Feasibility of 1.5T MRI-Guided Transurethral 3-D Conformal Ultrasound Therapy of the Prostate: A Simulation Study

M. Burtnyk[1,2], R. Chopra[1,2], and M. Bronskill[1,2]

[1]Imaging Research, Sunnybrook Health Sciences Centre, Toronto, ON, Canada, [2]Medical Biophysics, University of Toronto, Toronto, ON, Canada

Introduction: Prostate cancer is the most commonly diagnosed and the third-leading cause of cancer related deaths among Canadian men [1]. Conventional therapies for prostate cancer, prostatectomy and radiotherapy, have high rates of undesirable side-effects and can affect the quality of life of patients significantly [2]. This motivates the development of alternative, less invasive treatments, such as transurethral ultrasound prostate therapy, where a device is inserted into the urethra gaining direct access to the prostate gland. Multiple transducers along the device emit independent, directional ultrasound beams which can cause thermal coagulation (Tc≥55°C) of a target prostate volume while avoiding damage to surrounding structures. To shape the region of coagulation to a prostate boundary, feedback temperature control is required to modulate the device rotation rate and the power and frequency of the ultrasound beams. MR thermometry can provide quantitative temperature information; however, the temporal resolution and SNR of these measurements affect treatment accuracy [3]. This work uses numerical simulations and 3D patient-specific modeling to investigate the feasibility of treating men with prostate cancer with a transurethral ultrasound therapy device and clinically-relevant 1.5T MR thermometry feedback temperature measurements.

Methods: Three-dimensional prostate models (n=20) were created by manually segmenting the prostate in T2w axial MR images of prostate cancer patients (voxel: 0.55x0.55x3mm). Computer simulations were used to model transurethral ultrasound prostate therapy with rotating planar transducers and MR thermometry feedback. A scaled combination of 4x3mm, 4.73 / 9.70 MHz dual frequency transducers was used as the power deposition term in the Bioheat Transfer Equation (1mm^3, 1s) which calculated tissue temperature dynamics due to conduction, blood perfusion and ultrasound energy absorption. A proportional-difference feedback control algorithm adjusted the device rotation rate and the ultrasound power and frequency of each transducer based on the temperature measured at the prostate boundary. The goal of the controller was to raise the temperature along the target prostate boundary to 55°C while maintaining intervening tissues below 100°C. Baseline results were obtained with "idealistic" temperature measurements (0°C noise, 1s sampling) to evaluate accuracy and stability of the feedback control algorithm. Treatments were then simulated with temperature measurements typical of a 1.5T MRI (1°C noise stdev, 5s sampling) to assess the performance of the algorithm under a clinical setting.

Results: The treatment times for all 20 patients were less than 1 hour, with the average treatment just under 30 minutes, as shown and compared to transrectal High Intensity Focused Ultrasound (HIFU) in Figure 1 [4]. Treatment error was defined as the difference between the coagulation and prostate boundaries. The mean, standard deviation, maximum and minimum of the error relates to the accuracy and stability of the delivered treatment, and is shown in Figure 2 for the baseline results. For all 20 patients, the standard deviation of the error remained below 1mm, while the maximum and minimum were usually less than 5mm. Figure 3 shows the treatment error as a fraction of the prostate volume, providing a measure of therapeutic outcome. The under-treated fraction ranged from 1-5%, representing the amount of prostate tissue that was not coagulated and therefore potentially viable after treatment. The total error is the sum of the under- and over-treated fractions and remained below 10% of the corresponding prostate volume. The same analysis was performed on the treatment results obtained with realistic MR thermometry feedback temperature measurements. Figure 4 shows a surface rendering of a prostate and the corresponding coagulation boundary for baseline and practical MR thermometry measurements. For all 20 patients, treatment times were, on average, about 1 minute longer.

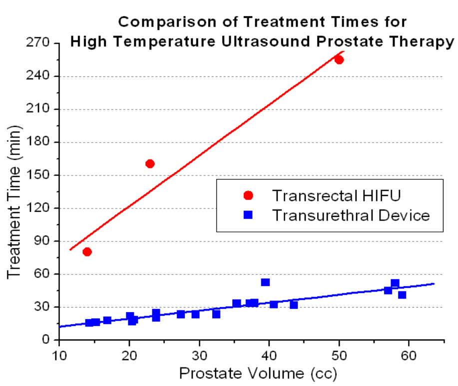

Figure 1: *Treatment times with the transurethral device are improved by a factor of 6 compared to transrectal HIFU procedures. [HIFU data, Ref 4]*

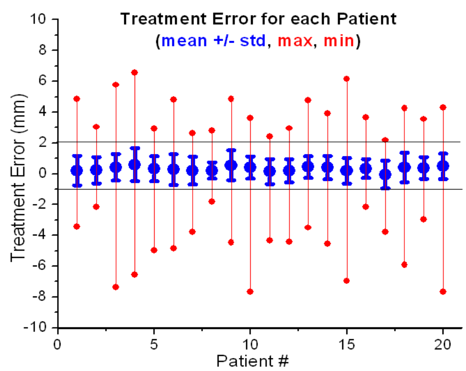

Figure 2: *The mean, stdev, max and min of the error. For all 20 patients, the stdev remained below 1mm, and the max and min were usually less than 5mm.*

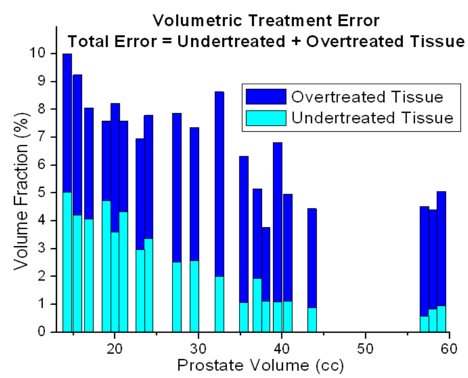

Figure 3: *Error volume fractions as a function of prostate volume. The under-treated and total error fractions remained below 5% and 10%, respectively.*

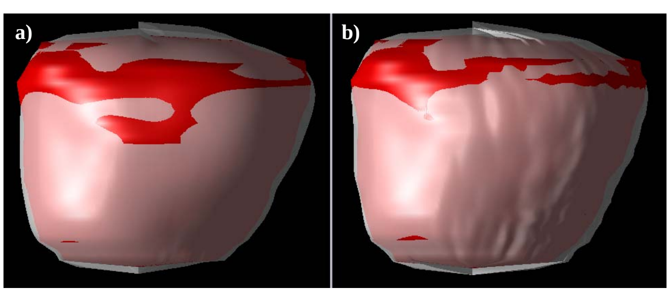

Figure 4: *Surface rendering of the prostate of patient #15 (red), and the corresponding coagulation boundary (transparent white) for treatments obtained with a) baseline, and b) practical MR thermometry feedback measurements.*

The mean treatment error did not change significantly, while its standard deviation, maximum and minimum increased by 0.1, 1.5 and 0.1mm, respectively. The under- and over-treated fractions increased by less than 0.5% each.

Conclusion: The capabilities of using active temperature feedback to control 3D conformal prostate ultrasound therapy with multiple transurethral transducers have been demonstrated through simulations on 20 patient-specific prostate geometries. Treatment times are improved by a factor of six as compared to transrectal HIFU procedures. The effects of temperature measurement noise and sampling time have shown to have little impact on treatment accuracy and therapeutic outcome for values typical of a clinical 1.5T MRI.

References:

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