3-D Control Over Spatial Heating Using Multi-Element Ultrasound Heating Applicators and Real-Time MR Temperature Feedback

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Introduction

Current primary therapies for localized prostate cancer achieve effective disease control, but are associated with significant long-term complications to urinary, rectal, and sexual function. MRI-guided transurethral ultrasound therapy is a minimally-invasive thermal treatment for localized prostate cancer using high-intensity ultrasound energy that has the potential for rapid and precise treatment of disease within the gland [1]. This is achieved by incorporating real time MR temperature feedback during treatment to target the prostate gland and spare surrounding tissues from unwanted damage. MRI-compatible heating applicators, motors and a prototype system for performing transurethral ultrasound therapy in a closed-bore MR imager have been designed and characterized [2]. In addition, the feasibility of using MR temperature feedback to achieve a precise pattern of thermal damage within the prostate gland has been demonstrated. The aim of this study was to evaluate the capability to produce targeted 3D patterns of thermal damage using a multi-element ultrasound heating applicator and real-time MR temperature feedback.

Methods

<u>Heating Applicator</u>: A multi-element applicator was constructed consisting of 5 planar transducers (3.5 x 9mm) operating at 7.7MHz (Figure 3). Rotation of the device, as well as independent modulation of each transducer element was used to control the spatial pattern of energy deposition around the device.
<u>Target boundaries</u>: Two prostate geometries were defined for this study, obtained from 3D MR images of prostate cancer patients. Five planes within the prostate were chosen from which target boundaries were identified. Each plane corresponded to the location of the centre of each element in the heating applicator.
<u>Gel experiments</u>: The heating applicator was inserted into a cylindrical tissue-mimicking gel phantom, and was rotated 360° during heating to generate a pattern of thermal damage around the entire device. MR thermometry was acquired during heating in 5 individual planes centred on each of the transducer elements. The PRF shift method was used to measure the spatial temperature distribution with a temporal resolution of 5 seconds and an in-plane spatial resolution of approximately 1.5 mm. All experiments were performed in a 1.5T closed bore MRI (Signa, GE Healthcare, USA). These temperature measurements were used to control the device output during treatment. The goal of the experiments was to elevate the temperature along the target boundary to 55°C. Heating experiments were repeated 5 times for each prostate geometry to evaluate the repeatability of this technique. T2-weighted MR images of the gel phantom were also obtained after heating to visualize the 3D pattern of thermal damage generated by the device.

Results

The volumes of the segmented prostates were 53 and 58 cm^3, and heating of the entire volume was achieved within 12 minutes for all experiments. The results from gel heating experiments for one prostate geometry are shown in Figure 7. Polar graphs depict the target boundary in each of the five planes during treatment. The mean 55°C isotherm measured with MRI in each of the five planes is also shown in the polar graphs. From these graphs it is evident that excellent spatial control over heating was achieved in all five planes using the multi-element transducer with active MR temperature feedback. The average distance between the 55°C isotherm and the target boundary was 0.75 ± 1 mm in these experiments. Figure 3 shows a T2-weighted image of a gel phantom acquired after heating in axial, coronal and saggital planes. The reduced signal intensity corresponds to regions of the gel that exceeded 55°C and represents the pattern of thermal damage produced by the device. The images demonstrate the continuity of the thermal damage pattern, even though it was produced by 5 individual transducers.

Conclusions

Multi-element transurethral ultrasound heating applicators were demonstrated to be capable of generating a 3D pattern of thermal damage that matched a target prostate geometry segmented from patient images. Treatment times were very short to coagulate large volumes as compared with other thermal therapies designed for the treatment of prostate cancer. These results in tissue-mimicking gels are very encouraging and motivate further exploration of this technology in vivo in the canine prostate model.

References

1. Diederich et al. Int J Hyperthermia, 20:739-56, 2004.
2. Chopra et al. Med Phys 35: 1346-57, 2008.

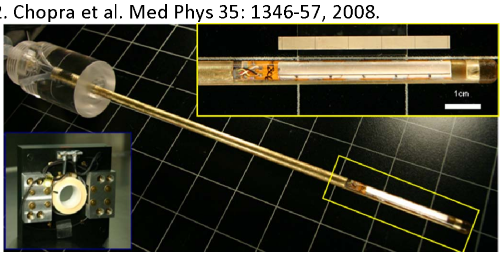

Figure 1: MRI-compatible transurethral heating applicators and motors have been developed for the delivery of this therapy in a closed-bore MR imager (1.5/3.0T).

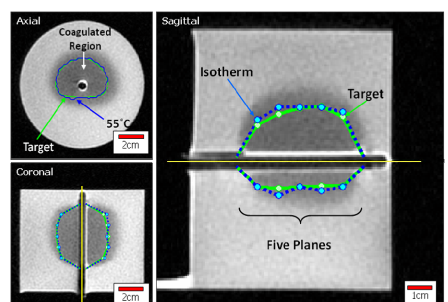

Figure 3: T2-weighted axial, sagittal, and coronal images of a gel phantom after transurethral ultrasound therapy. The 3D shape of the thermal damage pattern, and the agreement between the 55°C isotherm and target boundary are apparent from these images. The continuity of the thermal damage pattern from the individual elements is also apparent from this result.

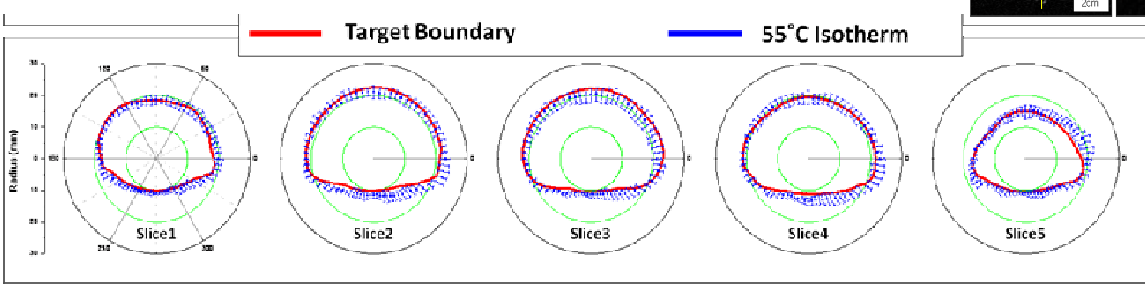

Figure 2: Polar plots of the target boundary in each of the five imaging planes. The average location (and standard deviation) of the 55°C isotherm across five experiments is also shown in each plane, demonstrating the capability to achieve accurate 3D targeting with this multi-element approach in the gel phantoms.