MRI Thermometry Calibration Concept for the Qualification of HIFU Tumor Ablation Real-Time Thermometry Protocols

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Introduction

Due to its potential as a minimally invasive technique, high intensity focused ultrasound (HIFU) tumor treatment has gained more and more importance during the last years. MR guidance of HIFU ablation allows real-time observation of tissue damage during ablation. The most direct method for observing this damage is an MR-based online temperature control during the HIFU ablation process. However, MR temperature monitoring during HIFU ablations is challenging: The small focus diameter and the high temperature gradients achieved by the HIFU heating can lead to errors due to partial volume effects and heating times of about 10 s lead to high demands on time resolution. Thus, one of the main tasks is to optimize MR acquisition for achieving the highest time resolution and spatial resolution coupled with the required temperature accuracy. The calibration of temperature sensitive sequences for different slice geometries is a challenging task. As a qualified experimental setup should be found before performing animal experiments a standardized procedure for qualifying MR parameter sets in advance is desirable.

In this paper we introduce a concept for identifying and testing adequate parameter sets, with which reliable MR temperature measurements with reproducible results in a pre-animal test phase can be achieved. This procedure is exemplified by testing an online temperature mapping setup that has been developed for monitoring HIFU ablation of fibroids in the human uterus. The tested parameter set is described below.

Methods

The described procedure allows a qualification of a thermometry protocol based on several measurements with different *foci*. It is based on *ex vivo* heated experiments as well as on volunteer 'zero-temperature' measurements:

1.) Temperature stability measurements: The temperature accuracy in a non-heating ('zero-temperature') volunteer experiment

The highest achievable temperature accuracy for a parameter set can be derived from temperature stability measurements on volunteers: Therefore protocol and experimental setup (coils, position of the volunteer) are chosen in a way as it is planned for the *in vivo* HIFU ablation. After taking the reference images, a continuous measurement of multiple temperature images is performed e.g.100 images during 5 min. For data evaluation the standard deviation (SD) of the temperature can be calculated for each single voxel over the complete time series. The resulting standard deviation map – which contains the SD of each voxel at the corresponding position in the map/image – can be used to visualize the temperature accuracy in a defined area of the image (see figure 1).

2.) Comparison of ablated tissue versus MR temperature: Correlation of ablated tissue and displayed temperature in meat samples

As partial volume effects may strongly influence the displayed MR temperature, the HIFU focus temperature can easily be underestimated for parameter sets with a large voxel size. To check this, several HIFU ablations are performed in a meat sample under identical conditions (power, heating time) on a regular grid. The meat is cut into slices afterwards and the HIFU "lesions" are compared to the temperature profiles measured by MR as shown in figure 2.

3.) Temperature calibration: Comparison between the MR temperature and a reference temperature measured by an external device

The calibration is performed by comparing the temperature calculated form the MR images with a reference temperature measured by an optical thermometer (Luxtron, Luxtron Corporation, Santa Clara, CA, USA). The reference temperature is measured with a small crystallite that is visible in the MR images. The calibration can be done in general by comparing the reference temperature with the temperature calculated from the MR phase difference images (see figure 3). Due to the high temperature gradients and the influence of the sensor, the determination of the MR temperature is challenging and will be discussed in detail.

Description of the temperature mapping experiment:

The MR thermometry was performed based on the proton resonance frequency method [1] using a GRE sequence (AQ = 3.0 s, TE = 16 ms; TR = 65 ms) with a FOV of 288 mm and a voxel size of (1.5 x 1.5 x 4.5) mm^3. Reference images are taken before starting the HIFU heating. During and after heating, temperature images are acquired continuously and subtracted from the reference images. The measurements were performed on a Siemens MAGNETOM Symphony 1.5T MR scanner.

For the acquisition of the external reference temperature, the Luxtron crystallite was placed in a meat sample at the expected HIFU focus position. The temperature was monitored during and after heating over a time period up to 30 min. HIFU heating was achieved by using a fixed-focus HIFU transducer (el. power: 100 W, Ø= 6 cm).

Results & Discussion

The proposed parameter set is adequate to monitor temperature changes during HIFU ablation of uterus fibroids.

- In the **volunteer stability measurements** a temperature accuracy of about 1.4°C could be achieved in the uterus region (see figure 1).
- The **correlation measurements** show a good correlation between MR temperature and the corresponding size and shape of the ablation zone (see figure2).
- From the **temperature calibration** measurements only small differences between the MR temperature and the temperature measured by the Luxtron were observed: An average deviation from Luxtron temperature of 3°C and a MR temperature "noise" +/-2°C (averaged over 3 voxels) could be determined. The MR temperature fits well to the Luxtron temperature even after 30 min of measurement time without new reference images (see figure 3).

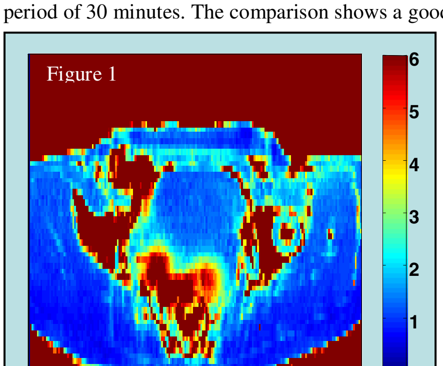
The necessity of MR thermometry is emphasized by the fact that different HIFU sonifications lead to different lesion shapes: The assumption of a uniform effect of one HIFU shot is not supported (fig. 2). A precise knowledge of the spatial temperature distribution is necessary to predict the damage that is generated by HIFU treatment.

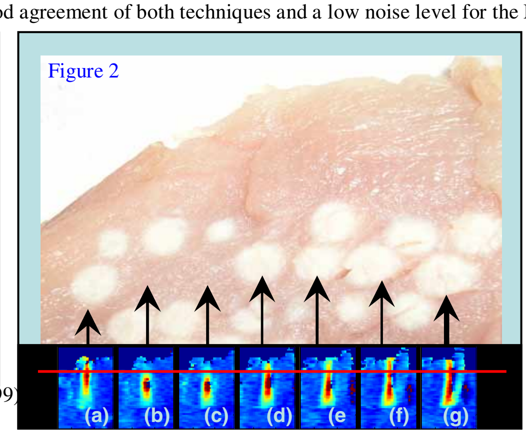
Figures

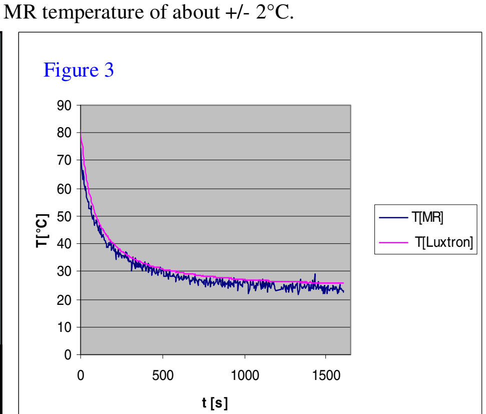
Figure 1: Standard deviation map of a transverse slice of a temperature image showing the uterus of a female volunteer. The scale shows the color for the corresponding standard deviation in °C. The standard deviation is calculated for each pixel over a time frame of 5 minutes (100 measurements) using the measured temperature image. The temperature standard deviation in that part of the MR image which shows the uterus is smaller than 1.4°C.

Figure 2: Coronal slice of a cut meat sample (turkey muscle) after HIFU treatment of equidistant points (distance: 5 mm). The slice originates from the higher part of the treated area. For the middle line the corresponding MR temperature profiles taken at max. temperature are displayed in insets 2(a-g) in a **transverse** cut. The black arrows show the correlation between each temperature profile and the corresponding HIFU spots. The red line cuts the temperature profiles at the height where the cut of the meat is assumed. For this line a very good correlation between the temperature and the ablation diameter of the HIFU spot can be found. Particularly for figures 2(b) and 2(c) obviously a sufficient heating to damage the tissue could not be achieved which fits well to the small temperature changes displayed in the profiles.

Figure 3: Time course of the temperature during and after HIFU heating. The temperature was measured by a Luxtron and compared to the MR temperature over a period of 30 minutes. The comparison shows a good agreement of both techniques and a low noise level for the MR temperature of about +/- 2°C.







Reference : [1] Phys. Med. Biol. 44, 607-620 (1999)