Gradient cumulative filtering to detect MRI thermometry artifacts

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Abstract— **Magnetic resonance imaging (MRI) thermometry is applied for guiding thermal therapy of tumorous tissues using high-intensity focused ultrasound (HIFU). Fast imaging sequences are needed for the on-line MRI operation, and strong artifacts on the temperature map can be found especially for image regions having poor signal-to-noise (S/N) ratio. Detection and masking of the regions with unreliable temperature measurement would be important to avoid unnecessary notification of the HIFU operator or even cancelation of the sonication procedure. This paper presents a specific image processing procedure to improve detection of typical MRI thermometry artifacts. First a region for well behaving temperature map is selected. Then, the remaining region of distorted temperature surface is processed with a novel method using oriented filter on the surface gradient. The result gives a more stable surface over the artifact regions, which can be used further to improve consistency in detection and masking of the temperature errors. Evaluation data is from N=7 patients having thermal therapy for uterine fibroid, including about 300 different sonications and 30,000 MRI thermometry images. The results show that the suggested method decreases variance of the temperature difference between consequent image frames in comparison with a conventional method using 2D phase unwrapping.**

I. INTRODUCTION

TEMPERATURE mapping with MRI for guiding the high-intensity focused ultrasound (HIFU) therapy of tumorous tissue is most often based on proton resonance frequency (PRF) shift thermometry method [1]. The phase difference between two images, acquired with MRI gradient-recalled echo (GRE) sequence, can be converted to a temperature change in aqueous tissue by:

$$\Delta T = \frac{\Delta \phi}{\nu \alpha B_0 t_E}, \qquad (1)$$

$\Delta \phi$	measured phase difference
ν	gyromagnetic ratio
α	PRF shift coefficient
B_0	magnetic field strength
t_E	MRI GRE echo time

The temperature change map (Tmap) is calculated on-line by selecting the first phase image of the sonication set as a reference and calculating the difference with the current phase image. However, the phase is not uniquely defined but given as modulo 2π radians, and the resulted Tmap surface includes discontinuities from the phase wraps. The standard method to resolve a continuous surface in MRI thermometry applies phase unwrapping, by making assumptions about zero phase difference over the manually selected reference region, which is recommended to contain homogeneous tissue, and where the true temperature effect is assumed to be negligible. Also, some time trend removal of cumulating phase errors can be done based on the selected reference region.

The PRF shift thermometry also has many artifacts, and especially variation in the magnetic field, caused by non-homogeneity in the magnetic susceptibility of tissue, can distort the measured temperature map. Typically, progressing and reshaping of inner body gas in moving organs or intestines may induce either increased or decreased false temperature values extending over several centimeters in distance. Detection of the unreliable Tmap regions would be important to prevent unnecessary stopping of the sonication by the operator.

The goal of the MRI temperature artifact modeling is either to mask out the unreliable Tmap regions or in the best case estimate the correct temperature. In the literature, the latter goal has been addressed most often, either by compensating the respiratory and heart beat induced cyclic motion by using set of multibaseline phase images [2], or alternatively using self-reference method by estimating the correct baseline surface by e.g. polynomial fitting [3]. However, these both methods are restricted especially by homogeneity of the tissue, and unfortunately are not always applicable. In the current practice, the unreliable Tmap regions are masked out based on both estimating the MRI signal to noise ratio and analyzing the variability of the measured temperature.

Our purpose is to develop an enhanced artifact detection method by modeling the dynamics of the artifacts. However, the complexity of the MR phase image data makes such artifacts modeling difficult. The phase wraps over 2π radians appear as contour curves with discontinuation in the phase map surface. At the same, the phase values at neighboring image pixels may show totally different time behavior if they are by chance separated by such a phase wrap curve. Many different unwrapping algorithms have been developed to form a continuous phase image surface, in principle by shifting the wrapped regions with exact integer multiples of 2π radians. However, over the under-sampled phase surface with steep gradient and poor S/N ratio, and especially at the MR thermometry artifacts regions, the unwrapping may become unstable.

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In this paper we show a more robust method to estimate a continuous temperature surface over the artifact regions, by leaving out the constraint of having exact phase unwrapping with integer multiples of 2π radians. In the result section, we shall measure the consistency between consequent frames for the corrected Tmap images and make comparison between the suggested method and a conventional 2D phase unwrapping method.

II. METHODS

A. *Measurement protocol*

MRI thermometry data were collected for seven patients having the HIFU thermal therapy for the uterine fibroid. Three coronal and one sagittal imaging slice positions, centred at the sonication cell, were used in this study. The image size was 160x160 pixels with 2.5 mm resolution. As an average, each sonication and follow up period took about 75 seconds time in total, and images for each slice position were taken with 3 seconds sampling period. HIFU therapy of uterine fibroid includes multiple sonications to cover the target volume, and altogether 295 different sonications and approximately 30,000 Tmap images were used in this study. New algorithm method was tested with Matlab using standard toolbox packages.

B. *Algorithm*

Our purpose is to estimate the smoothed surface of the temperature artifacts over the regions including wrapped phase or poor S/N ratio. The developed GradCum method includes multiple steps, specifically modified for processing of the phase images. Fig. 1 shows the GradCum method block diagram. Firstly, the increased temperature region over the sonication cell, i.e. hotspot, is masked out to continue with detection of the temperature artifacts only. Then, the continuous non-wrapped *base region* of the phase image is selected and smoothed. This region can be converted into temperature values directly with the PRF shift equation (1) but may already include temperature artifacts. The remaining surface region is estimated based on the phase image gradient. Finally, the estimated surface is aligned with the smoothed Tmap in the *base region* starting from the border between regions.

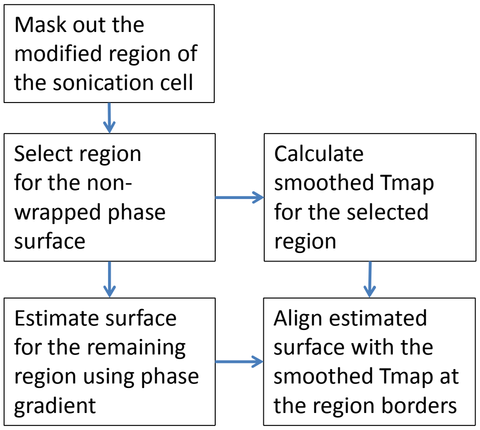

Fig. 1. Block diagram of the suggested GradCum method.

Fig. 2 shows an example of the GradCum method with intermediate steps. First graph shows MRI intensity image in sagittal plane over the abdominal region, showing large sized uterine fibroid in the middle. The anterior-posterior direction is from left to right, and the left side border shows part of the skin and the upper right corner shows a small fraction of the tail bone. The grid is given in pixel units, and total graph area corresponds approximately 140 mm in height and 170 mm in width. Because PRF shift thermometry can be applied for water molecules only, fat suppressed MRI is used and lipid tissue is shown with low MR signal intensity.

The second graph in Fig. 2 shows the measured Tmap. The color range of ±20°C is common with all the other colored temperature maps in this paper. The Tmap surface in the second graph is non-continuous over the wrapped phase regions, especially in the right hand side of the graph with strong noise. The phase image is wrapped also at the middle of the sonication cell at row 82 and column 80, and corresponding Tmap values at the actual temperature maxima are seemingly flipped into negative values mapped with dark blue color. The correct temperature increase exceeding +20°C could be resolved using phase unwrapping.

The expected HIFU radiation field is shown in the first graph with the red colored line, and is modified for the estimated shape of hotspot region, with true thermal increase, shown with black line in the second graph. The modified hotspot shape is estimated based on the measured temperature map, assuming that the temperature surface gradient should be monotonically decreasing starting from the sonication cell center, but should not reach negative

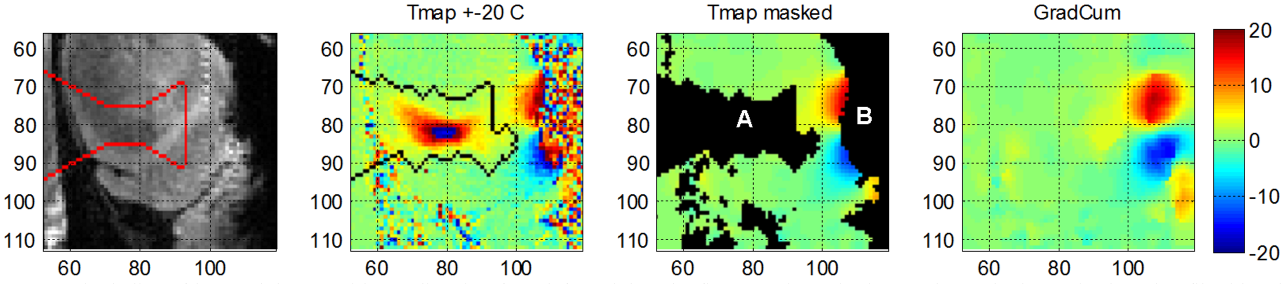

Fig. 2. Sagittal slice of lower abdomen with a-p direction from left to right. The first MRI intensity image shows the large sized uterine fibroid and expected HIFU radiation field. Second graph shows the measured temperature map and the modified sonication cell shape with black colored line. Third graph shows the masked regions with black color and the fourth graph shows the final GradCum result.

temperature values. Additional morphological operations are applied to simplify the estimated hotspot region, e.g. by removing holes and too complicated extensions.

Third graph of Fig.2 shows the smoothed Tmap values over the region of well behaving temperature map, having masked out both the modified hotspot region, marked with a letter 'A', and the wrapped phase regions, marked with 'B' on the largest part. The last graph shows the final resulted temperature map, by using both the smoothed Tmap values of third graph, and by estimating new temperature surface over the masked out regions. The estimation is based on the surface gradient of the phase image. Main purpose in here is that phase wrapping discontinuities can be removed simply by setting the gradient values into the limited range of ±π rad. An alternative would have been direct unwrapping of the phase image, which however is unstable and increases variance over the noisy and complicated wrapped phase surfaces, as shall be shown in the results section.

The limited phase gradient values are cumulated back into the estimated phase surface by using an oriented filter, which is illustrated in Fig. 3 with impulse responses. Note that these impulses responses are given for theoretical input gradients of step-like surfaces formed by infinitesimally thin line in horizontal, vertical or diagonal direction, correspondingly. The final result over the phase image shall be cumulated as a weighed average of such responses, using the corresponding MRI intensity image values as weighing coefficients to reduce effect of regions with low S/N ratio. Main drawback of the selected oriented filter is the high computational complexity in comparison with the standard linear space invariant (LSI) filtering, however, some alternative steerable filters with improved efficiency have been published by other studies [4], which we shall examine in the future for the final application.

Because the estimated surface is cumulated from the surface gradients, it is zero-averaged as default and needs shifting into the correct temperature level. This is done by aligning the estimated surface with the smoothed Tmap values firstly at the borders between the non-wrapped and estimated regions. Then, the estimated surface is aligned further inwards by iterating a new border using dilation operation on the previously processed region. As a result, we have formed a continuous temperature surface, using directly the smoothed temperature map in the accepted non-wrapped image region, and following the surface gradient in the masked out regions. Examples of the estimated surfaces are in the rightmost graphs of both Fig. 2 and Fig. 4.

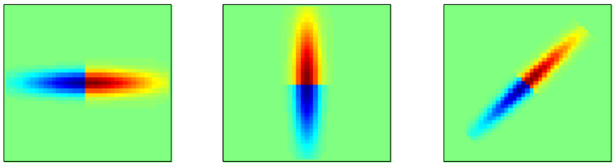

Fig. 3. Responses of oriented filter for theoretical gradient input impulses in different directions.

C. *Performance assessment*

The consistency of the temperature map for the consequent image frames is compared between the original measured Tmap, the suggested GradCum method, and finally using an exact 2D unwrapping for the phase images as a reference (Unwrap2D). After a literature survey, we selected the SRNCP method to calculate the unwrapped phase images [5], and downloaded the needed C++ source code from the Liverpool John Moores university web page [6]. We selected the SRNCP method also based on giving the best consistency for our MRI phase image test data, in comparison with some other unwrapping methods available for Matlab.

Fig. 4 shows two consequent frames for sagittal slice with anterior-posterior direction from left to right. The graph area is about 75 mm in height and 60 mm in width. The first column graphs with the measured Tmap shows about similar surface for the consequent image frames. The largest differences between the two Tmap images are naturally located at the abrupt surface variations, either at the phase wrap contour lines, or at the regions with low S/N ratio. The temperature map surface estimation should improve consistency in the both cases, firstly by forming a continuous surface and then by smoothing the noise.

However, the estimated surface is very different between the consequent image frames for the reference Unwrap2D method in the middle column graphs of Fig. 4. The obvious reasons for the unstable unwrapping result are both the under sampling of the phase image over the wrapped artifact regions and poor S/N ratio. Finally, the temperature surfaces estimated by the suggested GradCum method are very similar between the image frames in the right most column graphs.

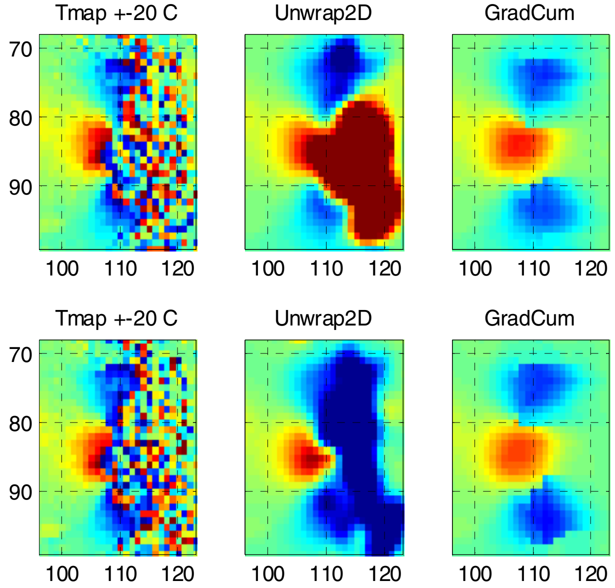

Fig. 4. Two consequent frames for sagittal slice of lower abdomen are shown in the first column for the measured temperature change map in the color range of ±20°C. Second column shows the estimated temperature surface for the Unwrap2D method and the last column for the GradCum method.

To test the consistency of the temperature surface estimation, we calculated the standard deviation (std) over the temperature difference images between the consequent image frames. This was done separately for the original measured Tmap and both methods in comparison. The same expected HIFU radiation field region was firstly masked out from all the images, to make the comparison for the plausible temperature artifacts region only.

III. RESULTS

The final result is collected for all the data consisting of about 30,000 MR thermometry images. Fig. 5 left hand side graph shows distribution of the standard deviations of the temperature difference images, calculated for the measured Tmap and for the both compared method. The suggested GradCum method has lowest variance and the reference unwrapping method results into the strongest variance.

The right hand side graph of Fig. 5 shows the normalized standard deviation, in which the variance of the temperature difference images is divided by the averaged variance over the corresponding temperature images. This should remove the effect of random pixel noise of the temperature images in the comparison, which clearly has stronger impact on the measured Tmap images than for the estimated temperature surfaces. The normalized variance is given also in purpose to have a fair comparison between the Unwrap2D and GradCum methods, because the Unwrap2D typically results into a larger temperature range and might otherwise give higher variance for the similar consistency between consequent image frames. As a result, the normalized variance of the GradCum method is approximately same with the original Tmap, but the Unwrap2D method is highest for the normalized variance also.

IV. CONCLUSIONS

This paper shows the preprocessing step of the MRI temperature map images to estimate the unwrapped surface of the MRI phase image and reduce the pixel noise. This is developed as a part of a larger study in purpose of modeling the MRI thermometry artifacts. The suggested GradCum method for Tmap surface estimation over the wrapped and noisy image regions does not increase variance in comparison with the original measured temperature map, while the standard method in comparison, using 2D image unwrapping, increased the variance significantly. Therefore, the GradCum method is more consistent and better applicable for further modeling of the temperature artifacts. However, unlike the standard 2D phase unwrapping, the GradCum method is not constrained on exactly adding integer multiples of 2π radians to the original phase values, and thus it cannot be applied for the general phase unwrapping problems. In many cases, one cannot anyhow calculate the correct temperature over the MRI thermometry artifact regions, and our purpose is rather to model the dynamics of artifacts, to mask out the regions with high uncertainty in the temperature measurement.

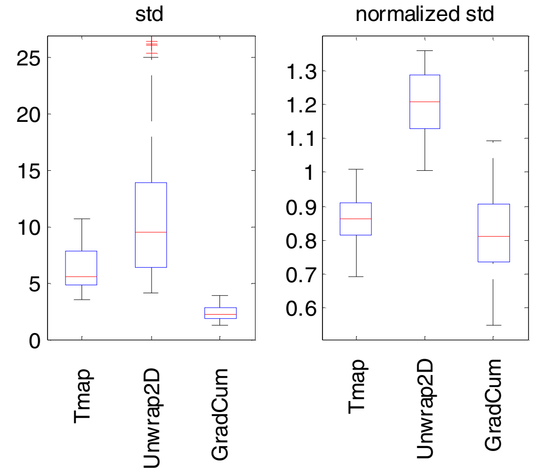

Fig. 5. Box plot of the standard deviations for the temperature difference between consequent image frames in the left hand side, and the corresponding normalized std in the right hand side. The box plot shows the median value in the middle line inside the box, and the bottom and top of the box shows first and third quartiles, correspondingly. The lower and upper whisker lines show the 2nd and 98th percentiles of the resulted std values.

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