

Evaluation of the Changes in the Shape and Location of the Prostate and Pelvic Organs Due to Bladder Filling and Rectal Distension

M Lotfi¹, MH Bagheri¹, MA Mosleh-Shirazi², R Faghihi³, M Baradaran-Ghahfarokhi^{4*}

¹Department of Radiology, Medical Imaging Research Center, ²Department of Radiotherapy, Center for Research in Medical Physics and Engineering, Nemazee Hospital, ³Department of Mechanical Engineering, Radiation Research Center, Shiraz University of Medical Sciences, Shiraz, ⁴Department of Medical Physics and Engineering, School of Medicine, Isfahan University of Medical Sciences, Isfahan, Iran

Abstract

Background: A steep dose gradient between prostate and organs at risk (rectum and bladder) is ideal in treatment modality, so prostate displacement and deformation due to bladder filling and rectal distension play an important role in critical organs dose. This study aims to evaluate the changes in the shape and location of the prostate and pelvic organs due to bladder filling and rectal distension.

Methods: Three patients who referred for transrectal prostatic biopsy (Shahid Faghihi Hospital, Shiraz, Iran) with different prostate sizes were enrolled. A 1.5-Tesla MRI system (Avanto, Siemens, Germany) and an ultrasound system (Logiq 500, GE medical systems, USA) were used to collect images of patients prostate at different stages of bladder and rectum fullness.

Results: The mean displacement of the prostate after bladder filling in the supine and left decubitus positions along the Anterior-Posterior (AP) axis was posterior by 4.9 mm (range: 0.7-6.3 mm) and along the Superior-Inferior (SI) axis was inferior by 3.4 mm (range: 1.4-5 mm). Prostate displacement in the Left-Right (LR) axis was negligible. The mean prostate displacement after rectal distension was anterior by 7.1 mm in the supine position, 5.1 mm anterior in the left decubitus position and along the SI axis was inferior by 2.5 mm in the supine and left decubitus positions. The maximum prostate deformation due to rectal distension and bladder filling in the supine position was as large as 3.2 mm, 1.9 mm and 1.2 mm in the AP, SI and LR directions respectively. While in the left decubitus position, it was 2.6 mm, 1.2 mm and 1.3 mm in the AP, LR and SI axis respectively.

Conclusion: It is probably of importance to evaluate the influence of the changes in the shape and location of the prostate due to bladder filling, rectal distension and patient position in post-implant brachytherapy dosimetry. Using images of the patients in the left decubitus position with full bladder and distended rectum for planning a treatment are suggested.

Keywords: Prostate; Displacement; Deformation; Bladder filling; Rectal distension; MRI; US

Introduction

In developed countries, prostate cancer is the second most frequently diagnosed cancer, and the third most common cause of death from cancer in men.¹ The

annular crude incidence rate of this cancer in Fars Province, southern Iran was shown to be 0.64 with an age specific rate of 1.00.² Its highest incidence was in Shiraz and in 2005.³ Today prostate brachytherapy has become an increasingly popular treatment for localized prostate cancer.⁴ In prostate brachytherapy a steep dose gradient between prostate and organs at risk (rectum and bladder) is ideal, so prostate displacement and deformation may be critical to the total dose delivered to each organ.⁵⁻⁷

*Correspondence: Milad Baradaran-Ghahfarokhi, MD, Department of Medical Physics and Medical Engineering, Isfahan University of Medical Sciences, Isfahan, Iran. Tel: +98-913-3155377, Fax: +98-311-6688597, e-mail: milad_bgh@yahoo.com

Received: October 10, 2010

Accepted: January 20, 2011

However, it is known that the anatomical position of the prostate gland can be affected by the physiological movements of the surrounding pelvic organs such as the rectum and bladder. A consequence of this motion in brachytherapy may be an increased radiation dose to surrounding normal tissues.

Previous authors have demonstrated that movements of the prostate relative to the bony pelvis were related to differential filling of bladder and bowel.⁸ Using Computed Tomography (CT) imaging, Deurloo *et al.* found that the prostate behaved as a rigid body,⁹ whereas, using cine-MRI, Ghilezan *et al.* found that it deformed in the anteroposterior (AP) direction.¹⁰ Most studies assessing prostate movement, have imaged the prostate gland by repeated computed tomography (CT) scans over the course of radiotherapy.^{11,12} Although these assessments have been serially repeated, all these studies have evaluated prostate position in a very limited time frame. Other direct imaging techniques such as seed implants and ultrasound imaging,¹³⁻¹⁵ kilovoltage (KV) cone beam computed tomography (CBCT)^{16,17} or CT on rails¹⁸ were used for studying prostate displacement.

Seed implants method is an invasive method, also the Fiducial Markers (FMs) might migrate within the gland. Shirato *et al.* observed a significant in-migration of prostatic FMs for patients treated without hormones, and some authors have observed no significant in-migration of prostatic FMs.¹⁹⁻²¹ However, other authors did not describe a time dependence of intermarker distances.^{22,23} Ultrasonography (US) is simple, quick, noninvasive, painless and repeatable. Its accuracy has been proven but less accurate than other methods and completely depends on radiologist skill. Also pressure from US probe caused additional organs motion. When images of the prostate were obtained with an endorectal ultrasound probe or magnetic resonance imaging (MRI) coil, it was apparent that the prostate could deform. CT method had low contrast in delineating soft tissue with slack of radiation protection. Modern imaging systems like Megavoltage (MV) portal imaging devices inherently had lower contrast than KV images because of a greater percentage of Compton interaction.²⁴ This might blur prostatic borders, especially at the bladder interface. MRI is a good method to assess prostate and its neighboring organs. It enables direct visualization of soft-tissue targets and organs at risk at the expense of time and cost, as opposed to US and CT.

The purpose of this study was to evaluate the interrelationship between normal rectal distension,

bladder filling and their movements, and to quantify total prostate displacement and deformation due to physiologic organs filling measured by using MRI based shifts and estimates the precision with which the shifts are made in supine and left decubitus positions.

It is our assumption that breathing does would not cause obvious prostate displacement.²⁵ We also used US imaging besides MRI. According to best of our knowledge, this is the first study of prostate displacement and deformation due to rectal distension and bladder filling simultaneously in two different encountered positions (Supine and left decubitus). Knowledge of these displacements is clinically relevant because planning a brachytherapy is limited to the supine and lithotomy positions with neglecting stages of organs filling and other patient-related daily positions (such as decubitus) encountered during post implant prostate irradiation period.

Materials and Methods

The study protocol was approved by the Medical Imaging Research Center at the Shiraz University of Medical Sciences. Patients were eligible if they had prostatic problems, and gave written, informed consent to the study and underwent diagnostic pelvic MRI and transabdominal US imaging for staging purposes. Table1 illustrates patients' characteristics.

Table 1: Patient characteristics.

Characteristic	mean (range)
Age (years)	54 (26-67)
interval between biopsy and MRI (weeks)	4 (3-5)
maximal anterior-posterior (AP) dimensions of the patients at the level of the prostate (mm)	44.6 (23.3-55.9)
Maximal lateral dimensions of the patients at the level of the prostate (mm)	47.2 (24.4-59.1)
prostate-specific antigen level (ng/mL)	10 (9.8-10.2)
Prostate size (mL)	54.6 (32-71)
Gleason biopsy score	5 (4-6)

A 1.5-Tesla MRI system (Avanto, Siemens, Germany) was used to collect sequential axial and sagittal images of patients prostate with different sizes. Routine T1- and T2-weighted sequences with a pelvic

coil were used for the MR imaging. Contrast agent was not administered. For each patient, four sets of images in three stages were obtained in a axial T1-weighted (T1-w) Turbo factor (spin echo) sequence; field of view [FOV]: 36 cm; matrix: 512×512; time repetition [TR]/time echo [TE]: 718/10 ms; slice thickness [ST]: 3 mm, T2-weighted (T2-w) Turbo factor (spin echo) sequence; field of view [FOV]: 36 cm; matrix: 512×512; time repetition [TR]/time echo [TE]: 3200/73 ms; slice thickness [ST]: 3 mm and in a sagittal T1-weighted (T1-w) turbo factor spin echo sequence; FOV: 25 cm; TR/TE: 350/12 ms; ST: 4 mm with 0 mm gap. A sagittal T2 spin echo sequence was acquired to accurately position the prostate apex on the cranio-caudal axis.^{26,27} For the imaging stages, first patients were scanned with full bladder and rectum 8 hours after their fibrous meal, instructed not to empty their bladder and rectum before planning the first MRI. They were imaged in the supine and left decubitus positions on a flat tabletop and set up using a set of triangulation lasers. Next, they were instructed to empty their bowels and bladder as much as possible and were imaged with previous protocol. Antiperistaltic medications were not employed because purge medications would affect normal physiological movement of the rectum. Furthermore, they were instructed to drink 1 liter (L) of fluid 1 hour (h) before planning the third MRI. This bladder and bowel regimen was intended to ensure that they were comfortably full or empty at the time of imaging. Tables 2 illustrates imaging study stages.

Table 2: Imaging study stages.

Study stages	Rectum	Bladder
I	F	F
II	E	E
III	E	F

F: Full, E: Empty

The images from all sequences were used to evaluate the interrelationship between rectal distension, and bladder filling and rectal, bladder movement, and the effect of their movement on prostate gland shape and position. The MR images were initially acquired using a separate program and then imported into advantage workstation software (ver. 4.3, G.E medical systems) for organs position measurements. An expert radiologist in prostate MRI interpretation reviewed all imaging sets. He contoured the prostate and its neighboring organs for each patient (Figure 1).

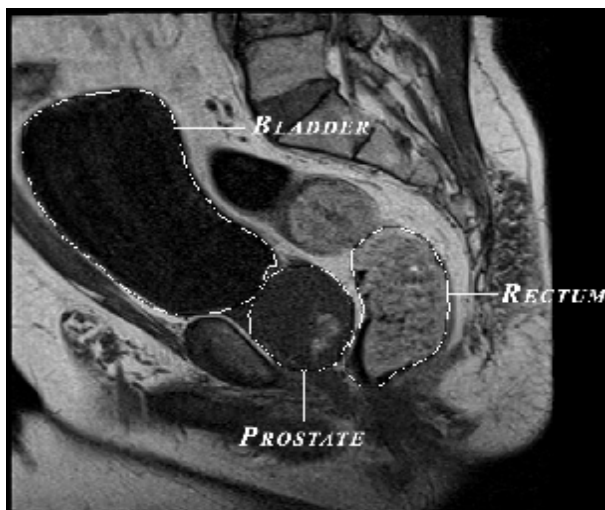


Fig. 1: Organs contouring in the stage I.

For each image, the rectum, bladder and prostate gland were outlined on the second stage images (baseline) and organs movements in the first and third stage measured relative to the baseline (second stage). The images were analyzed for the following features: magnitude of rectal distension and bladder filling, prostate deformation, displacement and rotation relative to the baseline prostate outline.

The volumes were calculated by manually determining the prostate outline on every axial T1-weighted MRI slices. The reader drew a freehand contour around the prostate on each imaging slice on advantage workstation. For each slice, the number of pixels within the contour was automatically established and with the known in-plane resolution and slice thickness, the prostate and bladder volume were calculated. They were measured by the product of the maximum bi-dimensional axial and sagittal diameters at the level of the prostate. The maximum bi-dimensional diameter product was calculated as the multiple of the longest and widest diameter of the rectum and bladder taken perpendicularly (Figure 2).

It was assessed by the maximum motion measurement in all three directions (AP: Anterior-Posterior, LR: Left-Right, SI: Superior-Inferior) in the axial and sagittal images relative to the baseline (second stage). For example, bladder motion in the lateral direction had the maximum membrane displacement in LR axis and in the axial image relative to fix bony pelvic. Reader assessed the changes of the prostate size in three directions relative to the second stage images. The largest medial AP and LR diameters were measured in the axial plane, and the largest SI

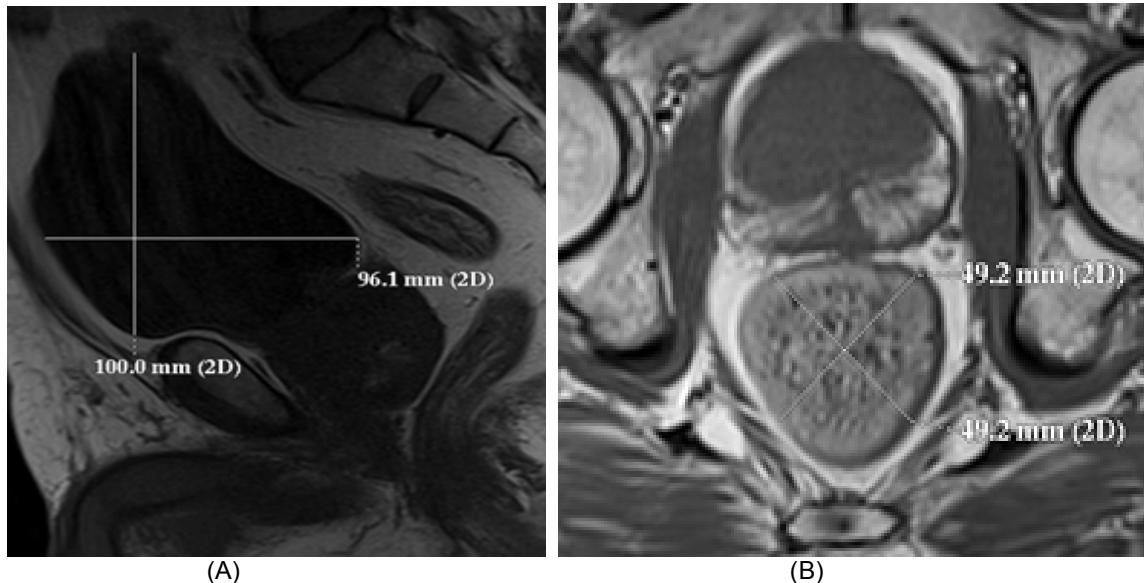


Fig. 2: Maximum bi-dimensional diameters of the organs in stage III and I, (A) Bladder sagittal, (B) Rectum axial.

diameter was assessed in the sagittal plane (Figure 3).

Prostate displacements from the baseline position in the AP, LR and SI directions occurring as a result of rectal distension and bladder filling were measured relative to pelvic bony structure in the sagittal and axial images.

Figure 4 and 5 show extreme examples of motion from an axial and sagittal scan of initial patient anatomy in both positions. Three different frames were shown for each plane. The initial frames showed the first image and one later in the series. The third frame shows the difference image obtained by superimposing the first two. Intraobserver error was estimated by performing the same measurements on a patient two times by single

observer. The same plane was found each time from the pixel coordinates. The position of the edge of the prostate along the plane defined by a particular x or y pixel value was assessed two times for the same image.

US imaging were done before each stages of MRI. It made us confidence of organ fullness. Suprapubic images were acquired with an ultrasound system (Logiq 500, GE medical systems, USA) with patient in the MRI positions by an expert radiologist. The US device was equipped with a digital display screen and a handheld transabdominal scanning head. Ultrasound localization of the prostate and neighboring organs was performed immediately before MRI to decrease the affect of organ filling on the measurements accuracy.

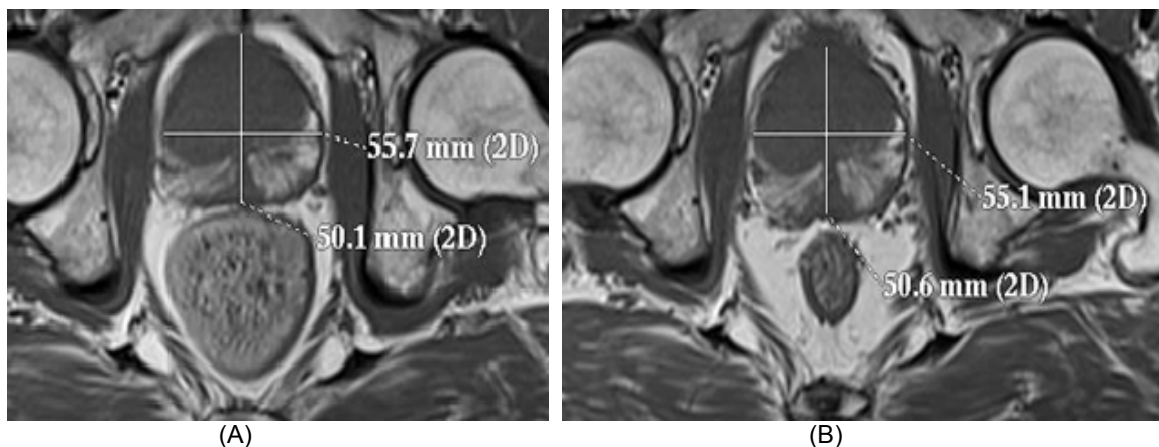


Fig. 3: Prostate deformation in the supine position stage I (A) relative to stage II (B) (base line)

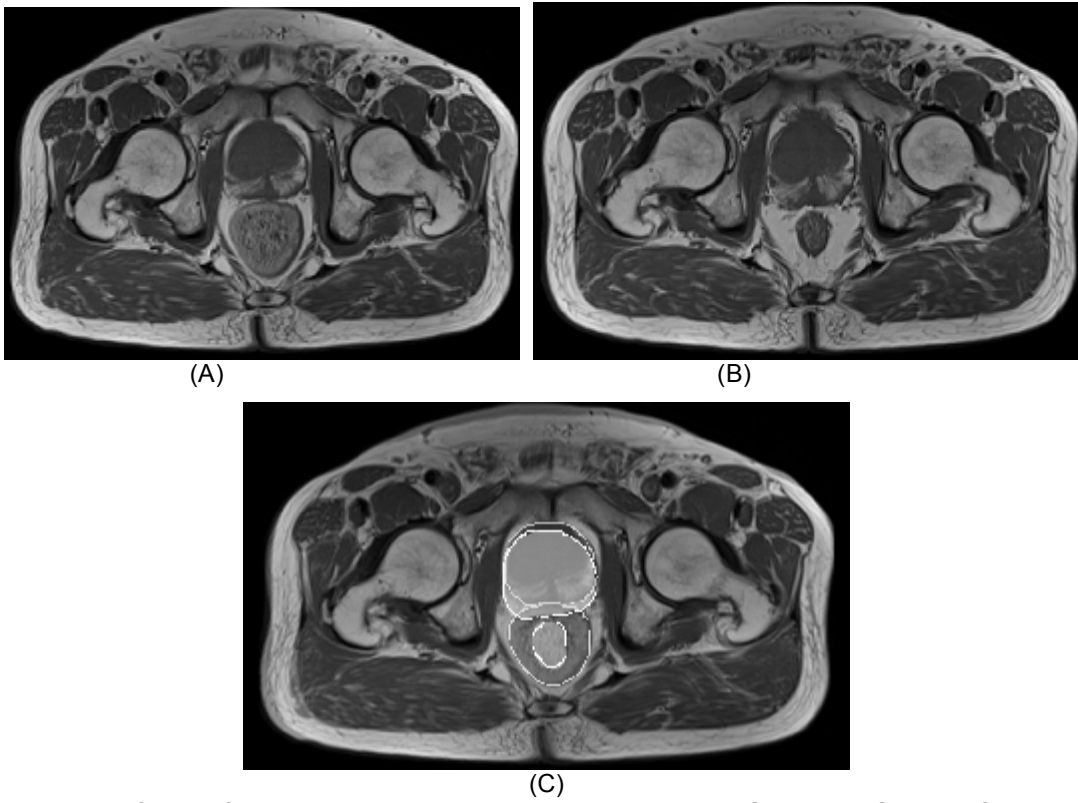


Fig. 4: Axial image fusion of the patient anatomy in the supine position (A) Stage I (B) Stage II (C) Fused image

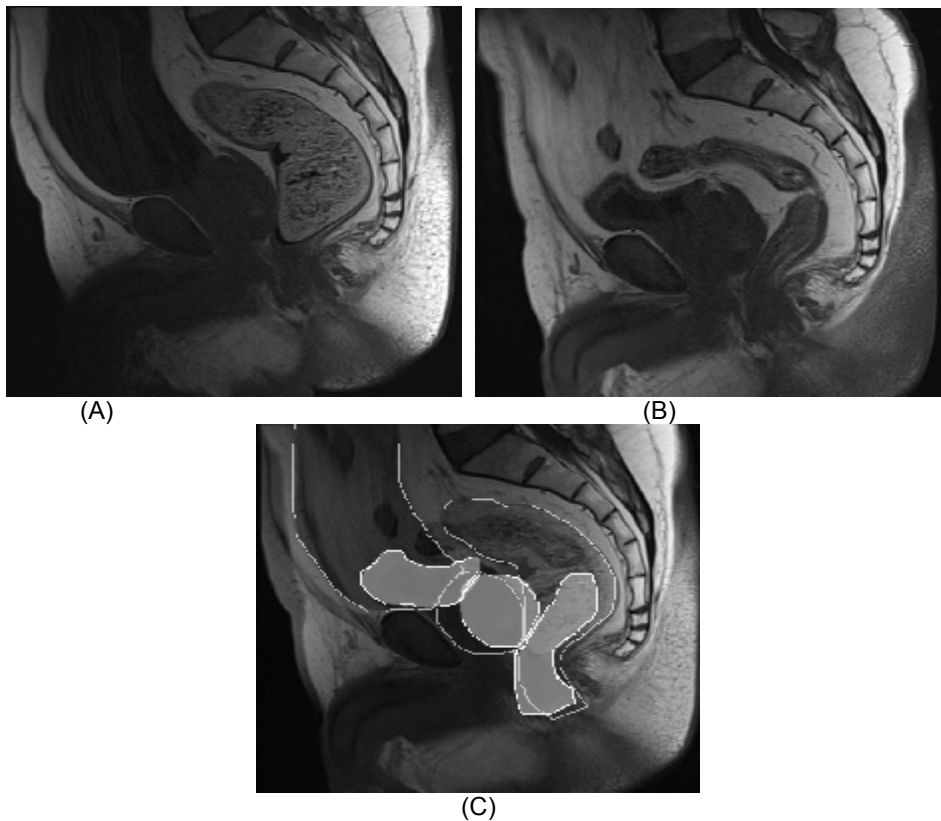


Fig. 5: Sagittal image fusion of the patient anatomy in the supine position (A) Stage I (B) Stage II (C) Fused image

Prostate and bladder volumes were measured by an expert radiologist. The scanning head was positioned at the midline above the pubic symphysis and the volume calculated manually by the radiologist. Longitudinal and transverse scans that give the greatest diameter were obtained with the transducer positioned above the symphysis pubis (Figure 6). The width (W), length (L) and the cranio-caudal diameter (height [H]) in the sagittal plane were recorded. We used the formula described by the radiologist to calculate the bladder and prostate volume.

$$V = H (W \times L) \times 0.52$$

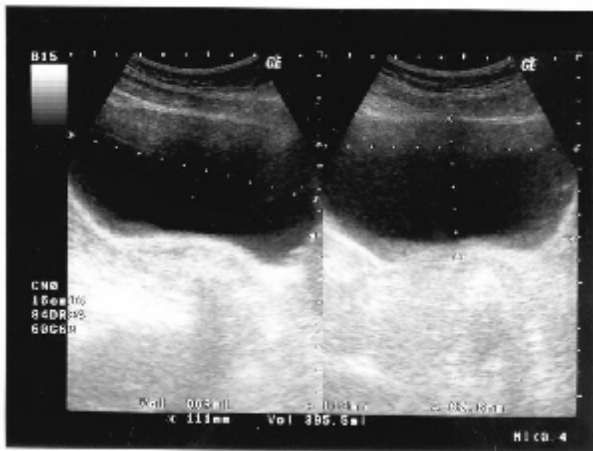


Fig. 6: Bladder volume calculation from the longitudinal and transverse scans.

Trained US and MRI measurements performed 2 times for each organ. For the Statistical analysis, the mean of measurements were denoted as V_{bl-US} , V_{pr-US} and V_{bl-MRI} , V_{pr-MRI} . For evaluating the relation between V_{bl-US} , V_{pr-US} and V_{bl-MRI} , V_{pr-MRI} , Wilcoxon test was performed. Data were analyzed using SPSS

software (version 16.0, Chicago, IL, USA). $P \leq 0.05$ was considered statistically significant.

Results

Table 3 and 4 illustrate bladder and rectal volume and surface area in the supine and left decubitus positions. As illustrated previously, Figure 4 and 5 show an example of organ motion due to changes in filling of the bladder and rectum. The maximum bi-dimensional area of the distended rectum was 68×65.9 mm while it was 43.4×33.8 mm for the empty one.

Bladder filling as well as rectal distension resulted in prostate displacements in all directions. Filling of the bladder resulted in the bladder displacement, especially in the anterior and cranial directions. Emptying the rectum but maintaining a full bladder resulted in an overall posterior movement of the bladder. The ranges for bladder motions in each of the directions were large, indicating a considerable variation in organ motion in each of the patients. Comparing MR images stage I and II, distension of the rectum resulted in rectal motion in the AP direction. In the left decubitus position, bladder tended to move in the LR direction more than rectum (Tables 5 and 6).

The maximum prostate deformation in the supine position was as large as 3.2 mm, 1.9 mm and 1.2 mm in the AP, SI and LR directions respectively. Maximum deformation in the left decubitus position was 2.6 mm, 1.2 mm and 1.3 mm in the AP, SI and LR directions respectively. The maximum and mean displacement of the prostate gland after bladder filling in the supine and left decubitus positions along the AP axis was posterior by 6.3 mm and 4.9 mm respectively

Table 3: Bladder volume and surface area in full and empty bladder.

	Stage ^{c)}	Volume (cm ³)	Supine surface area ^{a)} (cm ²)	Left decubitus surface area (cm ²)
P1 ^{b)}	F	383	228.9	239.9
	E	160	68.8	76.8
P2	F	256.8	108.8	150.7
	E	94.8	41.1	59.4
P3	F	180	105.1	115.2
	E	26	16.1	19.8
Average (SD)	F	266.6 (102.5)	147.6 (70.4)	168.6 (64.2)
	E	93.6 (67)	42 (26.4)	2 (29.2)

^{a)}Surface area is the product of maximum bi-dimensional diameter at the level of the prostate, ^{b)}P1 refers to the first patient, ^{c)}Patients instructed to drink 1 liter of water before the 3rd stage, F: Full, E: Empty

Table 4: Rectal surface area in distended and empty rectum.

Stage ^{a)}		Surface area (mm ²)	
		Supine	Left decubitus
P1	D	4481.2	3404.8
	E	1466.9	1467.0
P2	D	2730.0	2857.8
	E	450.5	491.6
P3	D	513.8	716.0
	E	262.7	278.5
Average (SD)	D	2575.0 (1988.2)	2326.2 (1421.0)
	E	726.7 (647.9)	745.7 (633.7)

^{a)}D: Distended, E: Empty

Table 5: Bladder motion in SI direction.

Stage		SI diameter (mm)	
		Supine	Left decubitus
P1	F	182.4	190.1
	E	29.3	34.1
P2	F	69.6	80.9
	E	6.1	10.3
P3	F	35.4	79.7
	E	6.0	10.2
Average (SD)	F	95.8 (76.9)	116.9 (63.4)
	E	13.8 (13.4)	18.2 (13.8)

Table 6: Rectal motion in AP direction.

Stage		AP diameter (mm)	
		Supine	Left decubitus
P1	F	44.8	47.5
	E	12.7	16.1
P2	F	34.9	40.2
	E	11.7	16.0
P3	F	10.3	26.3
	E	9.8	10.2
Average (SD)	F	30 (17.8)	38.0 (10.7)
	E	11.4 (1.5)	14.1 (3.4)

(range: posterior displacement of 0.7- 6.3 mm) and along the SI axis was inferior by 5 mm and 3.4 mm respectively (range: inferior displacement 1.4-5 mm). Prostate displacement in LR axis was negligible (Table 7). The maximum and mean prostate displacement after rectal distension was anterior by 8.3 mm and 7.1 mm respectively (range: anterior displacement of 0.7-8.3 mm) in the supine position, 7.3 mm and 5.1 mm anterior in the left decubitus position and along the SI axis was inferior by 3 mm and 2.5 mm in the supine and left decubitus positions (range: inferior displacement 1.1-4.4 mm). Prostate displacement due to bladder filling in the LR direction was negligible.

Large rectal movements were more likely to result in greater than 7.6 mm of prostatic displacement and 3.2 mm of its deformation (Table 8).

Large systematic rotations of the prostate about the LR axis have been observed (SD: 1°) Maximum and median rotation of the prostate was 5° and 4.6° after distension of the rectum (range: 4-5°) in the supine position and 4° and 3.6° (range: 3-4°) in the left decubitus position. Bladder filling causes negligible prostate rotation. In the Statistical analysis, Based on a total of 18 US measurements, good relation between V_{bl-US} , V_{pr-US} and V_{bl-MRI} , V_{pr-MRI} was found ($P=0.260$), indicating a high accuracy of the US.

Table 7: Prostate displacement after bladder filling.

	Supine (mm)			Left decubitus (mm)		
	AP	SI	LR	AP	SI	LR
P1	-5.3 ^{a)}	-4.0	1.6	-6.3	-5.0	4.7
P2	-2.4	-3.6	0.4	-4.0	-4.1	4.1
P3	-0.7	-2.0	0.4	-2.0	-1.4	0.8
Average (SD)	-2.8 (2.3)	-3.2 (1.1)	0.8 (0.7)	-4.1 (2.2)	-3.5 (1.9)	3.2 (2.1)

^{a)}It is our assumption that Anterior, Superior, left motion is positive so minus means prostate moves to the posterior, inferior and right

Table 8: Prostate displacement and deformation after bladder filling and rectal distension.

	Supine (mm)			Left decubitus (mm)		
	AP	SI	LR	AP	SI	LR
P1	6.5	-4.4	1.1	7.3	-2.9	1.7
P2	6.5	-3.5	1	4.1	-2.6	1.4
P3	8.3	-1.1	0.9	3.9	-2.0	1.1
Average (SD)	7.1 (1.0)	-3 (1.7)	1 (0.1)	5.1 (1.9)	-2.5 (0.5)	1.4 (0.3)

Discussion

In prostate brachytherapy, treatment plan was performed in the supine and lithotomy positions while we observed that moving to the left decubitus position leading to significant changes in the shape and location of the pelvic organs. This may increase hazards of the radiation to the normal surrounding organs in this treatment modality. Also in brachytherapy, US was used for the pre-implant dosimetry while its accuracy was completely dependent on radiologist skills and its field of view was restricted.

Magnetic resonance imaging is known to provide more reproducible delineation of the prostate than CT and US imaging. T1-weighted images have been shown to have excellent properties for soft-tissue imaging of the prostate and its neighboring organs (bladder and rectum). It also provides good delineation of their contact area. The organ volumes obtained on the MR image sets were highly reproducible. The most detailed previous study on prostate and seminal vesicle deformation was done by Deurloo *et al.*,⁹ who quantified the shape variations of the prostate and seminal vesicles using repeated CT scans. It could be argued that the prostate deformation observed in this study was due to rectal distension. However counteracting error could trace it. The maximum error of the contouring was less than 1 mm, which assessed by re-contouring process. Previous authors have demonstrated that movements of the prostate relative to the bony pelvis that were related to differential filling of bladder and bowel.⁶ In addition, prostate deformation

under the influence of changes in physiologic rectal filling was observed in a study using cine-MRI.¹⁰ According to our results, we were able to demonstrate that prostate deformation was significantly related to physiologic rectal filling.

There were significant differences in the magnitude of the prostate displacement due to bladder filling or rectal distension. For larger displacements, the base of the prostate has larger amplitude of motion than the apex, presumably because the levator muscles anchor the prostate at the apex. These findings were consistent with the observations of previous investigators.²⁸ However, most of the prostate displacements were in the superior and anterior directions. There was a statistically significant difference between the motions that occurred with the rectum being empty when compared to being full. For larger rectal motions, the prostate appeared to be both compressed in the AP direction and forced superiorly. Our results were generally consistent with the result of Padhani *et al.*,²⁹ who found a correlation between the degree of rectal distension and the prostate displacement.

Because we had different sized patient populations, our results had general data about prostate displacement, deformation and rotation. In addition, there were significant differences between the motions we measured in the AP, SI directions on both axial and sagittal scans with Padhani *et al.* The reasons for these differences may due to differences in organ sizes, patient diet and time since last meal. Another possible reason for the differences may be in our approaches to measure motion. Padhani *et al.*

measured the center of mass and we measured the border of the prostate. Nevertheless, the methods alone were not likely the reason.

We noted that there were no significant displacements of bony landmarks during the stages of scans (<1 mm). We did not correct for these small motions because during brachytherapy, it is the motion of the prostate relative to the neighboring organs and not the bony anatomy that affects the dose received by the organs.³⁰ After rectal distension, there were no differences in the magnitude of mean prostate movement when we compared patients with early prostate tumors to those with no tumors.

Bladder filling, rectal distension and patient position caused significant changes in the shape and location of the pelvis organs. It is important to evaluate the influence of the changes in the shape and location of the prostate due to bladder filling, rectal distension

and patient posture in post-implant brachytherapy dosimetry. Using images of the patient in the left decubitus position with full bladder and distended rectum for planning a treatment suggested.

Acknowledgement

The study was supported by a grant from the Medical Imaging Research Center, Shiraz University of Medical Sciences, Shiraz, Iran. The authors wish to thank Dr. M. Rastegari from the urology Department, Dena Hospital and Mr. A. Nehrir, Mr. M. R. Dizavandi and Ms. Z. Sharifi from the Radiology Department, Shahid Faghihi Hospital, Shiraz, Iran for their critical technical support and advice.

Conflict of interest: None declared.

References

- Damber JE, Aus G. Prostate cancer. *Lancet* 2008;**371**:1710-21. [18486743] [[http://dx.doi.org/10.1016/S0140-6736\(08\)60729-1](http://dx.doi.org/10.1016/S0140-6736(08)60729-1)]
- Mehrabani D, Tabei SZ, Heydari ST, Shamsina SJ, Shokrpour N, Amini M, Masoumi SJ, Julaei H, Farahmand M, Manafi A. Cancer occurrence in Fars Province, Southern Iran. *Iran Red Crescent Med J* 2008;**10**:314-322.
- Farahmand M, Khademolhosseini F, Mehrabani D. Trend of prostate cancer in Fars Province, Southern Iran, 2001-2007. *J Res Med Sci* 2009;**15**:1-3.
- Machtens S, Baumann R, Hagemann J, Warszawski A, Meyer A, Karstens JH, Jonas U. Long-term results of interstitial brachytherapy (LDR-Brachytherapy) in the treatment of patients with prostate cancer. *World J Urol* 2006;**24**:289-95. [16645877] [<http://dx.doi.org/10.1007/s00345-006-0083-1>]
- Pollack A, Zagars GK, Starkschall G, Antolak JA, Lee JJ, Huang E, von Eschenbach AC, Kuban DA, Rosen I. Prostate cancer radiation dose response: results of the M. D. Anderson phase III randomized trial. *Int J Radiat Oncol Biol Phys* 2002;**53**:1097-105. [12128107] [[http://dx.doi.org/10.1016/S0360-3016\(02\)02829-8](http://dx.doi.org/10.1016/S0360-3016(02)02829-8)]
- Storey MR, Pollack A, Zagars G, Smith L, Antolak J, Rosen I. Complications from radiotherapy dose escalation in prostate cancer: preliminary results of a randomized trial. *Int J Radiat Oncol Biol Phys* 2000;**48**:635-42. [11020558] [[http://dx.doi.org/10.1016/S0360-3016\(00\)00700-8](http://dx.doi.org/10.1016/S0360-3016(00)00700-8)]
- Ten Haken RK, Forman JD, Heimbürger DK, Gerhardtsson A, McShan DL, Perez-Tamayo C, Schoeppel SL, Lichter AS. Treatment planning issues related to prostate movement in response to differential filling of the rectum and bladder. *Int J Radiat Oncol Biol Phys* 1991;**20**:1317-24. [2045306] [[http://dx.doi.org/10.1016/0360-3016\(91\)90244-X](http://dx.doi.org/10.1016/0360-3016(91)90244-X)]
- van Herk M, Bruce A, Kroes AP, Shouman T, Touw A, Lebesque JV. Quantification of organ motion during conformal radiotherapy of the prostate by three dimensional image registration. *Int J Radiat Oncol Biol Phys* 1995;**33**:1311-20. [7493856] [[http://dx.doi.org/10.1016/0360-3016\(95\)00116-6](http://dx.doi.org/10.1016/0360-3016(95)00116-6)]
- Deurloo KE, Steenbakkens RJ, Zijp LJ, de Bois JA, Nowak PJ, Rasch CR, van Herk M. Quantification of shape variation of prostate and seminal vesicles during external beam radiotherapy. *Int J Radiat Oncol Biol Phys* 2005;**61**:228-38. [15629616] [<http://dx.doi.org/10.1016/j.ijrobp.2004.09.023>]
- Ghilezan MJ, Jaffray DA, Siewerdsen JH, Van Herk M, Shetty A, Sharpe MB, Zafar Jafri S, Vicini FA, Matter RC, Brabbins DS, Martinez AA. Prostate gland motion assessed with cinemagnetic resonance imaging (cine-MRI). *Int J Radiat Oncol Biol Phys* 2005;**62**:406-17. [15890582] [<http://dx.doi.org/10.1016/j.ijrobp.2003.10.017>]
- Beard CJ, Kijewski P, Bussi ere M, Gelman R, Gladstone D, Shaffer K, Plunkett M, Castello P, Coleman CN. Analysis of prostate and seminal vesicle motion: implications for treatment planning. *Int J Radiat Oncol Biol Phys* 1996;**34**:451-8. [8567348] [[http://dx.doi.org/10.1016/0360-3016\(95\)02081-0](http://dx.doi.org/10.1016/0360-3016(95)02081-0)]
- Roach M 3rd, Faillace-Akazawa P, Malfatti C. Prostate volumes and organ movement defined by serial computerized tomographic scans during three-dimensional conformal radiotherapy. *Radiat Oncol Invest* 1997;**5**:187-94. [9327498] [[http://dx.doi.org/10.1002/\(SICI\)1520-6823\(1997\)5:4<187::AID-ROI4>3.0.CO;2-U](http://dx.doi.org/10.1002/(SICI)1520-6823(1997)5:4<187::AID-ROI4>3.0.CO;2-U)]
- Simforoosh N, Dadkhah F, Hosseini SY, Asgari MA, Nasser A, Safarinejad MR. Accuracy of residual urine measurement in men: comparison between real-time ultrasonography and catheterization. *J Urol* 1997;**158**:59-61. [918632] [<http://dx.doi.org/10.1097/00005392-199707000-00016>]
- Bih LI, Ho CC, Tsai SJ, Lai YC, Chow W. Bladder shape impact on the accuracy of ultrasonic estimation of bladder volume. *Arch Phys Med Rehabil* 1998;**79**:1553-6. [9862299] [[http://dx.doi.org/10.1016/S0003-9993\(98\)90419-1](http://dx.doi.org/10.1016/S0003-9993(98)90419-1)]
- Scarborough TJ, Golden NM, Ting JY, Fuller CD, Wong A, Kupelian PA, Thomas CR Jr. Comparison of ultrasound and implanted seed

- marker prostate localization methods: Implications for image-guided radiotherapy. *Int J Radiat Oncol Biol Phys* 2006;**65**:378-87. [16563658] [<http://dx.doi.org/10.1016/j.ijrobp.2006.01.008>]
- 16 Smitsmans MH, Wolthaus JW, Arignan X, de Bois J, Jaffray DA, Lebesque JV, van Herk M. Automatic localization of the prostate for online or off-line image-guided radiotherapy. *Int J Radiat Oncol Biol Phys* 2004;**60**:623-35. [15380600]
- 17 Letourneau D, Martinez AA, Lockman D, Yan D, Vargas C, Ivaldi G, et al. Assessment of residual error for online cone-beam CT-guided treatment of prostate cancer patients. *Int J Radiat Oncol Biol Phys* 2005;**62**:1239-46. [15913917] [<http://dx.doi.org/10.1016/j.ijrobp.2005.03.035>]
- 18 Dong L, Crevoisier Rd, Bonnen M ea. Evaluation of an ultrasound-based prostate target localization technique with an in-room CT-on-rails [abstract]. *Int J Radiat Oncol Biol Phys* 2004;**60**:332-3.
- 19 Litzenberg D, Dawson LA, Sandler H, Sanda MG, McShan DL, Ten Haken RK, Lam KL, Brock KK, Balter JM. Daily prostate targeting using implanted radiopaque markers. *Int J Radiat Oncol Biol Phys* 2002;**52**:699-703. [11849792] [[http://dx.doi.org/10.1016/S0360-3016\(01\)02654-2](http://dx.doi.org/10.1016/S0360-3016(01)02654-2)]
- 20 Pouliot J, Aubin M, Langen KM, Liu YM, Pickett B, Shinohara K, Roach M 3rd. (Non)-migration of radiopaque markers used for on-line localization of the prostate with an electronic portal imaging device. *Int J Radiat Oncol Biol Phys* 2003;**56**:862-6. [1278819] [[http://dx.doi.org/10.1016/S0360-3016\(03\)00267-0](http://dx.doi.org/10.1016/S0360-3016(03)00267-0)]
- 21 Madsen BL, Hsi RA, Pham HT, Presser J, Esagui L, Corman J, Myers L, Jones D. Intrafractional stability of the prostate using a stereotactic radiotherapy technique. *Int J Radiat Oncol Biol Phys* 2003;**57**:1285-91. [14630263] [[http://dx.doi.org/10.1016/S0360-3016\(03\)00746-6](http://dx.doi.org/10.1016/S0360-3016(03)00746-6)]
- 22 Chung PW, Haycocks T, Brown T, Cambridge Z, Kelly V, Alasti H, Jaffray DA, Catton CN. On-line aSi portal imaging of implanted fiducial markers for the reduction of interfraction error during conformal radiotherapy of prostate carcinoma. *Int J Radiat Oncol Biol Phys* 2004;**60**:329-34. [15337572] [<http://dx.doi.org/10.1016/j.ijrobp.2004.03.038>]
- 23 Dehnad H, Nederveen AJ, van der Heide UA, van Moorselaar RJ, Hofman P, Lagendijk JJ. Clinical feasibility study for the use of implanted gold seeds in the prostate as reliable positioning markers during megavoltage irradiation. *Radiother Oncol* 2003;**67**:295-302. [12865177] [[http://dx.doi.org/10.1016/S0167-8140\(03\)00078-1](http://dx.doi.org/10.1016/S0167-8140(03)00078-1)]
- 24 Khan F. *The physics of radiation therapy*. ed r, editor. Philadelphia: Lippincott Williams & Wilkins; 2010.
- 25 Dawson LA, Litzenberg DW, Brock KK, Sanda M, Sullivan M, Sandler HM, Balter JM. A comparison of ventilatory prostate movement in four treatment positions. *Int J Radiat Oncol Biol Phys* 2000;**48**:319-23. [10974443] [[http://dx.doi.org/10.1016/S0360-3016\(00\)00751-3](http://dx.doi.org/10.1016/S0360-3016(00)00751-3)]
- 26 Khoo VS, Padhani AR, Tanner SF, Finnigan DJ, Leach MO, Dearnaley DP. Comparison of MRI with CT for the radiotherapy planning of prostate cancer: a feasibility study. *Br J Radiol* 1999;**72**:590-7. [10560342]
- 27 Krempien RC, Schubert K, Zierhut D, Steckner MC, Treiber M, Harms W, Mende U, Latz D, Wannemacher M, Wenz F. Open low-field magnetic resonance imaging in radiation therapy treatment planning. *Int J Radiat Oncol Biol Phys* 2002;**53**:1350-60. [12128138] [[http://dx.doi.org/10.1016/S0360-3016\(02\)02886-9](http://dx.doi.org/10.1016/S0360-3016(02)02886-9)]
- 28 Wu J, Haycocks T, Alasti H, Ottevell G, Middlemiss N, Abdolell M, Warde P, Toi A, Catton C. Positioning errors and prostate motion during conformal prostate radiotherapy using on-line isocentre set-up verification and implanted prostate markers. *Radiother Oncol* 2001;**61**:127-33. [11690677] [[http://dx.doi.org/10.1016/S0167-8140\(01\)00452-2](http://dx.doi.org/10.1016/S0167-8140(01)00452-2)]
- 29 Padhani AR, Khoo VS, Suckling J, Husband JE, Leach MO, Dearnaley DP. Evaluating the effect of rectal distension and rectal movement on prostate gland position using cine MRI. *Int J Radiat Oncol Biol Phys* 1999;**44**:525-33. [10348281] [[http://dx.doi.org/10.1016/S0360-3016\(99\)00040-1](http://dx.doi.org/10.1016/S0360-3016(99)00040-1)]
- 30 de Boer HC, van Os MJ, Jansen PP, Heijmen BJ. Application of the No Action Level (NAL) protocol to correct for prostate motion based on electronic portal imaging of implanted markers. *Int J Radiat Oncol Biol Phys* 2005;**61**:969-83. [15752876] [<http://dx.doi.org/10.1016/j.ijrobp.2004.09.035>]