Comparison of thermal dose models in canine brain using the Dice similarity coefficient

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Introduction

Thermal ablative therapy is a minimally-invasive alternative to conventional surgery for soft-tissue disease. Magnetic resonance thermal imaging (MRTI) facilitates guidance of these therapies by measuring temperature changes within 1ºC using the proton resonance frequency (PRF) method [1]. Models exist for predicting thermal damage from the temperature history provided by MRTI allowing this prediction of damage to work as a surrogate for post-therapy imaging. This should help provide better planning and control over the procedure. Various thermal dose models are presented in the literature, and within each model, different parameters or thresholds are often employed. In this work, the performance of multiple thermal dose models were compared using a statistical validation metric to compare the spatial overlap between predicted model damage for *in vivo* canine brain during thermal therapy and contrast-enhanced T1-W images acquired immediately after therapy. By varying the thresholds used in publications, the Dice similarity coefficient (DSC) was used to determine the parameters that maximized the correlation between these maps.

Methods

Animal studies were handled in accordance with protocols approved by the Institutional Animal Care and Use Committee (IACUC). Clinically normal mongrel hound dogs (n=4, 20-25 kg) were used. A 1 cm diffusing tip fiber encased in an actively cooled sheath (Visualase®, BioTex, Inc, Houston, TX) was inserted into the frontal lobe for therapy delivery. Imaging was performed on a 1.5T whole body MR scanner (EXCITE HD, GE Healthcare, Waukesha, WI) with an 8-channel, receive-only phased array head coil (MRI Devices Corp, Gainesville, FL). Laser fiber placement was planned and verified by using a 3D fast spoiled gradient-echo sequence. Using a temperature sensitive 8-shot EPI sequence in combination with parallel imaging, real-time monitoring of the temperature changes was obtained in 5 planes every 5 seconds (TE: 20ms, TR: 544ms, FOV: 20cm, matrix: 256x128, BW: ±250kHz). Feedback during the procedure was provided by a remote workstation (Visualase®, BioTex, Inc, Houston, TX). Subsequent MR imaging after ablation included post-contrast T1-W imaging (TE: 9.2ms,TR: 800ms,FOV: 20cm by 20cm,BW: ± 25Khz) and FLAIR imaging (TE: 147.2ms,TR: 10002ms,FOV: 20cm by 20cm,BW: ± 31.3 kHz) and T2-W (TE: 100ms,TR: 4000ms,FOV: 20cm by 20cm,BW: ± 19.2 kHz). Using Matlab (Mathworks Inc, Natick, MA) software, absolute temperature maps were input into models to obtain a predicted region of coagulation. The threshold for the model by Sapareto and Dewey (eq 1) [2] was varied from 10 cumulative equivalent minutes at 43°C (CEM43) to 400. The threshold temperature model [3] considered threshold temperatures from 51°C to 71°C. The Arrhenius rate process model (eq 2) [4], varied Ω from 0.2 - 10.2. To quantitatively evaluate each model's predicted region of damage, the DSC (DSC(A,B) = 2(A∩B)/(A+B)) [5] was used to calculate the spatial overlap between binary images of the model output and the manually segmented post-treatment images. The possible value of DSC ranged from 0 where no overlap occurred to 1 where complete overlap occurred. The standard deviation of the initial temperature images was used as a temperature uncertainty, which allowed for the temperature dependence of the various models to be evaluated.

$$t_{43} = \sum_{t=0}^{t=final} R^{43-\bar{T}} \Delta t$$

Equation 1: Sapareto-Dewey model: R=0.5 at temperatures > 43°C. R=0.25 below 43°C

$$\Omega(t) = \int_0^t A e^{-E_A/RT(\tau)} d\tau$$

Equation 2: Arrhenius model: A is the frequency factor, 3.1E98/sec, E_k is the activation energy, 6.28E05 J/mol, R is the universal gas constant

Results

For the Sapareto-Dewey method, the DSC reached a plateau at a thermal threshold of 390 CEM43 averaged over the four dogs with ≥220 CEM43 generating a 90% agreement (DSC ≥ 0.9) with the post-treatment image. For the temperature threshold model, the maximum DSC for the four dogs was at an average threshold temperature of 62°C with a 90% spatial overlap from 59°C-63°C. For the Arrhenius model, the maximum DSC was at an average of 0.6 with a 90% spatial overlap occurring over the range of 0.2-3.6. In all subjects, using previously reported thresholds for each model resulted in DSCs > 0.7 (DSC=0.90±0.02 at 240 CEM43, 0.88±0.03 at 57°C, 0.92±0.01 at Ω=1.0, respectively) corresponding to a good spatial overlap between images [6] and were further improved by changes in thresholds (max DSC=0.91±0.01, 0.92±0.01, 0.92±0.01, respectively). A ±0.1% difference from the maximum DSC for each model produced a threshold range of 358-400CEM43, 61.2-62.1°C, and 0.4-0.7 for the Sapareto-Dewey, threshold temperature, and Arrhenius models respectively. The uncertainty temperatures for the four dogs were measured to be 0.95°C, 2.18°C, 1.44°C, and 1.83°C. The threshold temperature and Arrhenius model at their respective peaks in DSC values tended to be less dependent on the baseline temperature compared to the Sapareto-Dewey thermal dose model.

Discussion

In this study, the utilization of parameters different from the previously reported thresholds increased the DSC values and could lead to a more accurate prediction of tissue response. In the Sapareto-Dewey model, higher thresholds resulted in the highest DSC values, contrary to other published studies [7], however, because of the leveling off of the curve, good agreement was found over a wide range of CEM43. The threshold temperature model had a maximum over a small range of temperature, but the high DSC showed temperature history independence for the rapid, high temperature laser treatments. The Arrhenius model accurately predicted damage over a wide range of parameters, making it the most robust out of the three models. It is of note that, in this study, comparisons were made from the acute damage rather than several hours later as previously established thresholds have used. The lack of time allowed for swelling likely influenced results and may account for other values reported in literature. Treatments involving longer exposures with lower temperatures should be evaluated to determine the effect on the damage prediction. In future studies, we will compare the different damage models after thermal ablation of brain tumors.

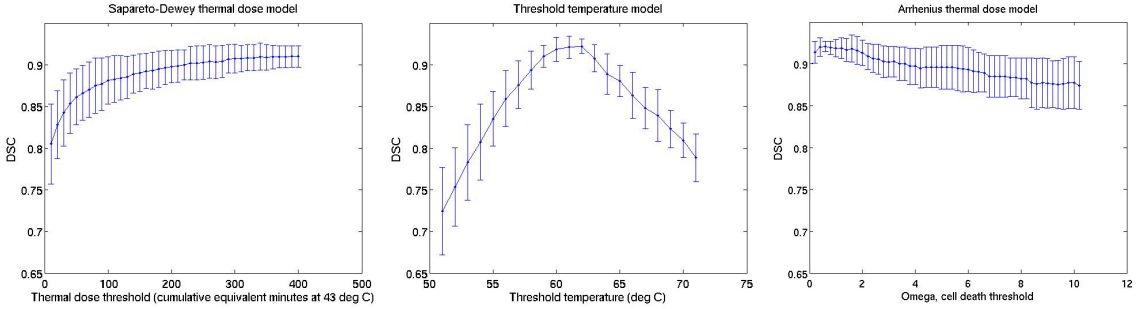

Figure 1: DSC values using the (L-R) Sapareto-Dewey thermal dose model, threshold temperature model, and Arrhenius model. In all models, subjects seemed to converge towards a peak threshold value.

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