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MRI-guided functional anatomy approach to prostate brachytherapy

Payal D. Soni[1], Alejandro Berlin[2], Aradhana M. Venkatesan[3], Patrick W. McLaughlin[1,*]

[1]Department of Radiation Oncology, University of Michigan, Ann Arbor, MI
[2]Department of Radiation Oncology, Princess Margaret Cancer Centre, Toronto, ON, Canada
[3]Section of Abdominal Imaging, Department of Diagnostic Radiology, MD Anderson Cancer Center, Houston, TX

ABSTRACT

PURPOSE: To provide an MRI based functional anatomy guide to prostate brachytherapy.

METHODS AND MATERIALS: We performed a narrative review of periprostatic functional anatomy and the significance of this anatomy in prostate brachytherapy treatment planning.

RESULTS: MRI has improved delineation of gross tumor and critical periprostatic structures that have been implicated in toxicity. Furthermore, MRI has revealed the significant anatomic variants and the dynamic nature of these structures that can have significant implications for treatment planning and dosimetry.

CONCLUSIONS: The MRI-based functional anatomy approach to prostate brachytherapy takes into account extent of disease, its relation to the patient's individual anatomy, and functional baseline to optimize the therapeutic ratio of prostate cancer treatment.

Keywords: Functional anatomy; Prostate; Prostate cancer; Brachytherapy; MRI

Introduction

There are over 3 million prostate cancer survivors in the United States, with the 15-year survival rate of prostate cancer reaching 95% (1). Therefore, the goal of prostate cancer treatment must emphasize preservation of quality of life just as much as cure. Brachytherapy is a highly effective and economical treatment for prostate cancer (2−10). The highly conformal nature of brachytherapy treatments allows for significant dose escalation to areas of disease while minimizing dose to vulnerable regional anatomy that is critical to daily functions and quality of life. The true potential of brachytherapy is becoming clearer as MRI plays a larger role in prostate cancer management.

There are profound limitations to traditional CT-based postimplant dosimetry (11, 12). The prostate boundaries are obscured, the actual tumor is not defined, and critical adjacent structures merge with and are commonly included in the "prostate" contour, leaving patients at risk of treatment failure and urinary, bowel, and sexual dysfunction. Functional outcomes after prostate brachytherapy typically fall on a spectrum that ranges from complete preservation of function, to bothersome symptoms which may be transient or controlled with medication, to severe reversible complications which have significant morbidity and may require invasive remedies, and finally to severe irreversible complications which can be life-altering events. Although the majority of severe complications are reversible as demonstrated in brachytherapy trials with long-term followup (13−15), it is difficult to accept even a small number of severe irreversible complications given the impact they have on a patient's quality of life, in the context of a frequently curable or indolent disease course such as early-stage prostate cancer.

The MRI functional anatomy approach replaces CT with MRI-based preimplant and postimplant planning that can improve tumor and functional anatomy delineation, improve implant quality, and ultimately shift the goal of treatment from avoiding complications to preserving function. MRI-based postimplant dosimetry has already defined the mechanism responsible for many severe complications. For example, MRI has clearly identified dose delivery below the prostate apex which contributes nothing to cure and has been implicated in complications such as stricture and rectal-urethral fistula, demonstrating the need for further technical refinement. Vessel-sparing

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* Corresponding author. Department of Radiation Oncology, University of Michigan, Assarian Cancer Center, 47601 Grand River Avenue, Novi, MI 48374. Tel.: 248-465-4300; fax: 248-465-5471.

E-mail address: mclaughb@med.umich.edu (P.W. McLaughlin).

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radiation is one example in which the MRI-based functional anatomy approach has demonstrated an unprecedented level of sexual function preservation, with further improvement likely as other candidate targets are defined (16).

Functional anatomy is an umbrella term for a wide variety of anatomic categories impacting brachytherapy practice and outcomes (Table 1). Functional anatomy includes mobile (17−19) and immobile (20−22) adjacent structures that play a role in genitourinary, gastrointestinal, and sexual function. One cannot surmise functional status of an active tissue from anatomic configuration alone. For example, an extremely enlarged prostate does not reliably predict urinary obstructive symptoms (23), just as a small prostate does not guarantee normal urination. Furthermore, most common functions adjacent to the prostate are not single tissue dependent but rather are coordinated and carefully sequenced activations of several structures. Variant anatomy is the recognition of the wide diversity in functional anatomic structures and the variable capacities to dose limit some of these variants (24−26). Implant anatomy refers to the profound effect that probe placement has on adjacent anatomic relationships and the potential for misinterpretation of implant quality with the probe in place (27). Postimplant dynamic anatomy refers to the active motion of the prostate and adjacent musculature, and their ability to impact seed position after an implant has been completed (28). Finally, tumor anatomy as defined by multiparametric MRI (mpMRI) may define the actual tumor grade and location within the prostate (peripheral zone or transition zone) and beyond the prostate (29).

Table 1
Anatomic categories

1) Functional anatomy
a) Mobile (dynamic)
i) Bladder neck
ii) Genitourinary diaphragm
iii) External sphincter
iv) Rectourethralis
v) Seminal vesicle
vi) Levator ani
vii) Rectum, lower rectal segment, and anal sphincter
b) Immobile
i) Neurovascular elements
ii) Internal and accessory pudendal arteries
iii) Corpus cavernosa
iv) Penile bulb
v) Dorsal vascular complex
vi) Verumontanum
vii) Ejaculatory ducts
viii) Prostatic and membranous urethra
2) Variant anatomy
a) Bladder neck
i) Intact
ii) Expanded
iii) Effacement (intrabladder extension)
iv) Asymmetric intrabladder extension (median lobe)
b) External sphincter
i) Apex to penile bulb length
ii) Intraprostate extension
c) Neurovascular elements
i) Bundle configuration
ii) Plexus configuration
3) Implant anatomy (probe effects)
i) Potential space (bound by rectum, apex, and GU diaphragm)
ii) Prostate rotation
iii) Asymmetric swelling
iv) Rectourethralis extension
4) Postimplant dynamic anatomy
i) Rectourethralis recoil (potential space obliteration)
ii) Bladder neck
iii) Levator ani and GU diaphragm
5) Tumor anatomy (mpMRI)
a) Peripheral zone and:
i) Extraprostatic extension
ii) Seminal vesicle involvement
iii) GU diaphragm extension
iv) Anterior extension
b) Transition zone and:
i) Absence of bladder neck involvement
ii) Bladder neck involvement
iii) Intrabladder extension
iv) Urethra involvement

mpMRI = multiparametric MRI.

To achieve a balance in functional and disease-specific outcomes, it is important to properly define the target volumes and the functional anatomy at risk. Superimposing tumor distribution obtained from mpMRI over individual functional anatomy (best seen on T2-weighted MRIs) will reveal opportunities to achieve cure while protecting quality of life. Herein, we review all relevant anatomic categories by region (base, mid, and apex) and discuss the implications for treatment planning and the unique implant and dosimetric challenges to consider to enhance the therapeutic index of brachytherapy for prostate cancer.

Brachytherapy challenge at the base

The bladder neck and seminal vesicles are two key structures in close proximity to the base of the prostate that play important roles in urinary and sexual function, respectively. The prostate base is comprised purely of transition zone, a region at low risk of harboring prostate cancer in most patients. Using MRI to identify patients with no evidence of disease at the base can allow for de-escalation of dose in this region to reduce urinary and sexual dysfunction after prostate brachytherapy. Most acute urinary toxicity, whether obstructive or irritative, can be attributed to dose at the base.

Mobile functional anatomy

The point of connection between the bladder and the prostate base is a highly active region in the adult male. There is still significant controversy over the true structure of the bladder neck and its mechanism of action (18, 30, 31). Increasing evidence from pathologic and radiographic studies