the temperature in the ablation area.

The in vivo experiment demonstrates accuracy limitations when the ablation area is in the vicinity of an organ boundary and does not allow the fitting ROI to encompass the ablation area. In this case, the polynomial fit can not be used to interpolate the background phase, but to perform an extrapolation. This leads to reduced precision of the fit, in particular since the susceptibility variations on the organ boundaries lead to large B_0 fluctuations. This can be seen by comparing the temperature evolution obtained with both methods in Fig. 4b,e. The temperature curve obtained with the referenceless method is slightly higher (~1°C) compared to the curve obtained with the correction based on a multibaseline correction. Note that the presented referenceless data is the best of several attempts to place a suitable ROI around the ablation area which produces a temperature evolution with a peak temperature comparable to the phase model.

Combined Multibaseline and Referenceless MR-Thermometry

Due to the fact that the main limitations of multibaseline and referenceless MR-thermometry are largely complementary, the presented hybrid approach represents an attempt to overcome these limits by combining both approaches.

Although multibaseline MR-thermometry is able to provide accurate temperature and thermal dose measurements in the presence of periodical motion over the entire field of view, its main limitation is its inability to cope with spontaneous motion. The hybrid approach compensates for this inability by switching automatically to a polynomial fit for background phase estimation when such an event is detected, which is similar to the approach used for the referenceless method. However, the two main disadvantages of the referenceless method, its dependence of the accuracy of the selection of the fitting ROI location and, in particular when mini-invasive interventions are considered, its inability to provide background phase estimates which include the effect of strong local susceptibility variations, are thereby avoided: The initial observation of the temperature evolution using multibaseline MR-thermometry allows to continuously adapt the fitting ROI to avoid the inclusion of heated or unstable areas and to provide an offset correction which removes the effect of local susceptibility variations. Note that although the polynomial fit for the background phase estimation is similar to the referenceless method, the latter correction represents a phase reference (i.e., the hybrid approach is never truly "referenceless").

However, the proposed hybrid approach can not eliminate all the limitations of the multibaseline and the referenceless methods. The hybrid still requires a lengthy initial acquisition of a phase correction dataset and inherits the accuracy limitations for long experiments of both methods, either due to a possible contamination of the fitting ROI due to heat diffusion, or due to an imperfect spatio-temporal B_0 drift correction, depending on the operation mode.

Motion Correction

In this study all incoming images are first coregistered on a voxel-by-voxel basis to a common reference position similar to Ref. (6). Compared to the originally proposed implementation of the referenceless approach by Rieke et al. (5) and its refined implementation by Holbrook et al. (17), this preparational step is a significant improvement:

First, the ROI used for the polynomial fit remains valid for all target positions, independent of the actual presence or the knowledge of the spatio-temporal evolution of the temperature in the target area. Holbrook et al. suggest a spatial adaptation of the ROI position based on the successful detection of the focal point position on the temperature maps. However, since the result of the referenceless MR-thermometry depends on the choice of the ROI position, the presence of one temperature artifact during the experiment can destabilize all successive measurements. Furthermore, the approach of Holbrook et al. allows the motion correction only to be applied after a significant temperature rise has already been achieved, i.e., after the beginning of the intervention.

Second, since the presented approach corrects motion on a voxel-by-voxel basis during the entire respiratory cycle independent of the form or even the presence of any temperature evolution, it is fully compatible with volumetric ablation patterns, diffusion effects and also permits the calculation of the thermal dose for on-line necrosis estimates, similar to the approach suggested by (6).

CONCLUSION

Temperature and thermal-dose measurements using PRF based MR-thermometry in abdominal organs are complicated by the bulk displacement of the target, which hamper direct voxel-by-voxel comparisons, and the additional phase variations which are introduced by the target displacement through an inhomogeneous and time-variant magnetic field.

Provided that a suitable motion correction addresses the problem of bulk displacement, both the multibaseline and the referenceless approach generally allow to eliminate dynamic phase artifacts and thus to follow the temperature and thermal dose evolution with comparable accuracy and precision. Since both methods differ more in their practical aspects, the choice of the most suitable approach depends largely on the particular requirements of the application scenario:

For noninvasive ablations deep within abdominal organs, the referenceless approach was found to be a robust and simple solution, which is not hampered by time-consuming preparations and the complexity of additional corrections for the effects of temporal drifts or occasional spontaneous motion. Its main disadvantages, the accuracy dependence of the ROI placement and its limited ability to provide accurate results in areas with strong local susceptibility variations, are of little practical consequence in this type of application scenario.

For interventions that require accurate temperature estimates over larger areas, or in areas with strong local B_0 variations, such as in the vicinity of invasive ablation devices, major vessels or organ boundaries, the multibaseline approach was found to lead to more accurate results and thus appears to be the method of choice. Nevertheless, the fact that the multibaseline approach is unable to cope with spontaneous motion and also requires additional preparation time, has to be carefully taken into account, in particular when paired with low frame-rate imaging.

However, for the case of generic applications, where the presence of exclusion criteria of either method are a priori not entirely known, a pragmatic way forward to guarantee accurate and precise temperature and thermal dose estimates, is to tailor a suitable combination of multibaseline and referenceless MR-thermometry. The presented hybrid approach represents one of several possible solutions for such a combination and demonstrates that it is possible to achieve accurate and precise PRF-Thermometry during periodical displacement even in the presence of spontaneous motion and strong susceptibility variations in the target area.

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