Treatment of Prostate Cancer using MRI-Controlled Transurethral Ultrasound Therapy: from 2D to 3D

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Introduction

Traditional treatments of localized prostate cancer are associated with long-term complications in patients [1, 2]. MRI-controlled transurethral ultrasound therapy is being developed as a minimally-invasive, image-guided treatment for this disease. The potential advantages of this treatment include a shorter treatment time and quicker recovery for patients.

Treatment Overview

High-intensity ultrasound is delivered to the prostate from a transurethral device for controlled tissue thermal coagulation. The device contains a multi-element transducer which produces individually controlled ultrasound beams to treat the target boundary. Using a motor, the device is rotated 360° to treat the entire prostate volume.

The treatment is performed within an MR scanner to provide temperature images during heating. This quantitative temperature feedback enables real-time adjustment of treatment parameters (ultrasound power & frequency, rotation rate) for precise spatial treatment.

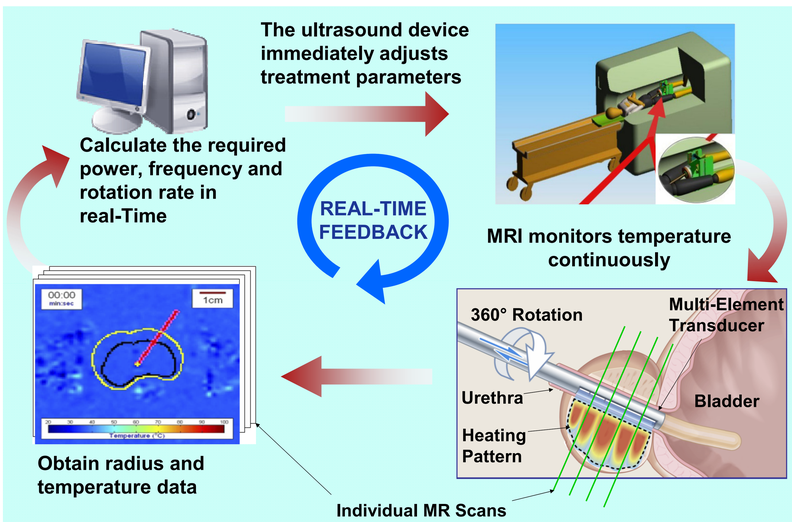


Figure 1. The required power, frequency and rotation rate are calculated and ultrasound is delivered to the prostate with continuous MR monitoring. The updated temperature and prostate radius measurements then once again determine treatment parameters.

Research Goals

A recent human study was completed at SHSC to establish the feasibility and safety of this treatment. The technology was primitive and the treatment delivered to the prostate was very conservative, consisting of a single transducer treating one 2D plane within the prostate gland (Figure 2)

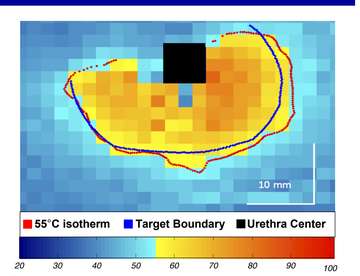


Figure 2. A temperature map from a human study. Notice that the device is not rotated the full 360° and only a 2D slice of the prostate is treated.

The goal this summer was to be able to treat full prostates, from the base to the apex, using a series of these 2D slices such that the overall heating boundary resembles the 3D shape of the prostate. The table below summarize the necessary changes.

The original technology:

- Treated a 2D prostate slice
- Used 1 ultrasound element
- Operated at a single frequency
- Was performed in the 1.5 T scanner

The new evolution of the treatment:

- Treats an entire (3D) prostate
- Uses up to 8 ultrasound elements
- Operates at dual-frequency
- Is performed at 3 T

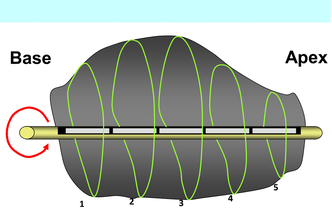


Figure 3. The simultaneous treatment of numerous 2D slices, like those in figure 2, creates a heating pattern which conforms to the 3D shape of the entire prostate.

Results

Step 1. Segmentation of Pelvic Anatomy and Development of 3D Models

The first step to achieve full prostate treatments was to develop accurate 3D models of the prostate gland and surrounding anatomy for treatment experiments. Using MR scans from the human feasibility study, the boundaries of the rectum, bones, and prostate were traced and confirmed by a radiologist. Interpolation of these slices was used to construct a 3D model of the pelvic anatomy.

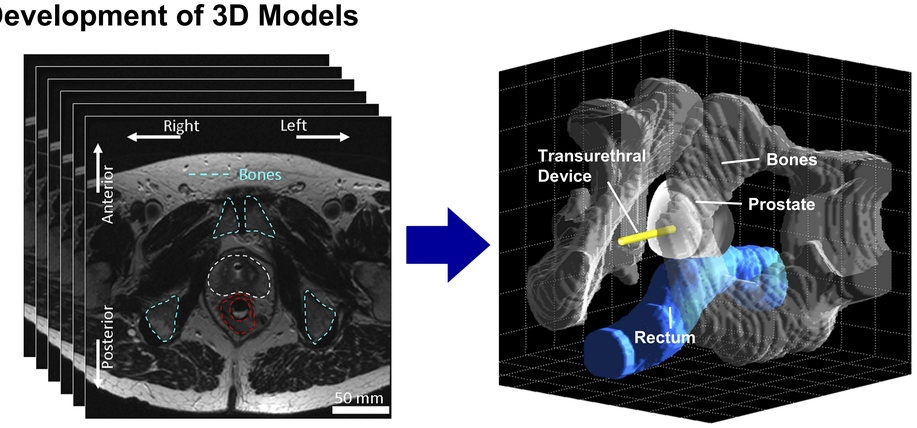


Figure 4.

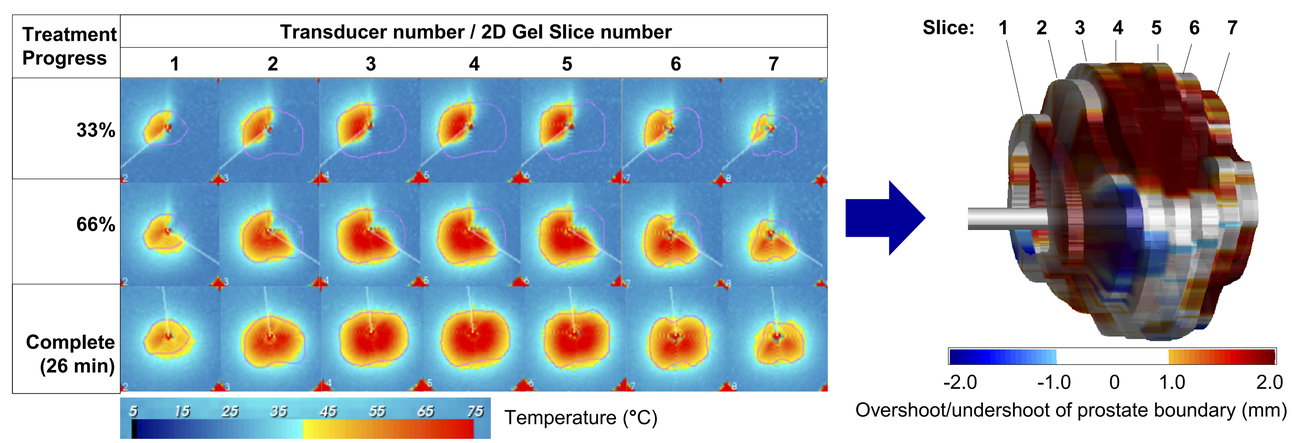
The bones, rectum and prostate of the human patients were traced on a series of 2D scans and used to produce a 3D model of the prostate for treatments and simulations.

Step 2. Transforming the technology for Dual-Frequency and 3D boundary treatment

To modify the power and frequency of each transducer and the rotation rate of the device in response to real-time temperature feedback, software is required to mediate the communication between the hardware controlling the treatment. The original software was rewritten to facilitate the increased number of elements and provide dual-frequency capabilities. As the treatment involves numerous ultrasound elements, more MR images are required to ensure accurate temperature data. To maintain both treatment time and image SNR, the treatment was moved to the 3 T scanner and new hardware and cabling was constructed

Step 3. Testing the New Technology in Gels which Mimic Prostate Tissue

To test the new technology, the 3D human prostate models from Step 1 were treated in agar gels whose ultrasound attenuation properties mimic prostate tissue. 18 of these full-prostate treatments were completed. The largest model treated was 35 mm long from base to apex and seven 2D slices (corresponding to seven ultrasound elements) were heated at the single frequency of 4.6 MHz to treat the 3D boundary. The results are shown in figure 5, and on average the discrepancy between the treatment and prostate boundaries is 1.5 ± 2.0 mm. Accuracy margins for radical prostatectomy and ionizing radiation treatments are on the order of 10 mm [3], therefore these gel results establish that a full prostate treatment with high intensity ultrasound is not only possible, but that the treatment is accurate and safe.



Treatment Analysis

Prostate volume	46 cm³
Treated volume	53 cm³
Volumetric undershoot	0.4 cm³ (0.9%)
Volumetric overshoot	5.2 cm³ (11.3%)
Average radial error	1.5 ± 2.0 mm (overshoot)

Figure 5. A gel treatment using the prostate boundary of a human patient. Seven 2D slices are treated at low frequency, each spaced 5mm apart as the prostate is 35 mm from base to apex (see fig. 3). The heating progression as the device rotates counter-clockwise is shown at three stages during the treatment **(left)**. The pink boundary corresponds to the prostate. A 3D model of the treated volume superimposed on the prostate volume **(right)** depicts overshoot (red) and undershoot (blue). The average accuracy is 1.5 ± 2.0 mm.

Summary

- The treatment technology was recreated to use up to 8 ultrasound elements and operate at two frequencies. This increases treatment accuracy and allows heating of the entire prostate.
- Prostate boundaries from human patients were traced and used to generate 3D models which were treated in 18 gel experiments.
- A 35 mm prostate 3D boundary was fully treated in a gel using 7 ultrasound transducers with an average treatment accuracy of 1.5 ± 2.0 mm.

Future Work and Conclusions

Following more gel treatments, a canine study will test the technology in vivo. A second human treatment will then follow, aiming to treat entire human prostates.

Results show that a full prostate volume can now be treated with an accuracy of 1.5 ± 2.0 mm. Considering that conventional radiation therapy uses a 10 mm accuracy margin (and similarly for radical prostatectomy), the advantages of MRI controlled ultrasound therapy both in terms of accuracy as well as treatment safety have been demonstrated.

References

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2. Chapelon JY et al. *Eur J Ultrasound* 1999; 9(1):31-38
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