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Investigation of factors affecting hypothermic pelvic tissue cooling using bio-heat simulation based on MRI-segmented anatomic models

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ABSTRACT

This study applied a simulation method to map the temperature distribution based on magnetic resonance imaging (MRI) of individual patients, and investigated the influence of different pelvic tissue types as well as the choice of thermal property parameters on the efficiency of endorectal cooling balloon (ECB). MR images of four subjects with different prostate sizes and pelvic tissue compositions, including fatty tissue and venous plexus, were analyzed. The MR images acquired using endorectal coil provided a realistic geometry of deformed prostate that resembled the anatomy in the presence of ECB. A single slice with the largest two-dimensional (2D) cross-sectional area of the prostate gland was selected for analysis. The rectal wall, prostate gland, peri-rectal fatty tissue, peri-prostatic fatty tissue, peri-prostatic venous plexus, and urinary bladder were manually segmented. Pennes' bio-heat thermal model was used to simulate the temperature distribution dynamics, by using an in-house finite element mesh based solver written in MATLAB. The results showed that prostate size and periprostatic venous plexus were two major factors affecting ECB cooling efficiency. For cases with negligible amount of venous plexus and small prostate, the average temperature in the prostate and neurovascular bundles could be cooled down to 25 °C within 30 min. For cases with abundant venous plexus and large prostate, the temperature could not reach 25 °C at the end of 3 h cooling. Large prostate made the cooling difficult to propagate through. The impact of fatty tissue on cooling effect was small. The filling of bladder with warm urine during the ECB cooling procedure did not affect the temperature in the prostate or NVB. In addition to the 2D simulation, in one case a 3D pelvic model

Abbreviations: MRI, magnetic resonance imaging; ECB, endorectal cooling balloon; 2D, two-dimensional; NVB, neurovascular bundle; PSA, prostate specific antigen; NFS-T2WI, non-fat-saturated T2 weighted images; FS-T2WI, fat-saturated T2 weighted images; FSE, fast spin echo; FOV, field of view; TR, repetition time; TE, echo time; P, prostate gland; RW, rectal wall; RF, peri-rectal fatty tissue; PF, peri-prostatic fatty tissue; PV, peri-prostatic venous plexus; B, urinary bladder; ROI, region of interest; FEM, finite element model; HIFU, high-intensity focused ultrasound; 3D, three-dimensional; IV, intravenous; LIIT, laser induced interstitial thermotherapy.

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was constructed for volumetric simulation. It was found that the 2D slice with the largest cross-sectional area of prostate had the most abundant venous plexus, and was the most difficult slice to cool, thus it may provide a conservative prediction of the cooling effect. This feasibility study demonstrated that the simulation tool could potentially be used for adjusting the setting of ECB for individual patients during hypothermic radical prostatectomy. Further studies using MR thermometry are required to validate the in silico results obtained using simulation.

1. Introduction

The impact of radical prostatectomy on the quality of life, including the complications on the continence and sexual function, is the main concern for patients electing to receive surgery [1,2]. In patients receiving radical prostatectomy, the dissection of the bladder neck, mobilization of the neurovascular bundles (NVBs), and transection of the urethra–external sphincter complex, cause primary acute traumatic injury. The tissue damage is associated with the direct mechanical trauma of dissection, traction, as well as thermal energy that leads to neurapraxia or axonotmesis of pelvic autonomic nerves and muscle degeneration [3,4]. The tissue inflammation may lead to the secondary wave of damage. Radical prostatectomy undoubtedly causes direct trauma and inflammatory damage to surrounding neuromuscular tissues (i.e., bladder, urethra, and nerves) that may contribute to urinary incontinence and sexual dysfunction. The inflammatory cascade includes neutrophil and macrophage infiltration with subsequent release of proteolytic enzymes, activation of coagulation factors, proinflammatory cytokine formation, hypoxia, acidosis, free radical production, and apoptosis [5,6]. It has been shown that the use of local hypothermia during robot-assisted laparoscopic prostatectomy can attenuate this injury [7–10]. Preemptive hypothermia protects tissues from damage by lowering their metabolic rates and oxygen demands [11–16]. For each degree the temperature is decreased, a 5% reduction in oxygen consumption is achieved [11], which results in less lactate formation, preserved protein synthesis and cell signaling, and decreased inflammatory response [12].

It has also been established that cooling using endorectal cooling balloon (ECB) can significantly reduce the recovery time to regain urinary continence and sexual function in men [1,2,4,17], presumably due to the profound effects in reducing an array of tissue damage coming from the direct trauma and the inflammatory reaction [11]. The ECB was fabricated using a 5″ × 2.5″ elliptical balloon fused to a 40 cm, 24-french, three-way latex urethral catheter. The balloon, which was cycled continuously with 4 °C saline, was inserted through anus and conformed to the rectal wall [18]. Previous studies have shown that among men 65 years or older, there was a significant shortening of time in regaining continence and sexual function with lower temperatures [18–23], thus the use of ECB may lead to a better surgical outcome with improved quality of life.

Currently, the ECB procedure is done for all patients in a standard fashion. Anatomically, the ECB is designed to extend from the membranous urethra to the seminal vesicles. All patients are cooled using the same set-up, and there is no consideration for the different anatomy of individual patients to ensure effective cooling of the NVBs and the prostate gland [18,19]. For example, the size of the prostate, the amount of fat, and the presence of blood vessels in the pelvic regions may affect the cooling results significantly. An individualized temperature distribution map for each patient can be obtained using a thermal simulation model, by using the bio-heat transfer equation based on the anatomical distribution of different tissues and their respective thermal properties in the pelvic region. The purposes of this exploratory simulation study are: (1) to investigate the effectiveness of ECB cooling by estimating the temperature that can be reached in NVB and the whole prostate in patients with different pelvic anatomies and tissue characteristics; (2) to evaluate how different tissue components will impact the effectiveness of ECB cooling. In particular, the amount of blood vessels, such as the peri-prostatic venous plexus, may be very different from patient to patient, and this “heat sink” effect will diminish the cooling effect, which can be investigated by comparing patients with and without extensive peri-prostatic venous plexus. The size of the prostate also varies among patients, and thus a patient with a large prostate may not be cooled efficiently. To investigate this effect, patients with large and small prostates are compared. In addition, the influence of the fat volume and the filling of bladder are considered.

In this work the simulation was focused on a 2-dimensional (2D) transverse slice that had the largest cross-sectional area of the prostate. At the base of the prostate the venous plexus was the most abundant, thus representing the worse scenario in cooling; also the NVB was very close to the prostate at this location, and most likely to be damaged by the surgical procedure. Therefore, the simulation done on this 2D slice can provide important clinically relevant information. In one case, we also constructed a 3-dimensional (3D) model for simulation, and the obtained results were compared to those of the 2D model. Similar to the concept of developing individualized treatment planning tool for radiation therapy, the ultimate goal of this project is to develop a patient-specific hypothermia surgical planning tool.

2. Materials and methods

2.1. *Subjects and image acquisition*

Four subjects with different pelvic tissue anatomy, including fatty tissue abundance, periprostatic venous abundance and prostate size were analyzed in this study. These subjects were clinically suspected to have prostate cancer due to elevated