Building Individualized 3D Anatomic Model Based on Prostate MRI for Hypothermia Bioheat Simulation

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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, 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. The benefit is likely coming from the decreased inflammatory reaction during the surgery by cooling down the temperature of tissues near the prostate. Among these, the neurovascular bundle (NVB), which is close to the rectum hence the cooling balloon, is likely to benefit the most from hypothermia, and can lead to a faster recovery of sexual function. However, every patient has his own anatomy and tissue compositions, and they will affect the cooling range of the ECB. Currently, there is no treatment planning tool for adjusting the setting of ECB. The bioheat simulation based on the tissue components segmented on prostate MRI provides a feasible solution for personalized optimization of hypothermia. The purpose of this study is to build an individualized anatomic model by using each patient's prostate MRI for simulating the hypothermia effect of the endorectal cooling balloon. The temperature that can be reached at several different tissue locations are simulated, and particularly how the cooling is affected by the distance of the NVB from the cooling balloon and the abundance of venous plexus (blood volume) were investigated.

Methods:

Twenty-nine (N=29, age range 53-86, mean age 68) patients who received prostate MRI were analyzed in this study. These patients received MRI because of: 1) screening due to elevated PSA but with repeated negative biopsies, 2) cancer staging due to positive biopsy, 3) radiotherapy planning after hormonal treatment, or 4) post R/T with biochemical failure. In each MRI, several different tissues were segmented based 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 were 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 were considered in the simulation. The Penns bio-heat transfer function was applied to compute the temperature changes over time by using the finite element method. Five regions of interest (ROI) were marked for the analysis, including the anterior and posterior prostate, neurovascular buddle (NVB), bladder neck, and urethra. The temperature time course was plotted. The equilibrium temperature was defined as the temperature where the change per minute was < 5%, and the time to reach equilibrium was also recorded. They were used as the quantitative parameters to evaluate the hypothermia efficacy.

Results:

Fig. 2 shows the temperature maps of Case #1 and Case #2 at three time points (2, 16, and 120 min) after the cooling starts. Case #1 has Prostate size= 25 cm^3, Blood volume= 17 cm^3; Case #2 has Prostate size= 30 cm^3, Blood volume= 37 cm^3. Their prostate sizes are comparable, but a higher blood volume in Case #2 makes cooling more difficult than in Case #1. **Fig. 3** shows the temperature time curves measured from the NVB and the posterior and anterior region of the prostate in 2 cases #22 and #29. It can be seen that the distance of the NVB to the cooling balloon is a critical factor affecting the cooling efficiency. In Case #22, the distance is only 1.7 cm and the temperature can be cooled down to 20.6°C after 31 min; in contrast, in Case #29 with a much longer distance of 11.2 cm the temperature can only reach 27.5°C after 45 min. The 2D plot of NBV equilibrium temperature with NVB-ECB distance and the total venous blood volume are shown in **Fig. 4**. It can be seen that the temperature is strongly affected by the NVB-ECB distance, less affected by the venous blood volume.

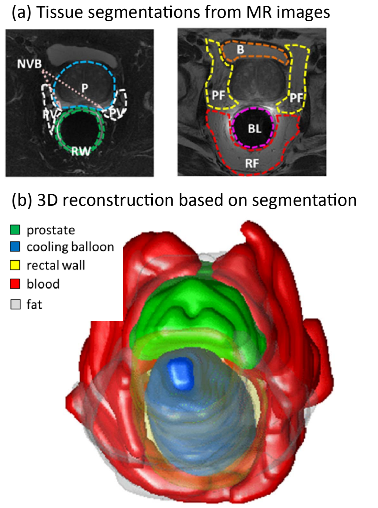

Fig. 1: (a) Segmentation of different tissues is done manually on fat-sat and non-fat-sat T2 weighted images. (b) The slice-by-slice segmented tissues are reconstructed into a 3D anatomic model for bioheat simulation.

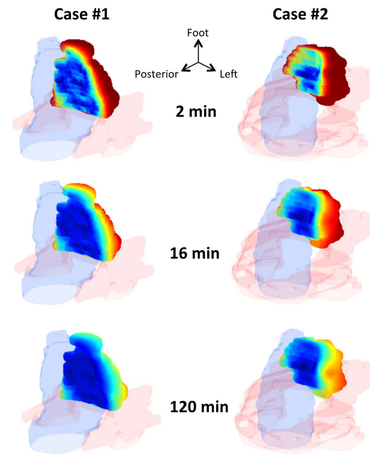

Fig. 2: Simulated surface temperature at 3 time points. The solid color shows the gradual cooling in the prostate, turning from red to blue. The light blue shade is the boundary of ECB. The light red shade is the blood tissue surrounding prostate. Case #1: Prostate size= 25 cm^3, blood volume= 17 cm^3; Case #2: Prostate size= 30 cm^3, blood volume= 37 cm^3. It can be seen that the higher blood volume in Case #2 makes the cooling more difficult.

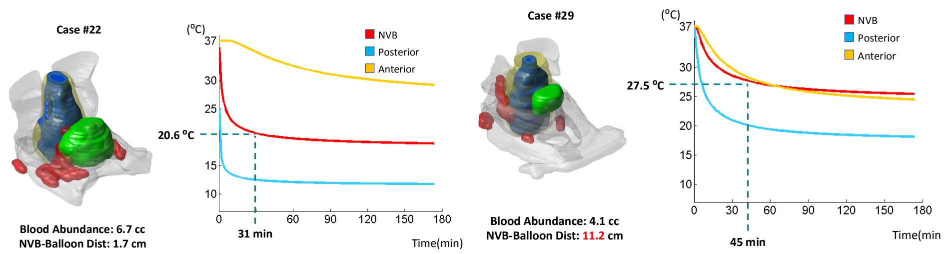

Fig. 3: The cooling time curves in 2 cases. Case #22 has a low blood volume (6.7 cc) and a very short NVB to balloon distance of 1.7 cm. The cooling in the posterior prostate and NVB is very effective (reaches 20.6°C in 31 min). Case #29 has a much longer NVB to balloon distance of 11.2 cm, and despite of a small blood volume (4.1 cc) the cooling is not efficient (reaches 27.5°C after 45 min). The anterior prostate is far away from ECB; can't be cooled down well.

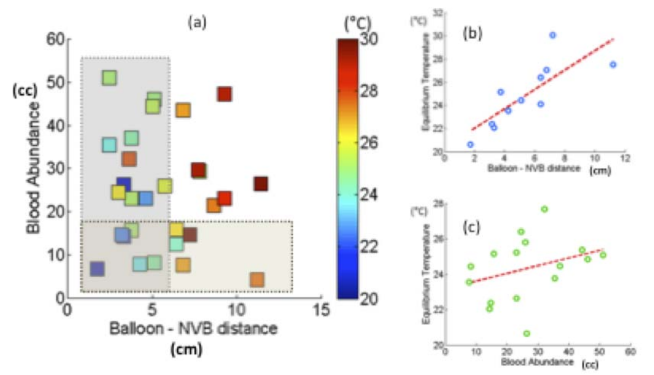

Fig. 4: (a) 2D plot of NVB temperature wrt Blood volume, NVB-ECB distance. (b) When selecting 11 cases with similar blood volume (<18cc), the temperature linearly increases with NVB-ECB distance. (c) When selecting 16 cases with NVB-ECB distance < 7 cm, the temperature increases with blood volume.

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 simulation model generates reasonable results, and is currently being validated by comparing the predicted temperature with the measured temperature using MR thermometry imaging.

References: [1] Finley et al. Urology. 2009 Apr;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.