Respiratory-Induced Prostate Motion
Characterization and Quantification in Dynamic MRI

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Background and Purpose: To investigate prostate movement during deep breathing and contraction of abdominal musculature by means of dynamic MRI and analyze implications for image-guided radiotherapy of prostate cancer.

Patients and Methods: A total of 43 patients and 8 healthy volunteers were examined with MRI. Images during deep respiration and during contraction of abdominal musculature (via a coughing maneuver) were obtained with dynamic two-dimensional (2D) balanced SSFP; 3 frames/s were obtained over an acquisition time of 15 s. Images were acquired in sagittal orientation to evaluate motion along both the craniocaudal (cc)-axis and anteroposterior (ap)-axis. Prostate motion was quantified semi-automatically using dedicated software tools.

Results: Respiratory induced mean cc-axis displacement of the prostate was 2.7 ± 1.9 (SD) mm (range, 0.5–10.6 mm) and mean ap-axis displacement 1.8 ± 1.0 (SD) mm (range, 0.3–10 mm). In 69% of the subjects, breathing-related prostate movements were found to be negligible (< 3 mm). The prostate displacement for abdominal contraction was significantly higher: mean cc-axis displacement was max. 8.4 ± 6.7 (SD) mm (range, 0.6–27 mm); mean anteroposterior movement was 8.3 ± 7.7 (SD) mm (range, 0.7–26 mm).

Conclusion: Dynamic MRI is an excellent tool for noninvasive real-time imaging of prostate movement. Further investigations regarding possible applications in image-guided radiotherapy, e.g., for individualized planning and in integrated linac/MRI systems, are warranted.

Key Words: Dynamic MRI ∙ Organ motion ∙ Prostate

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Ateminduzierte Bewegung der Prostata: Charakterisierung und Quantifizierung mittels dynamischer MRT

Zielsetzung: Ziel dieser Studie war die nicht-invasive Analyse der ateminduzierten Prostatabewegung mittels dynamischer MRT-Bildgebung im Hinblick auf die Auswirkungen für die bildgestützte Radiotherapie beim Prostatakarzinom.


Ergebnisse: Die Prostata bewegte sich synchron mit der Zwerchfellbewegung. Die kraniokaudale atembedingte Prostatabewegung betrug 2,7 ± 1,9 (SD) mm (Range 0,5–10,6 mm), während die anteroposteriore Bewegung bei 1,8 ± 1 (SD) mm (Range 0,3–10 mm) lag. 69 % der Prostatabewegungen waren kleiner als 3 mm. Bei maximaler abdominaler Muskelkontraktion bewegte sich die Prostata signifikant mehr als allein aufgrund der Atmung. Die Muskelkontraktion verursachte eine kraniokaudale Prostatabewegung von max. 8,4 ± 6,7 (SD) mm (Range 0,6–27 mm). Die AP-Bewegung betrug 8,3 ± 7,7 (SD) mm (Range 0,7–26 mm).


Schlüsselwörter: Dynamische MRT ∙ Organbewegung ∙ Prostata

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Introduction
The biochemical control rate (PSA recurrence free survival) of prostate cancer after definitive radiotherapy could be significantly improved by escalating the total dose above 72 Gy [5, 11, 15, 22, 24, 29], especially in patients with intermediate (stage T2b, Gleason score 7, or PSA level 10.1–20 ng/mL) and high risk disease. However, the treatment toxicity can be increased with the use of higher radiation doses, particularly regarding the rectum and bladder, unless high precision radiotherapy techniques are used to limit exposure of normal tissues [8, 9, 13, 30]. To increase the dose to the target volume and decrease radiation exposure of adjacent normal organs, modern methods of radiation delivery can be used. First, a conformal dose distribution that restricts the high dose area to the prostate should be generated, e.g., by three-dimensional conformal radiotherapy (3D-CRT), intensity-modulated radiotherapy (IMRT), or particle therapy with protons or heavier ions.

Second, the movements of the prostate both between fractions (interfractional) and during treatment (intrafractional) should be taken into account by individualized margins or by compensation and correction techniques during delivery. In this context, daily online imaging and correction of prostate position, e.g., by cone-beam CT, can be employed to minimize the effects of systematic and random interfractional prostate motion and setup variation. However, it does not address the remaining intrafractional variation of the prostate position. It is known that the anatomical position of the prostate gland and seminal vesicles is influenced by the physiological movements of respiration and of the surrounding pelvic organs [1, 20, 21]. This has direct implications for radiotherapy planning and delivery, especially in conformal radiotherapy where the treatment planning margins can be much more closely tailored to the prostate.

Recent studies have evaluated the anatomical variability of the position of the prostate gland within the pelvis during a 6–7 week course of radical irradiation for prostate cancer [16, 19]. Furthermore, it was shown that internal organ movement during a period similar to the delivery of a single fraction of radiotherapy (approx. 10 minutes) may be significant but not as important as interfractional organ displacements. Several methods have been proposed to evaluate prostate motion, including fluoroscopy, sonography, magnetic resonance imaging (MRI), and recently the implantation of magnetic intraprostatic fiducials [17]. MRI techniques have been recently successfully introduced for the evaluation of thoracic tumor motion [6, 25].

The objective of the presented study was to investigate the feasibility of cine MRI imaging for quantitative evaluating prostate movements in real time and to analyze possible implications for image-guided radiotherapy.

Patients and Methods
Subjects’ Characteristics
A total of 8 healthy volunteers with a median age of 30.2 years (range, 24.2–32.7) were enrolled in this study. None of them had any prior surgery in the pelvis. In addition, 43 patients with biopsy-proven adenocarcinoma of the prostate were analyzed in this study. Median age was 67.4 years (range, 49.9–79.6). Patients included in this study had T1c–T2c prostate cancer with C3 certainty (histology confirmed by needle biopsy and staging with MRI and endosonography). Patients were excluded if they had any prior radiation therapy or surgery within the pelvis.

After the nature of the procedure had been fully explained, informed consent was provided by all participants under an institutionally approved subject research protocol.

MRI Examination
All examinations were performed in supine position using a clinical 1.5-T whole-body scanner (Magnetom Symphony, Siemens Medical Solutions, Erlangen, Germany) equipped with eight receiver channels, a 6-channel coil, endorectal coils, and a high performance gradient system (30 mT/m; slew rate 120 mT/m/s). The following standard MR sequences for pelvic imaging were initially performed: axial turbo spin-echo (TSE) T1- and T2-weighted, sagittal and coronal T2-weighted turbo spin-echo imaging. All volunteers were examined without an endorectal coil. The use of an endorectal coil for the patients was optional, but not obligatory. While 15 patients agreed to be examined with and without an endorectal coil during the same session, 28 patients declined and were examined without the endorectal coil. A true fast imaging with steady-state precension (balanced SSFP; TrueFISP) sequence was adapted to acquire dynamic MRI scans of the pelvis. For measurement of the

Figure 1. Collection of images obtained with a time-resolved balanced 2D SSFP study during free breathing (temporal resolution 3 images/s). The series covers a full respiratory cycle. For the analysis of displacement, the images are overlaid with a white reference line which allows identification of prostate motion.