

Prediction of Hypothermia during Radical Prostatectomy by Using an Endorectal Cooling Balloon: A Bioheat Simulation Based on 3D Pelvic Structure Segmented from Prostate MRI

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Background and purpose:

Hypothermia induced by using the endorectal cooling balloon (ECB) during robot-assisted radical prostatectomy and post-surgery recovery has been shown to significantly shorten the recovery time to regain urinary continence and sexual function in men [1-3]. 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. However, every individual patient has his own anatomy and tissue compositions, and this will affect the cooling range of the ECB. Currently, there is no treatment planning tool for adjusting the setting of ECB to optimize the cooling effect for each individual patient. The bioheat simulation based on the tissue anatomy segmented on prostate MRI provides a feasible solution for personalized optimization of hypothermia effect. Therefore, the purpose of this study is to evaluate the impact of 4 different factors on the hypothermia that can be reached in different tissues: 1) the blood abundance; 2) the distance of different tissue regions from the ECB; 3) the balloon temperature that is determined by the temperature of cold saline irrigated into the ECB; 4) the application of arterial ligation to decrease the blood supply.

Methods:

Six subjects who received prostate MRI for screening purposes were analyzed in this study. They do not have any abnormality in the prostate. Tissue compartments were segmented based on MR images of each individual subject on fat-sat and non-fat-sat T2 weighted images, including: rectal wall, perirectal fat, prostate gland, peri-prostatic fat, and venous plexus (blood). The segmented tissues on each 2D imaging slice are reconstructed into a 3D model, as illustrated in Fig.1, with different tissues represented by different colors. Different heat transfer properties for prostate gland, blood, muscle, and fat are considered in the simulation. The Penns bio-heat transfer function is applied to compute the temperature changes over time by using the finite element method. Five regions of interest (ROI) are selected in the analysis, including the anterior and posterior prostate, neurovascular bundle (NVB), bladder neck, and urethra (Fig. 1). The temperature time course was obtained, and based on that the equilibrium temperature and the time to reach equilibrium are used as the quantitative parameters to evaluate the hypothermia efficacy. In addition, it is known that NVB is constantly perfused by warm blood supplied by arteries, and very difficult to be cooled down. To take this effect into consideration, we incorporated an arterial supply term to the NVB in the simulation, and compared the results when the arterial ligation was performed.

Results:

Fig. 2 shows the temperature maps of subject #2 at three time points (2, 14, and 120 min) after the cooling starts. The simulation results of all 6 analyzed subjects, including the prostate volume, blood volume, the distance of NVB to ECB, and the equilibrium temperature and the time to reach equilibrium, are in Table 1. The temperature time course of Subject #2 in three conditions are illustrated in Fig. 3. As seen in the Table and Fig.3, the posterior prostate is the closest to the ECB, and can be cooled effectively. In contrast, the anterior and the bladder neck is far away from the ECB and have much worse hypothermia effect, especially in cases with a high blood volume. The arterial ligation can effectively decrease the NVB temperature (in Fig.3).

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Discussion:

We have shown that the hypothermic cooling by ECB can be simulated for each subject using an individualized 3D anatomic model reconstructed based on tissues segmented on prostate MR images. The results show that the cooling temperature and the required time are affected by the blood abundance, the ECB temperature, and the anatomical distance of tissues to the ECB. Arterial ligation can effectively decrease the perfusion of warm blood to NVB, and improve the hypothermia that can be reached to protect nerve injury. The method demonstrated in this work may be further applied to model the thermal dynamics of any heating or cooling interventions, and provides a feasible tool to evaluate the heating/cooling effect for individual patients.

References: [1] Finley et al. Urology. 2009;73(4):691-6. [2] Finley et al. J Endourol. 2009;23(9):1443-50. [3] Finley et al. J Endourol. 2010;24(7):1111-6.

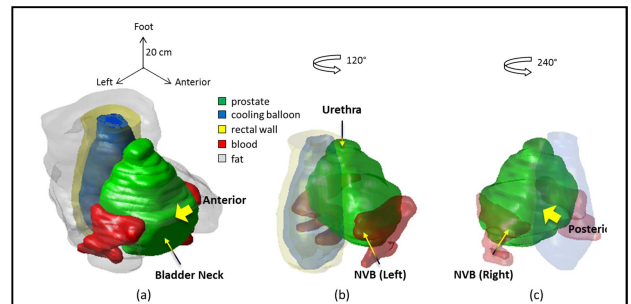


Fig 1: The 3D reconstruction of the pelvic tissue from segmentation of MR images, and the five ROIs that will be analyzed in this study: NVB (left/right), bladder neck, urethra-external sphincter complex (abbr. urethra), posterior and anterior of the prostate. The ROI size is 44 mm³ for NVB, 56 mm³ for bladder neck, 17 mm³ for urethra. These three ROIs are related to urinary incontinence and sexual dysfunction. The damage induced during radical prostatectomy can be alleviated by regional cooling from the inserted endorectal cooling balloon (ECB).

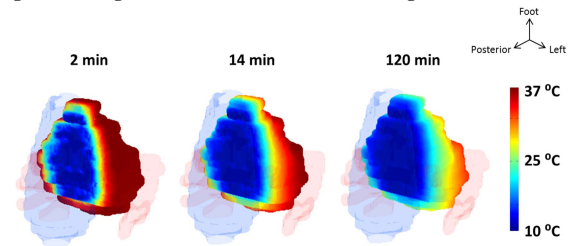


Fig 2: Simulated surface temperature of prostate at different time points. The solid color shows the gradual cooling in the prostate, turning from red to blue. The light blue shade is the boundary of ECB. The light red shade is the blood tissue surrounding prostate. The simulation covers a 3-hour period, with ECB temperature at 10 °C.

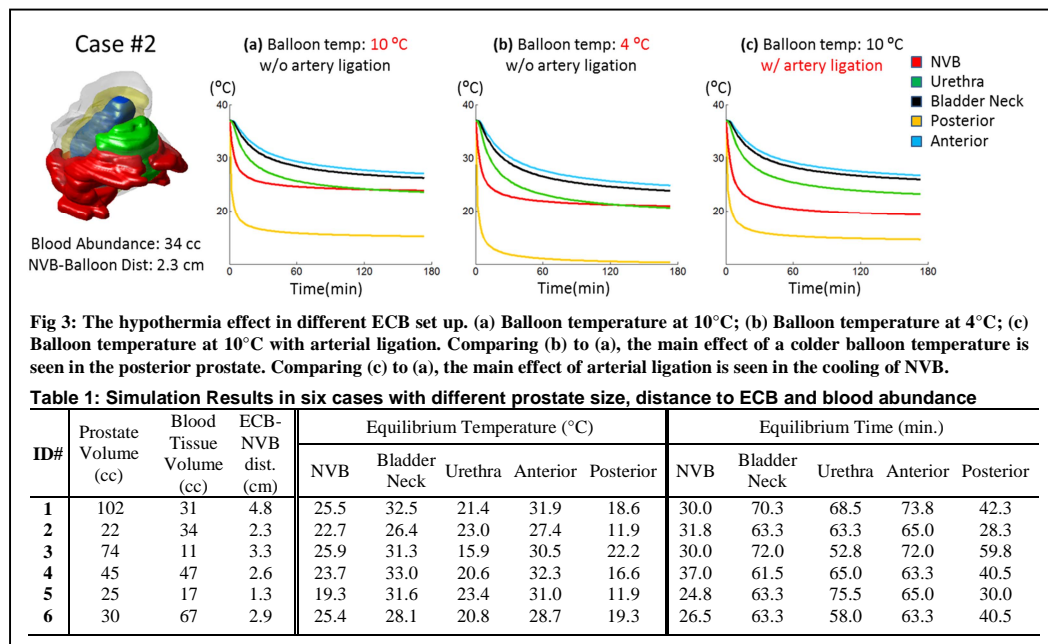


Fig 3: The hypothermia effect in different ECB set up. (a) Balloon temperature at 10°C; (b) Balloon temperature at 4°C; (c) Balloon temperature at 10°C with arterial ligation. Comparing (b) to (a), the main effect of a colder balloon temperature is seen in the posterior prostate. Comparing (c) to (a), the main effect of arterial ligation is seen in the cooling of NVB.

Table 1: Simulation Results in six cases with different prostate size, distance to ECB and blood abundance

ID#	Prostate Volume (cc)	Blood Tissue Volume (cc)	ECB-NVB dist. (cm)	Equilibrium Temperature (°C)					Equilibrium Time (min.)				
				NVB	Bladder Neck	Urethra	Anterior	Posterior	NVB	Bladder Neck	Urethra	Anterior	Posterior
1	102	31	4.8	25.5	32.5	21.4	31.9	18.6	30.0	70.3	68.5	73.8	42.3
2	22	34	2.3	22.7	26.4	23.0	27.4	11.9	31.8	63.3	63.3	65.0	28.3
3	74	11	3.3	25.9	31.3	15.9	30.5	22.2	30.0	72.0	52.8	72.0	59.8
4	45	47	2.6	23.7	33.0	20.6	32.3	16.6	37.0	61.5	65.0	63.3	40.5
5	25	17	1.3	19.3	31.6	23.4	31.0	11.9	24.8	63.3	75.5	65.0	30.0
6	30	67	2.9	25.4	28.1	20.8	28.7	19.3	26.5	63.3	58.0	63.3	40.5