Brain temperature measurement using MR tomography images

N Bogatov, M Voloshin, L Grigoryan, A Sinitsyn and S Shapovalov

Department of Physics and Information Systems, Kuban State University, 149 Stavropolskaya Street, Krasnodar 350040, Russian Federation

E-mail: bogatov.n@inbox.ru, bogatov@phys.kubsu.ru

Abstract. Volumetric MRI thermometry is undergoing active development. The measurement bases on the resonance response of protons inside molecules (i.e., water, fat, methylene, lipids) of the examined body. The difference between resonance frequencies gives information about the temperature of the tissue. Various MR thermal image construction methods exist because temperature influences the state of a living object in numerous ways. As a result of this, contrast characteristics of MR images of tissue depend on the value of the magnetic field induction, tissue characteristics itself, and temperature. This paper deals with brain temperature measurement based on digital analysis of $T_2$-weighted MR images. MR images of homogenous and inhomogeneous phantoms at different temperatures were analyzed. The relationship between image brightness, temperature, and phantom composition was determined. The temperature of the cerebrospinal fluid was calculated.

1. Introduction

Neurotrauma, subarachnoid hemorrhage, or stroke cause temperature heterogeneity of brain tissue with high-temperature areas [1, 2]. Brain temperature depends on the metabolic activity of neurons and therefore affects functions of the central nervous system and metabolism [1]. The design and development of methods of non-invasive brain thermometry is a vital task. Such methods are MRI thermometry [3, 4], microwave thermometry [5, 6], acoustic thermometry [7]. A comparison of these methods showed that MRI thermometry has the best spatial resolution [8].

The temperature influences the state of a living object in numerous ways, and that leads to the existence of a variety of MR thermal image construction methods. Measured parameters that depend on the temperature are: spin-lattice relaxation time $T_1$, spin-spin relaxation time $T_2$, magnetization $M_0$ linked to proton density, diffusion coefficient $D$, chemical shift $\delta$. The paper [4] deals with a comparative analysis of different image construction methods. The following papers discuss MRI based thermal field registration methods in a given area heated using various heating techniques: microwave heating [9], laser heating [10], usage of tiny electrical heaters [11].

Relaxation times $T_1$ and $T_2$ depend on the magnetic field induction. The dependency is more pronounced for $T_1$ than for $T_2$. As a result, contrast characteristics of tissue on $T_1$-weighted MR images depend on the value of the magnetic field induction [12].

Currently, methods of intentional heating of tissues for activation or suppression of chemical-biological processes are being developed. These methods include local spot heating, regional heating, and full body heating. Local hyperthermia requires a high degree of control over the tissue exposure to
radiation, which can be of ultrasound, laser, RF, or microwave nature. The paper [13] deals with the application of high precision MRI thermometry with motion correction in the clinical practice of liver tumor ablation.

The paper [14] discusses the importance of calibration measurements in MRI thermometry applied to brain temperature measurements. Physical principles of MRI thermometry for medical applications and unsolved problems in the area are dealt with in the paper [15].

The purpose of this paper is brain temperature measurement based on digital analysis of $T_2$-weighted MR images.

This paper describes the analysis of the change in the grey-level (intensity) value $I$ of pixels in the $T_2$-weighted MR image. The intensities were normalized in such a way that $I \in [0, 255]$. The increase in the resolution was achieved by using a pseudo color MR image palette and by using image transformation methods. The surface temperature of homogeneous and inhomogeneous phantoms was measured with the help of Nihon Konden BSN 2301K contact thermal sensor.

2. Digital analysis of MR images of phantoms

Inhomogeneous phantoms were studied with the help of 1T Panorama HFO 1.0 MRI scanner. The phantoms (denoted by D, E) were 1.5L plastic bottles filled with a mixture of water (D1, E1) and refined sunflower oil (D2, E2). The temperatures of the phantoms were: $t_D = 13^\circ\text{C}$, $t_E = 38^\circ\text{C}$. Figure 1 shows the $T_2$-weighted images of an axial view of the phantoms. The images were acquired using the TSE pulse sequence. Figures 2, 3 show the dependency of intensity $I$ on length $L$ (measured in pixels) for lines 1,2,3,4 shown in figure 1.

$T_2$-weighted images of inhomogeneous phantoms D, E in areas D1, D2, E1, E2 are reasonably uniform, which is proved by signal intensity distribution along lines 1, 2. (figure 2, figure 3). The intensity $I$ on the $T_2$-weighted image is decreasing with the increase of temperature for water (figure 2A), but on the other hand, the intensity is increasing with the increase of temperature for refined sunflower oil (figure 2B).

The difference between intensities $\Delta I$ at the water-oil boundary on $T_2$-weighted image is consistent with the following values:

For phantom D (figure 3A): $\Delta I_D = I_{D2} - I_{D1} \approx -170$.

For phantom E (figure 3B): $\Delta I_E = I_{E2} - I_{E1} \approx -25$.

A sharp $T_2$-signal peak was observed at the water-oil boundary for phantom E (figure 3B). This peak corresponds to the chemical shift. The chemical shift value $\delta$ is considerably higher for phantom E than for phantom D. Therefore, the dependency $\delta(t)$ should be studied and considered to be another possible source of data for temperature measurement. The increase in the intensity $I$ in the area E1 (figure 3B) requires further research. It might be attributed to the diffusion of lighter atoms from area E2 to area E1 in the phantom with a higher temperature.
Figure 2. Signal intensity distribution: A – along line 1, B – along line 2.

Figure 3. Signal intensity distribution: A – along line 3 B – along line 4.

Average values of intensities for substances D1, E1, D2, E2 were $I_{D1} = 229.2; I_{E1} = 137.5; I_{D2} = 60.8; I_{E2} = 113.5$. Corresponding standard deviations were $S_{D1} = 3.3; S_{E1} = 4.5; S_{D2} = 2.5; S_{E2} = 2.1$. Intervals $I_{D1} \pm S_{D1}; I_{E1} \pm S_{E1}; I_{D2} \pm S_{D2}; I_{E2} \pm S_{E2}$ do not overlap, therefore temperatures of substances D1, E1, D2, E2 can be measured unambiguously using a $T_2$-weighted image.

3. Brain temperature measurement

$T_2$-weighted images of both the phantom and the brain were acquired with the help of 1.5T Toshiba MRI scanner using the TSE pulse sequence. The homogeneous phantom was composed of 5 plastic jars filled with water at different temperatures: $1 - t_1 = 15\, ^\circ C, 2 - t_2 = 21\, ^\circ C, 3 - t_3 = 33\, ^\circ C, 4 - t_4 = 38\, ^\circ C, 5 - t_5 = 50\, ^\circ C$. The image of the phantom was used to construct the table 1 with temperatures and their corresponding intensity values, where $I_{av}$ – average intensity value, $I_{min}$ – minimum intensity value, $I_{max}$ – maximum intensity value, $S$ – standard deviation averaged over several slices.

Average values $I_{av}(t_i)$ were used to plot the trendline (figure 4) and derive the equation for temperature calculation:

$$t = (194.6 - I_{av}) / 1.846.$$  \hfill (1)

Figure 5 shows the color-coded $T_2$-weighted image of the head. On the right side of the head the test object, which is a plastic bottle filled with water, is seen. The color palette maps colors to intensities of the original grey value image.
Table 1. Intensity-temperature values.

| №  | $t$, °C | $I_{av}$ | $I_{min}$ | $I_{max}$ | $S$  |
|----|---------|----------|-----------|-----------|------|
| 1  | 15      | 162      | 151       | 200       | 4.9  |
| 2  | 21      | 161      | 146       | 195       | 6.8  |
| 3  | 33      | 131      | 123       | 142       | 2.9  |
| 4  | 38      | 131      | 121       | 148       | 3.7  |
| 5  | 50      | 98       | 93        | 108       | 2.4  |

Figure 4. The dependency of intensity on temperature for axial views of the phantom on $T_2$-weighted images.

Figure 5. $T_2$-weighted image of the head and the test object.

The test object in figure 5 had the lowest temperature, that is the reason why the test object was the brightest. The average intensity value for the test object was 140.3. Substituting this value into equation 1 gave us the average temperature estimation for the water in the test object, which was equal to $29.3\, ^\circ C$.

The brightness of cerebrospinal fluid was lower as with the increase of the temperature the brightness gets lower. The average intensity value of lateral ventricles was $125.2$, substituting this value into formula 1 gave us an average temperature estimation of $37.6$. This value matches the normal physiological value of brain temperature.
4. Conclusion

$T_2$-weighted images of the homogeneous phantom acquired with the TSE pulse sequence have a rather uniform intensity distribution, therefore these images are well-suited for temperature estimation. On the other hand, the accuracy requirements for the model describing the dependency of spin-spin relaxation time on the magnetic field induction, temperature, and chemical composition of the body examined are strict.

$T_2$-weighted images of inhomogeneous objects show a pronounced dependency of the chemical shift on the temperature on the boundary. Besides that, the model should take into account the influence of the temperature on the diffusion of molecules into the low-concentration area.

It was shown that the intensity value on $T_2$-weighted images of water at different temperatures gets lower as the temperature gets higher. This dependency can be used to derive an equation for temperature estimation. The derived equation was used to estimate the temperature of cerebrospinal fluid. The estimated value is in agreement with the physiological value of brain temperature.

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