

Simulation of temperature distribution in the pelvic tissues during radical prostatectomy with insertion of an endorectal cooling balloon

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Introduction: It has been shown that hypothermia via an endorectal cooling balloon (ECB) applied during robotic radical prostatectomy and in several hours post-surgery can significantly reduce the time to regain urinary continence and sexual function in men [1, 2]. These two beneficial outcomes improve the patient's long term quality of life (QOL), and significantly augment the positive consequence of successful removal of the cancerous prostate via surgery. Previous studies have shown that among men 65 years or older, there is a trend toward improved continence with lower temperatures. In practice, regional pelvic cooling was achieved with an endorectal cooling balloon (ECB), which is cycled continuously with cool saline. However, every individual patient has different anatomy and tissue compositions, and this will affect the cooling range of the ECB. Currently, there is no treatment planning tool for ECB design to optimize the balloon temperature for each individual patient. Before the ECB can successfully enter the clinical practice, several questions must be answered, including: 1) Which areas are effectively cooled within the urogenital pelvis? 2) What cooling temperatures are achieved near the rectum/neurovascular bundle? 3) How significant will the 'cool sink' effect of vascularized structures (i.e. the neurovascular bundle and periprostatic venous plexus) diminish the cooling effect? 4) How can the endorectal balloon design be optimized for individual patients? In order to begin addressing these questions, we used a bio-heat simulation model to map the temperature distribution through the pelvis during ECB cooling. These tissue compartments were segmented on MR images of individual patients: rectal wall, perirectal fat, prostate gland, urinary bladder, peri-prostatic fat, venous plexus, and seminal vesicle, and different heat transfer properties are considered in the simulation.

Methods: The bio-heat thermal model is used to describe the temperature distribution dynamics: $\rho c \frac{\partial T(r)}{\partial t} = \nabla \cdot [k \nabla T(r)] + \omega_b c_b (T_a - T(r))$. The tissue density, heat capacity, thermal conductivity are presented by ρ , c and k . The second term on the right side of the equation represents the blood perfusion term where, ω_b is the blood perfusion rate, c_b is the blood specific heat and T_a is the supplying blood temperature (37°C) and T is the spatial distribution of temperature. A finite element framework is used to solve the time-dependent partial differential equation numerically. MR images of two subjects are acquired from a GE 3.0T MR scanner for this simulation study. Non-fat-sat T2WI and fat-sat T2WI of prostate MR images were used for the segmentation of different tissue types (Figure 1). The segmentation is performed by an experienced radiologist. The use of local hypothermia should confer no additional risk to the patient. The target temperature (below 25 °C) and hypothermia time are set well above the limits of what has been safely reported (i.e. 4°C) for human use. Two balloon temperatures, 5°C and 10°C, are used in the simulation. The average temperature in the prostate and the temperature close to the neurovascular bundle are calculated from the simulated temperature distribution maps.

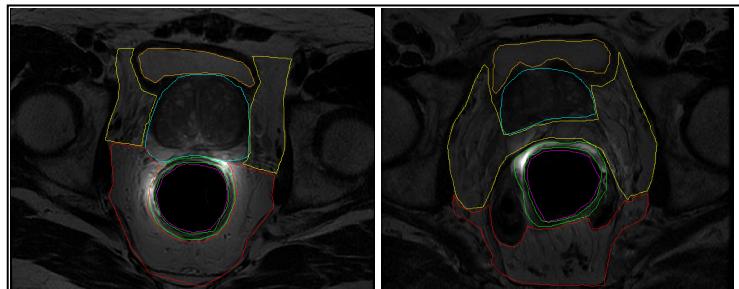


Figure 1. Segmentation of different tissue compartments. **Purple:** endorectal cooling balloon, **Green:** rectal wall, **Red:** perirectal fat; **Turquoise:** prostate gland, **Orange:** urinary bladder, **Yellow:** peri-prostatic fat (for case 1); venous plexus & seminal vesicle (for case 2).

Results: The results are shown in Figure 2. The temperature distribution map is overlaid on MR image at 1 hour, 2 hours and 3 hours after the cooling starts.

Case#1 had larger prostate size and more abundant peri-rectal fatty tissue than Case#2. For Case#1 treated with 5°C ECB, the nerve bundle near prostate reached 23.7°C after 1 hour, and the whole prostate reached 23.6°C after 3 hours. When a less powerful 10°C balloon was used, the nerve bundle near prostate reached 23.2°C after 2 hours. Case#2 had a remarkable amount of peri-prostatic venous plexus, and as expected the blood circulation would carry away the cooling effect of the ECB. Using the same 5°C ECB, it took 3 hours to reach 24.9°C near the nerve bundle (only 1 hour for Case#1), and the temperature of the prostate could not drop down to < 25°C in 3 hours. When using the less powerful 10°C ECB, neither the prostate nor nerve bundle could be cooled down to < 25°C. The results strongly suggest that such 'cool sink' effect from vascular structures needs to be taken into account for optimized ECB nerve-sparing cooling and prostate cooling.

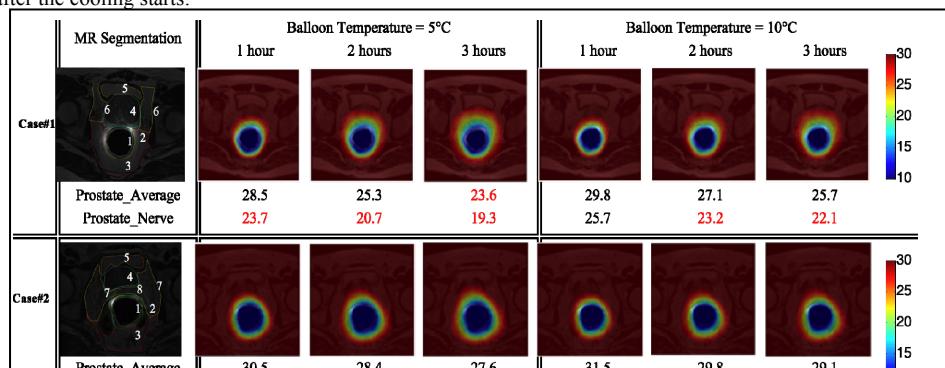


Figure 2. The temperature distribution map is overlaid on the MR image. Two ECB temperatures, 5°C and 10°C, are used. The averaged temperature from all pixels contained within the prostate gland (Prostate_Average) and the temperature close to neurovascular bundle (Prostate_Nerve) are shown. The temperature is marked as red color when it reaches the target of <25°C. Labeled tissue components: 1. endorectal cooling balloon, 2. rectal wall, 3. perirectal fat 4. prostate gland, 5. urinary bladder, 6. peri-prostatic fat, 7. venous plexus and 8. seminal vesicle.

Discussion: We have shown that the hypothermic cooling through the rectum wall across the urogenital pelvis can be simulated for each individual subject based on the MRI. The time needed to achieve the target temperature (below 25 °C) can vary significantly depending on the anatomy. The venous plexus will act as the cooling sink, and carry away the cooling effect. For patients with a considerable amount of vascular structure in pelvic region, it may be difficult to reach the target temperature. A patient specific treatment planning is needed to achieve optimized cooling effect using ECB. The prostate MR image may provide the required anatomy and tissue components for such thermal modeling. This simulation model needs to be further refined and verified using thermometry mapping experiments acquired from human subjects [3]. MR thermometry can provide detailed spatial/temporal distribution of temperature across the entire pelvic region, but the ECB needs to be modified to become MR-compatible first. If the model can be verified in human subjects, it may provide a very helpful tool for ECB cooling planning during prostatectomy.

References : 1. Finley D, et al. *J Endourology* 2009; 23(9): 1443-50. 2. Finley D, et al. *J Endourology* 2010; 24(7): 1111-16. 3. Rieke V and Pauly KB. *J Magn Reson Imaging* 2008; 27(2): 376-390.

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