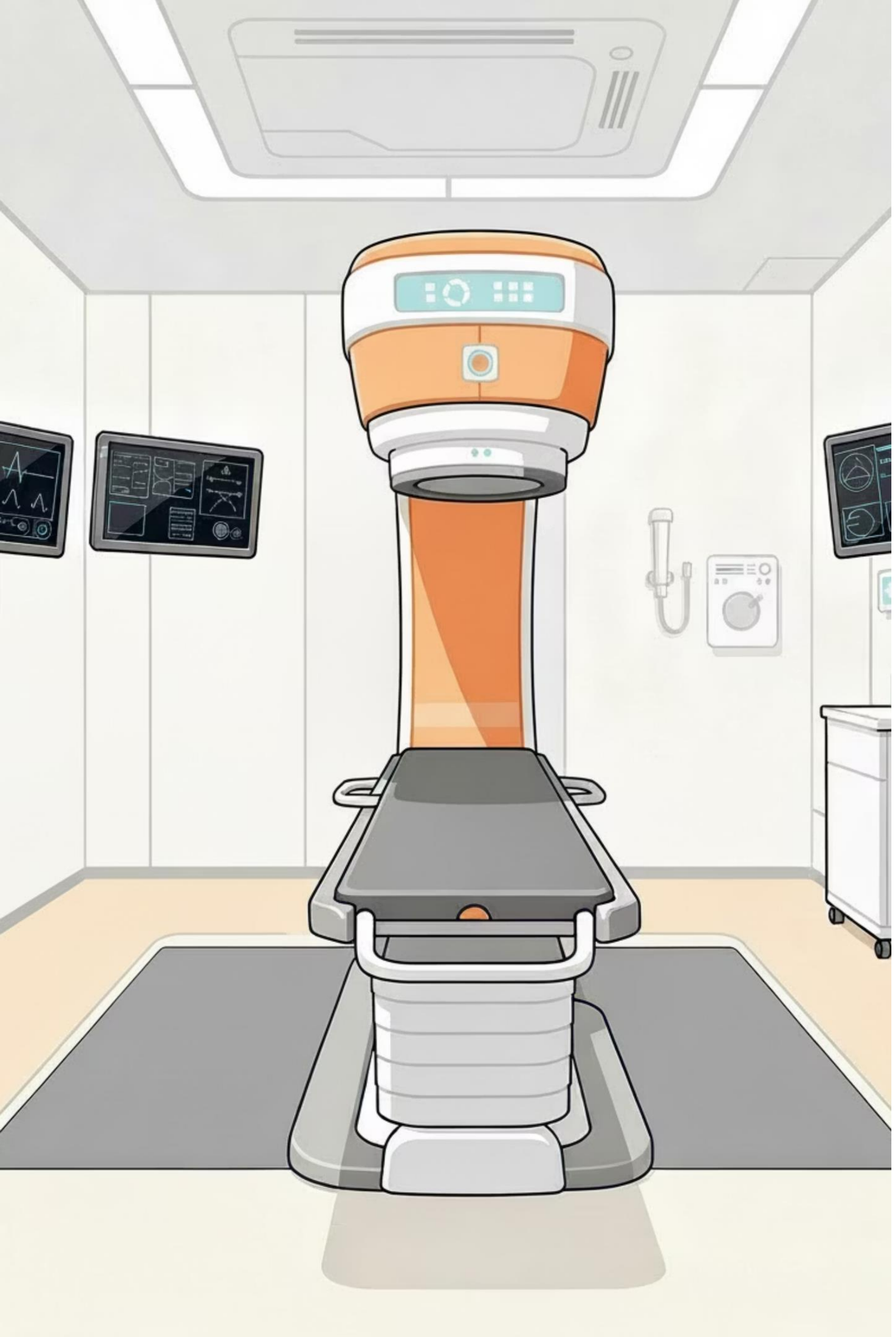

Motion Management in Prostate SBRT:

Impact of Technological Innovations on SBRT Delivery

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Disclosures

Speaking Honorarium

Received honorarium and travel support for participation in this meeting

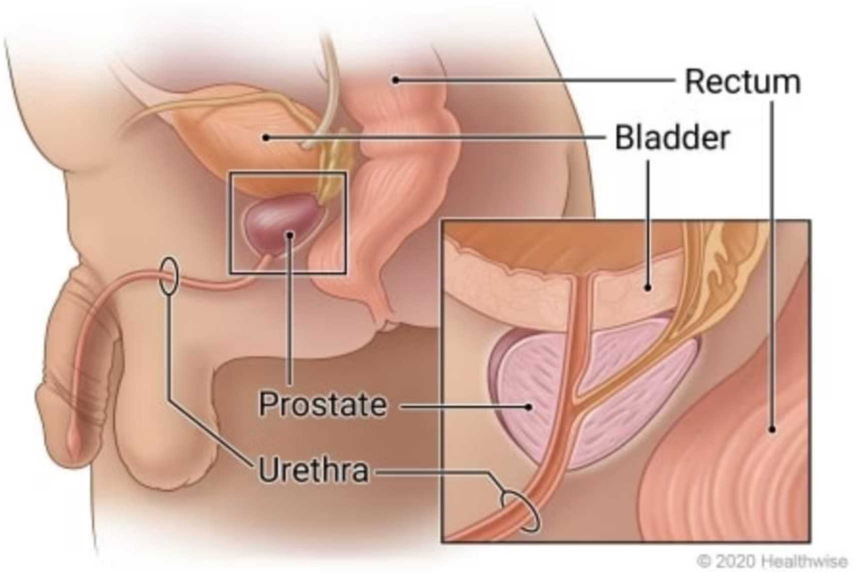
Research Collaborations

Montefiore Medical Center maintains ongoing research collaboration agreements with Accuray and Varian Medical Systems

Presentation Overview

1. **Introduction**
   Understanding the clinical importance of motion management in prostate SBRT
2. **Sources of Prostate Motion**
   Identifying physiological and anatomical factors driving target displacement
3. **Measuring Prostate Motion**
   Examples of measured prostate motions
4. **Accounting for Prostate Motion**
   Gating and compensation strategies across treatment platforms
5. **PTV Margin Reduction**
   Clinical evidence supporting reduced margins with motion management
6. **Future Directions**
   Emerging technologies and adaptive treatment paradigms

Introduction: The Challenge of Prostate Motion



Even when patients remain perfectly still during treatment setup and delivery, the prostate exhibits significant motion within the body. This motion stems primarily from bladder filling dynamics and transient rectal gas passage.

SBRT delivery protocols compound this challenge with longer setup and treatment times compared to conventional fractionation, increasing exposure to intrafraction motion.

Effective motion management enables substantial PTV margin reduction, directly decreasing dose to surrounding normal tissues including rectum, bladder, and neurovascular bundles.

Treatment systems address motion through gating (beam interruption) or real-time compensation (dynamic adjustment).

https://www.cigna.com/knowledge-center/hw/anatomy-of-the-prostate-tp10105

Sources of Intrafraction Motion: Patient Movement

Despite comprehensive immobilization systems designed to maximize patient comfort and minimize gross body movement, residual motion remains inevitable.

Patient motion characteristics exhibit significant variability both between patients and across treatment fractions for the same individual. This stochastic nature makes motion prediction challenging and necessitates real-time monitoring approaches.

Bio-mechanical Considerations

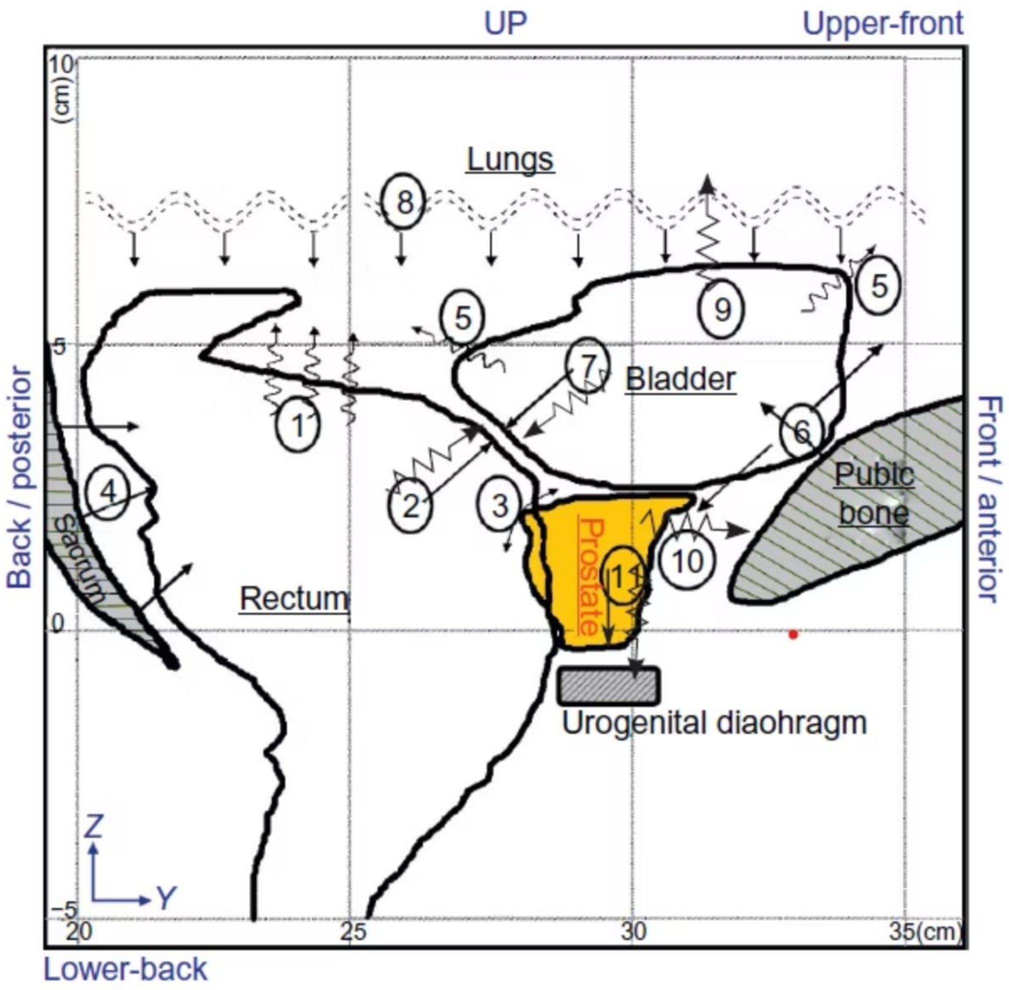
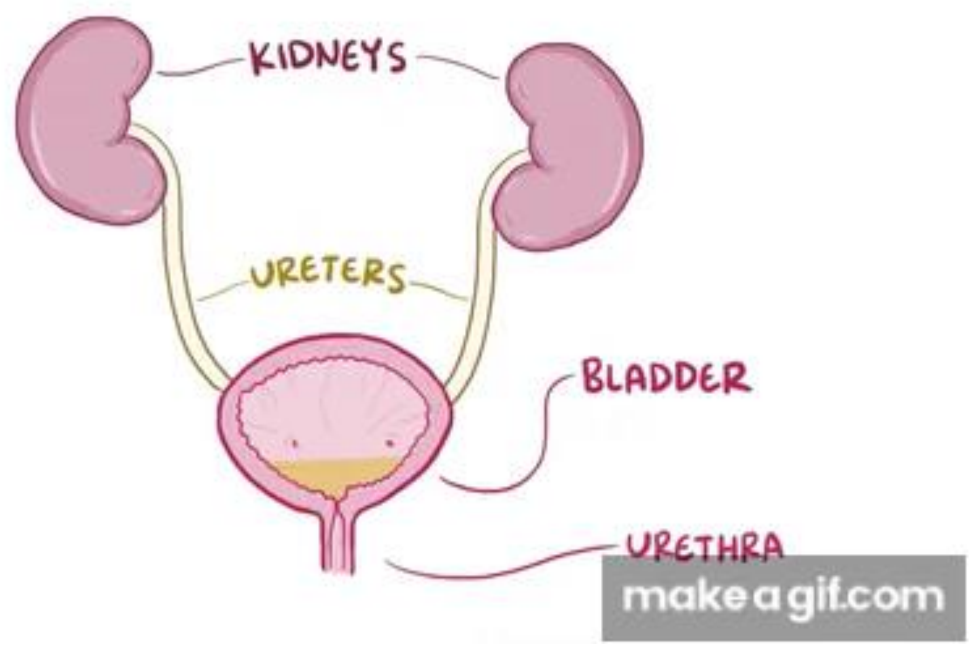


FIG. 2

A schematic view of the pelvic area: representation of the interaction forces (contact) (→) and deformations (⇝) of organs within the pelvic area. ①: Rectal distension under bladder and lung pressure. ②: Compressive load applied by the rectum onto the bladder. ③: Prostate swing zone. ④: Sacrum reaction. ⑤: Bladder distension under rectum and lung pressure. ⑥: Pubic bone reaction. ⑦: Compressive load applied by the bladder onto the rectum. ⑧: Compressive pressure applied by the lungs onto the pelvic area. ⑨: Bladder upward expansion. ⑩: Prostate forward movement. ⑪: Prostate downward movement into the urogenital diaphragm.

Source: Biomechanics of Living Organs: Hyperelastic Constitutive Laws for Finite Element Modeling

Sources of Intrafraction Motion: Bladder Filling



1

Gradual Drift

Continuous bladder filling causes systematic posterior and inferior prostate displacement over time

2

Angular Changes

Bladder pressure can induce rotational prostate displacement, not just translational shifts

3

Voiding Events

Patient voiding during treatment produces rapid, significant positional changes

Clinical Optimization: While full bladder protocols are standard, excessive bladder distension can paradoxically increase patient discomfort and motion, and elevate voiding risk during treatment. Optimal bladder volume represents a balance between organ displacement and patient tolerance.

Sources of Intrafraction Motion: Bowel Gas

Peristaltic Motion

Normal gastrointestinal peristalsis propels gas through the intestinal tract and rectum, creating dynamic pressure changes adjacent to the prostate.

Unlike the gradual drift associated with bladder filling, bowel gas movement typically produces rapid, discrete displacement events.

Motion Characteristics

Primary displacement occurs in the anterior direction as rectal gas expands posteriorly, pushing the prostate forward.

Large gas boluses can induce substantial rotational components in addition to translational shifts.

Gas-induced positional changes may persist for extended periods, distinguishing them from transient motion that typically resolves quickly.

Technologies for Measuring Prostate Motion

Ultrasound Monitoring

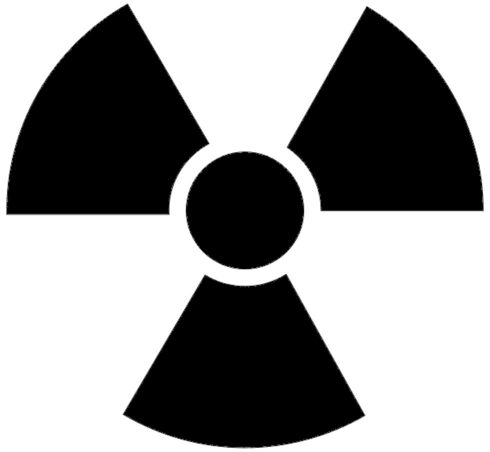
Non-invasive surface or transperineal ultrasound systems provide real-time soft tissue visualization at approximately 2 Hz acquisition frequency, enabling continuous target monitoring without ionizing radiation.

EM Transponder Tracking

Implanted electromagnetic beacons enable high-frequency position monitoring (10-25 Hz) with submillimeter precision, offering the fastest update rates among current technologies.

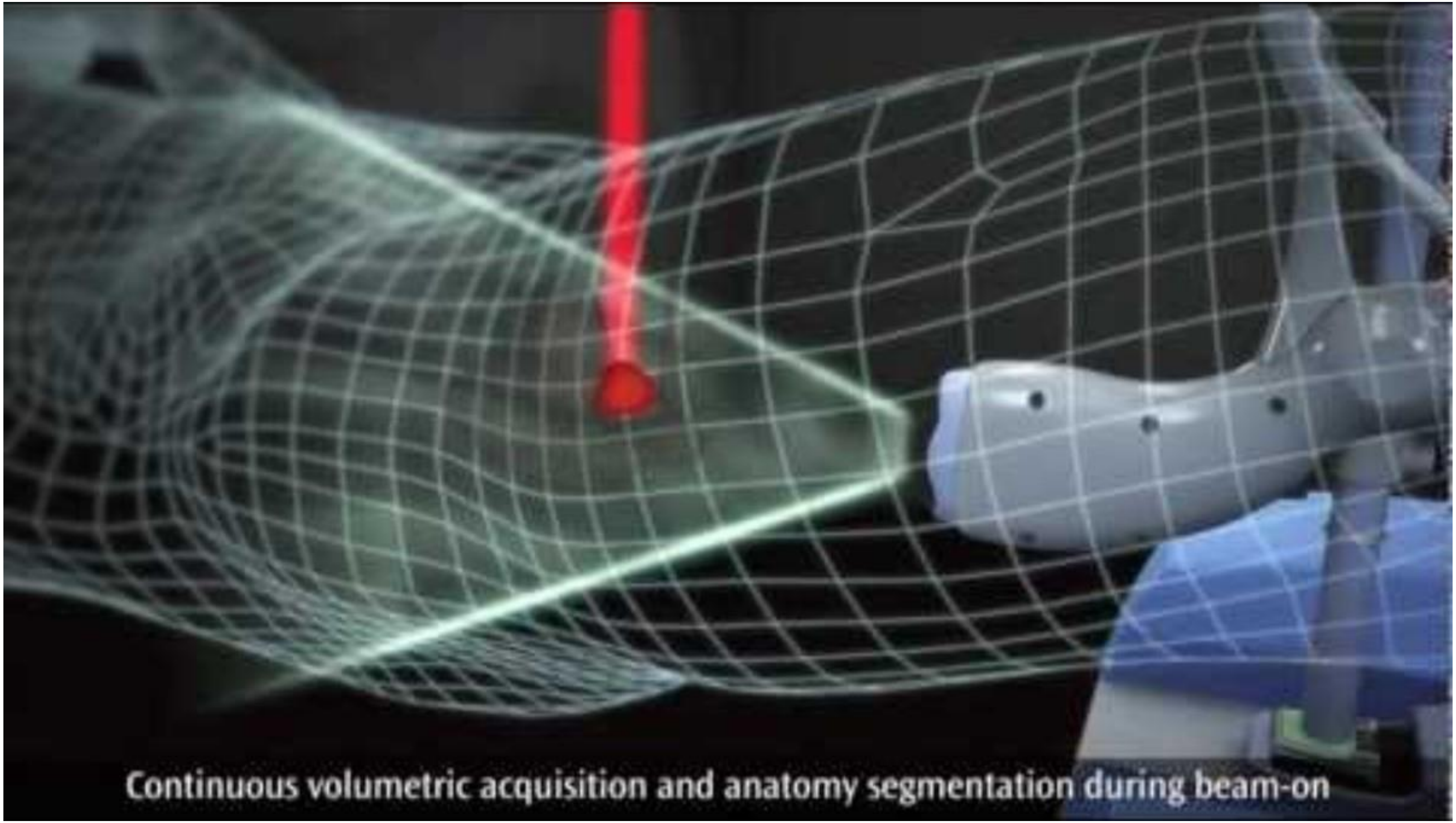
Cine MRI

Real-time magnetic resonance imaging provides superior soft tissue contrast at approximately 2 Hz, enabling direct target visualization without fiducial markers.



kV Radiographic Imaging

Planar or stereoscopic kV imaging detects implanted fiducial markers with high spatial accuracy, though acquisition frequency remains limited by radiation dose considerations.


Continuous volumetric acquisition and anatomy segmentation during beam-on

Ultrasound System Clinical Integration

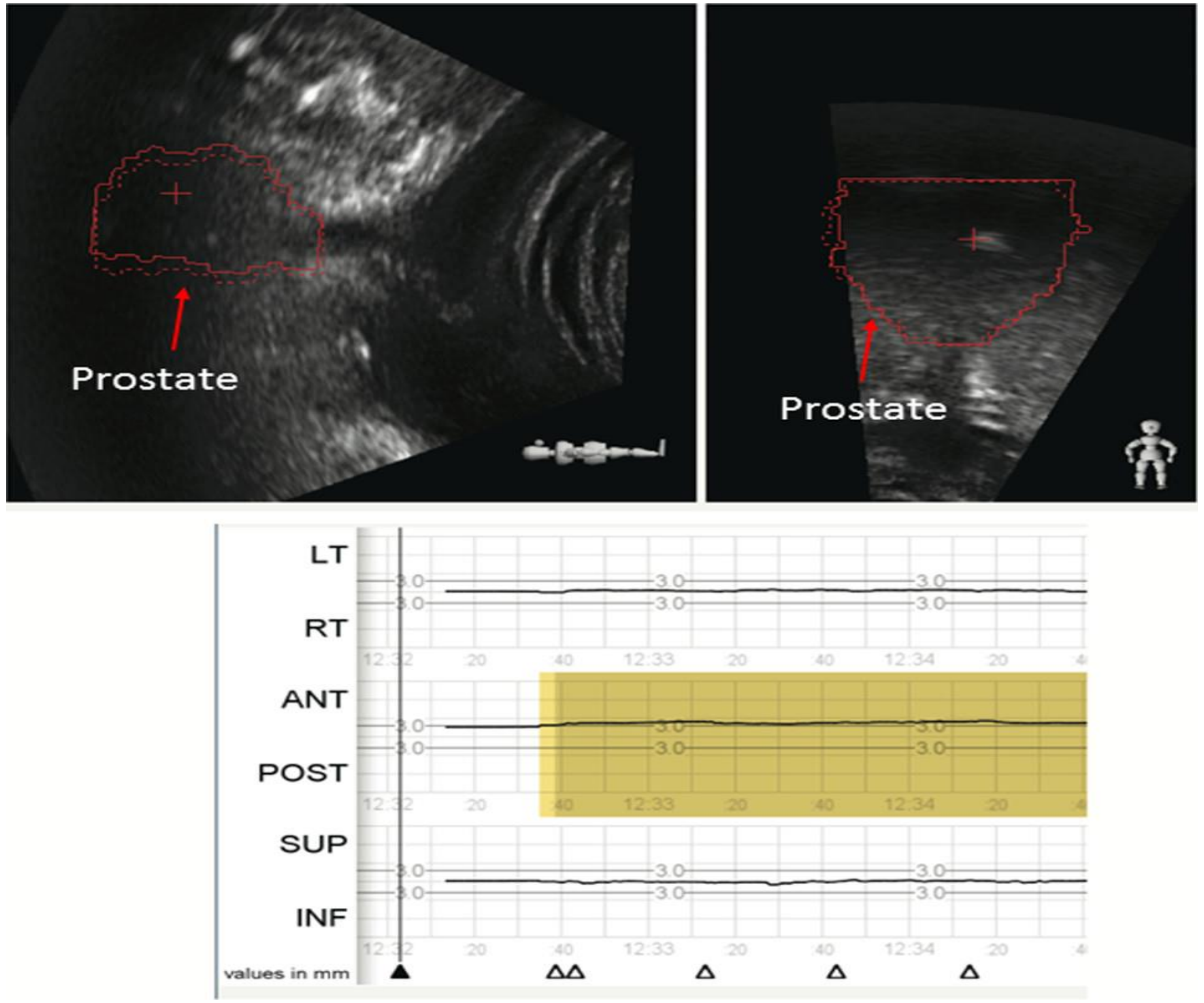


Figure 6. The zero position was set based upon an initial cone beam computed tomography (CT) and a 3 mm threshold was set. Motion in any direction (left/right, superior/inferior, or anterior/posterior) will signal an out-of-tolerance alert as shown in yellow. A prostate shift of more than 3 mm is identified in the anterior direction just prior to initiating treatment.

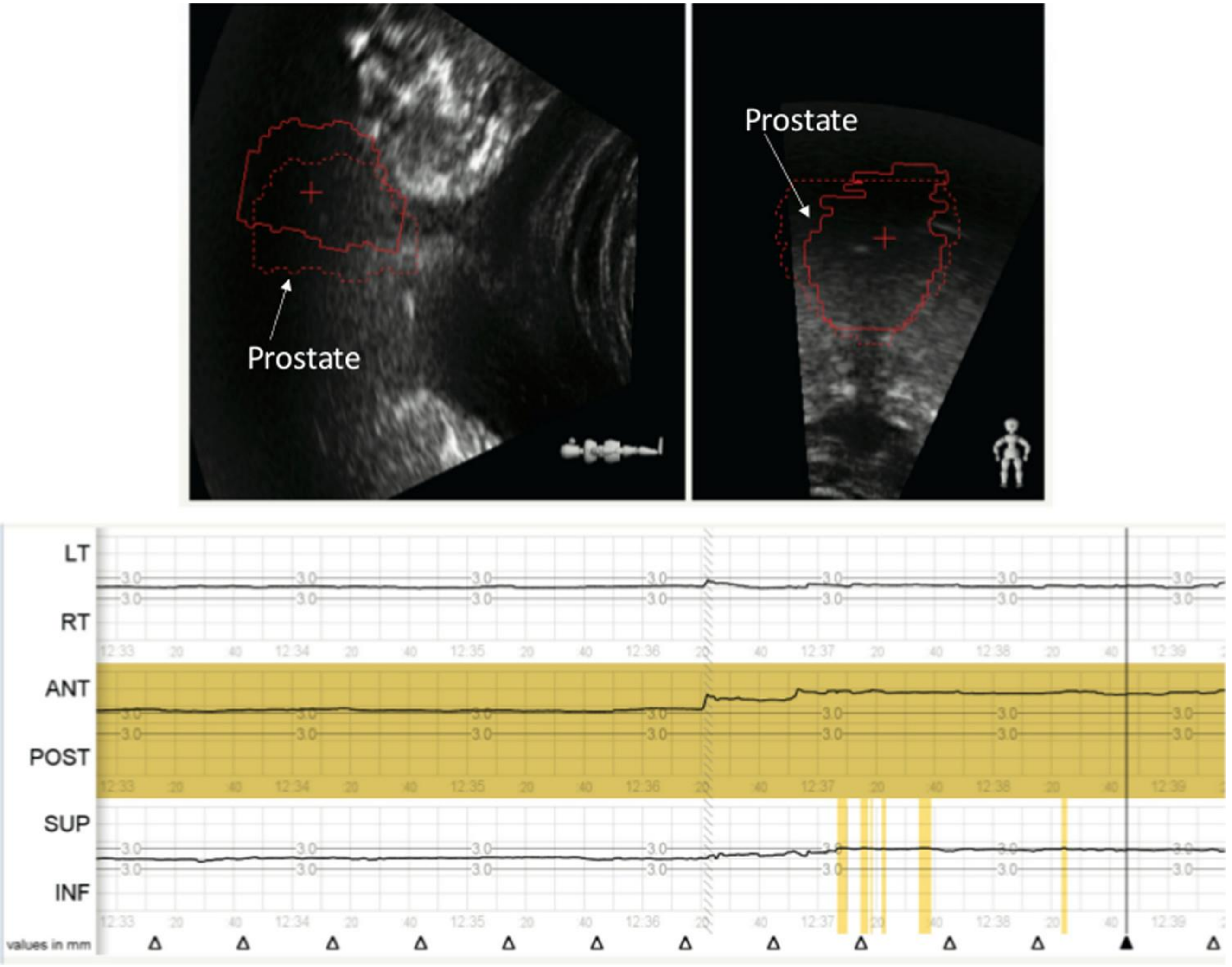
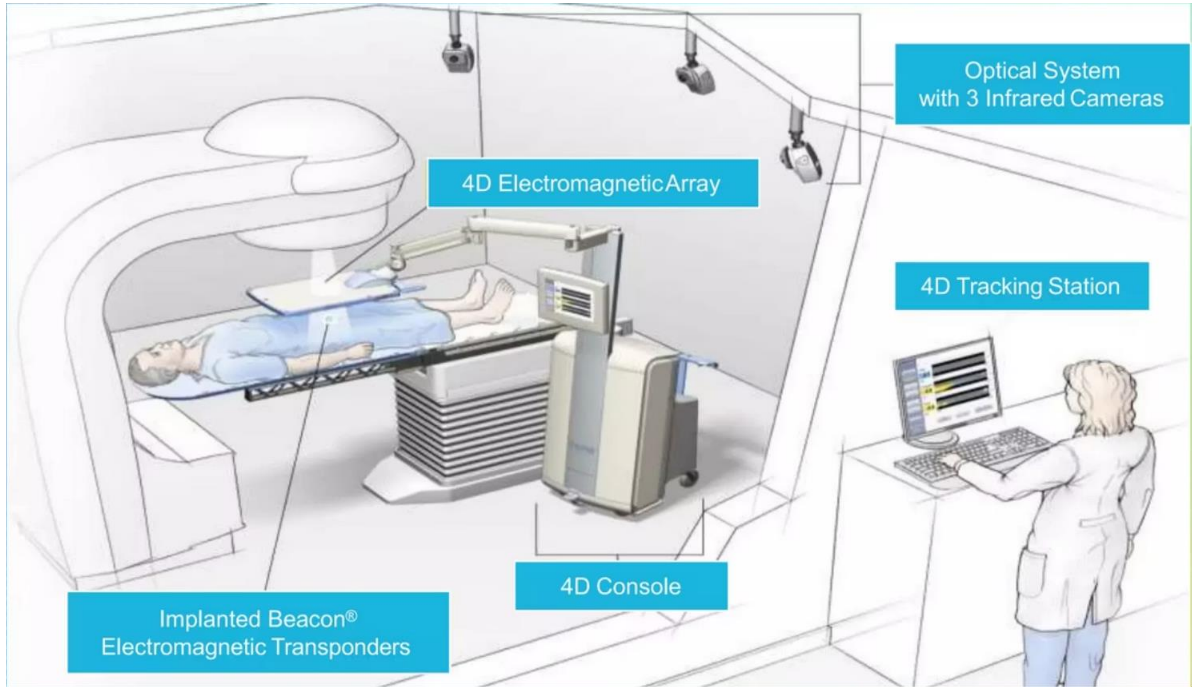


Figure 7. The ultrasound system shows an anterior prostate shift of 1 cm. The red prostate contour (solid line) has moved anterior to the zero position (red dotted line) by 1 cm as noted in the lower panel and maintains this position over several minutes. The red contour is contoured during the planning process on the planning computed tomography (CT) and transferred to the ultrasound (US) image during the registration of the 2 images in the Clarity system. On the first treatment, the contour is imported into the monitoring system.

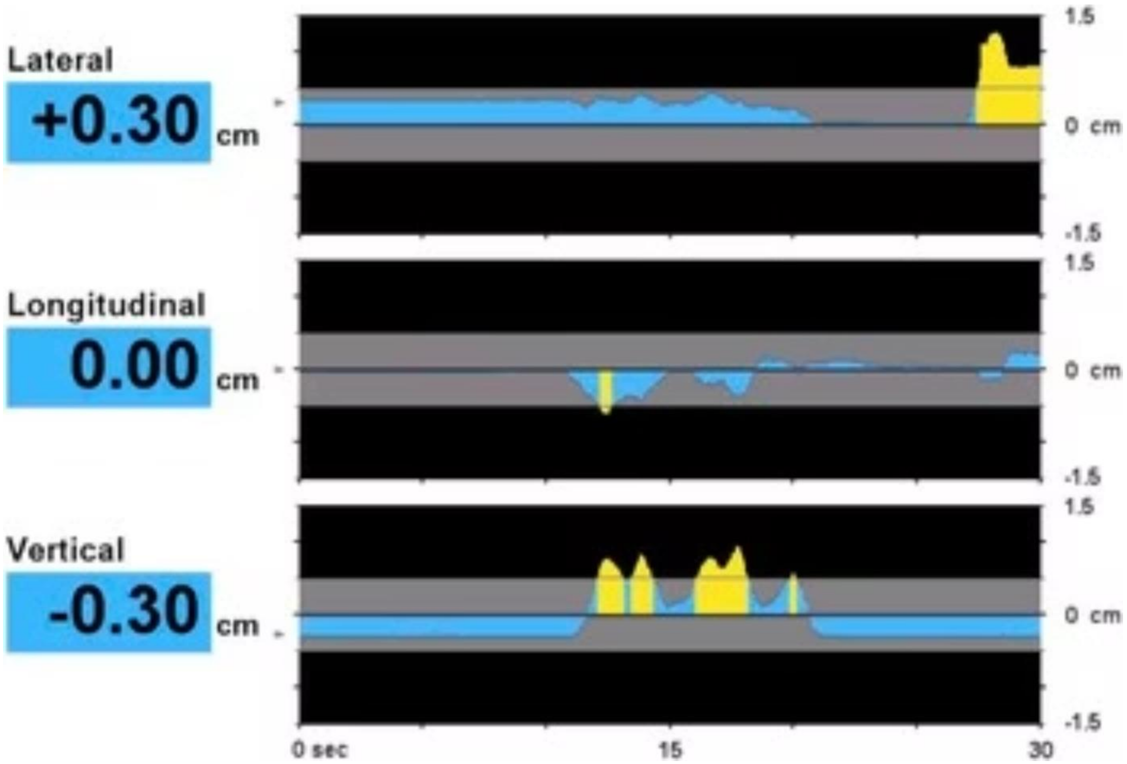
https://journals.sagepub.com/doi/10.1177/1533034617728643

Calypso System



Calypso System Components

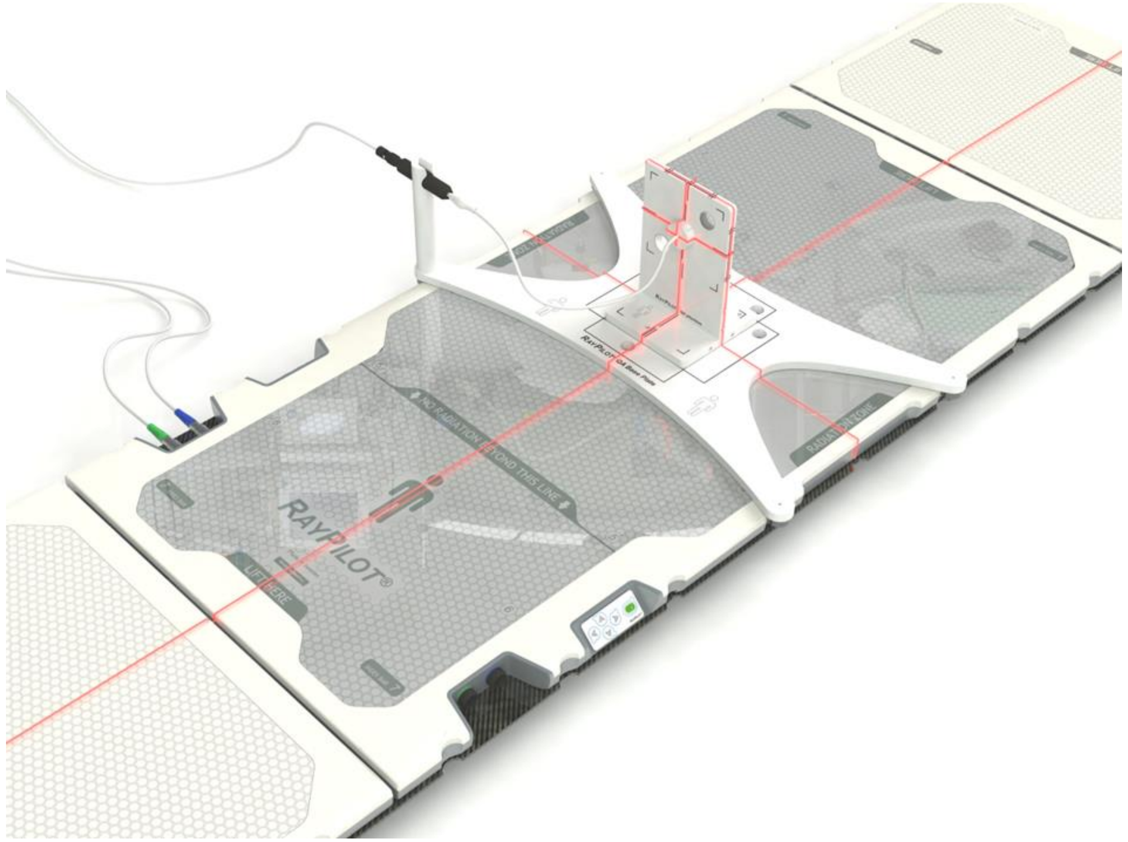
Three wireless electromagnetic transponders implanted within the prostate communicate continuously with external detector arrays.



Real-Time Tracking Interface

High-frequency position updates (10-25 Hz) enable submillimeter accuracy motion detection in all three axes, with minimal latency between position change and system response.

RayPilot System



Transponder (RayPilot HypoCath / Catheter):
A thin catheter containing an electromagnetic transmitter placed in the urethra; it emits signals corresponding to the prostate position.

Electromagnetic Field Generator / Antenna Array:
Positioned beneath the treatment couch to create a low-energy electromagnetic field used to localize the transponder in 3D space.

Interfaces:
Connects with the linear accelerator and record-and-verify systems to enable motion-based gating or treatment interruption.

The RayPilot system measures prostate position at approximately 30 Hz

MR-Guided Radiation Therapy

MR-Linac systems integrate MRI with radiation delivery, enabling superior soft tissue visualization without requiring fiducial implantation.
Cine MRI sequences provide continuous target monitoring at approximately 2 Hz throughout treatment delivery, supporting both gating and adaptive strategies.

https://www.elekta.com/products/radiation-therapy/unity/

Visualizing Real-Time Prostate Motion

Time-lapse visualization demonstrates the magnitude and complexity of prostate displacement during a typical SBRT treatment timeframe. This 4-minute sequence, shown at 4× speed, captures the dynamic interplay of bladder filling and rectal gas effects.

Source: Hegde JV, Cao M, Yu VY, et al. (2018) Magnetic Resonance Imaging Guidance Mitigates the Effects of Intrafraction Prostate Motion During Stereotactic Body Radiotherapy for Prostate Cancer. Cureus 10(4): e2442.


kV Radiographic Imaging

On planar kV imaging the prostate itself is poorly visualized.
Implanted fiducials provide high-contrast landmarks that reliably represent prostate position.
kV imaging has excellent spatial resolution and contrast for high-Z markers with low imaging dose, making fiducials ideal surrogates for the prostate.

Fiducial materials:
Gold/Platinum/Polymer-carbon coated
High radiopacity on kV imaging (sometimes) paired with MRI-positive materials.

Fiducial shapes and designs:
Cylindrical “seed” markers: Simple, compact, widely used.
Coil or helical markers: Increased surface area improves visibility and reduces migration.
Segmented or multi-bead markers (strands): Reduced positioning uncertainty.





Radixact

Ghilezan et. al. 2005 Cine MRI Study

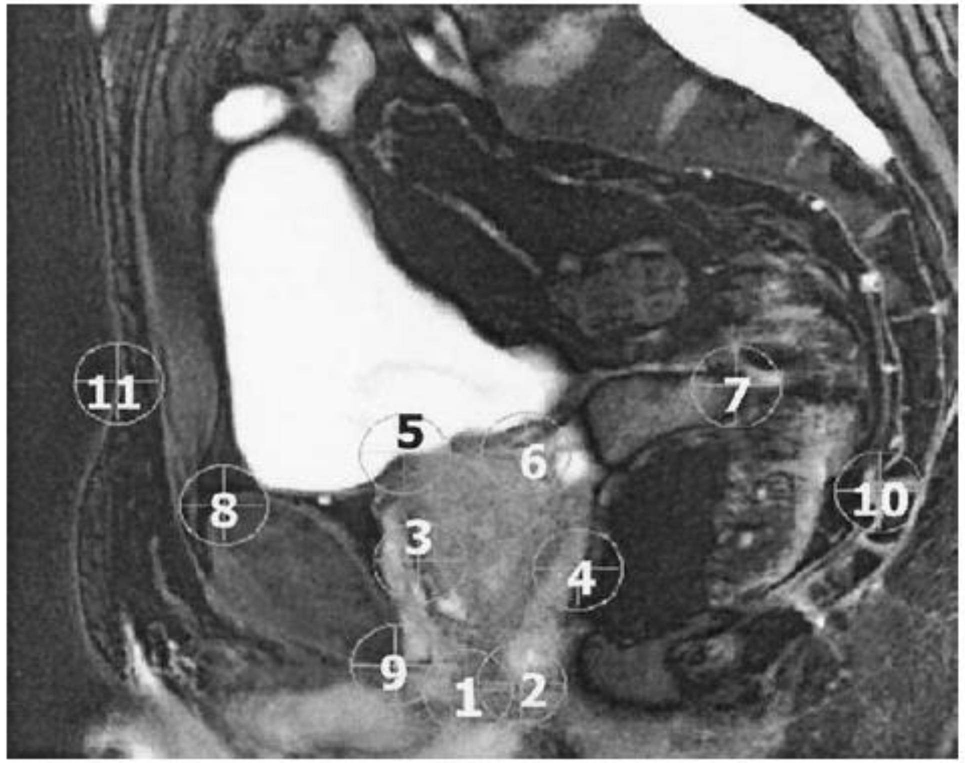


Fig. 1. Location of points of interest in a representative sagittal slice. 1 = apex; 2 = inferior-posterior; 3 = mid-anterior; 4 = mid-posterior; 5 = base-anterior; 6 = base-posterior; 7 = tip SV; 8 = pubic – superior; 9 = pubic – inferior; 10 = sacrum; 11 = abdominal wall.

Cine-MRI investigation acquired three one-hour imaging sequences per patient across five weeks of treatment for six patients, establishing foundational motion probability data.

Time to significant motion

1 minute

elapsed before 10% probability of ≥3mm displacement with **full rectum**

20 minutes

elapsed before 10% probability of ≥3mm displacement with **empty rectum**

Ghilezan MJ et al. Prostate gland motion assessed with cine-magnetic resonance imaging. Int J Radiat Oncol Biol Phys. 2005;62(2):406-417.

Langen et. al. 2008: Electromagnetic Tracking Data

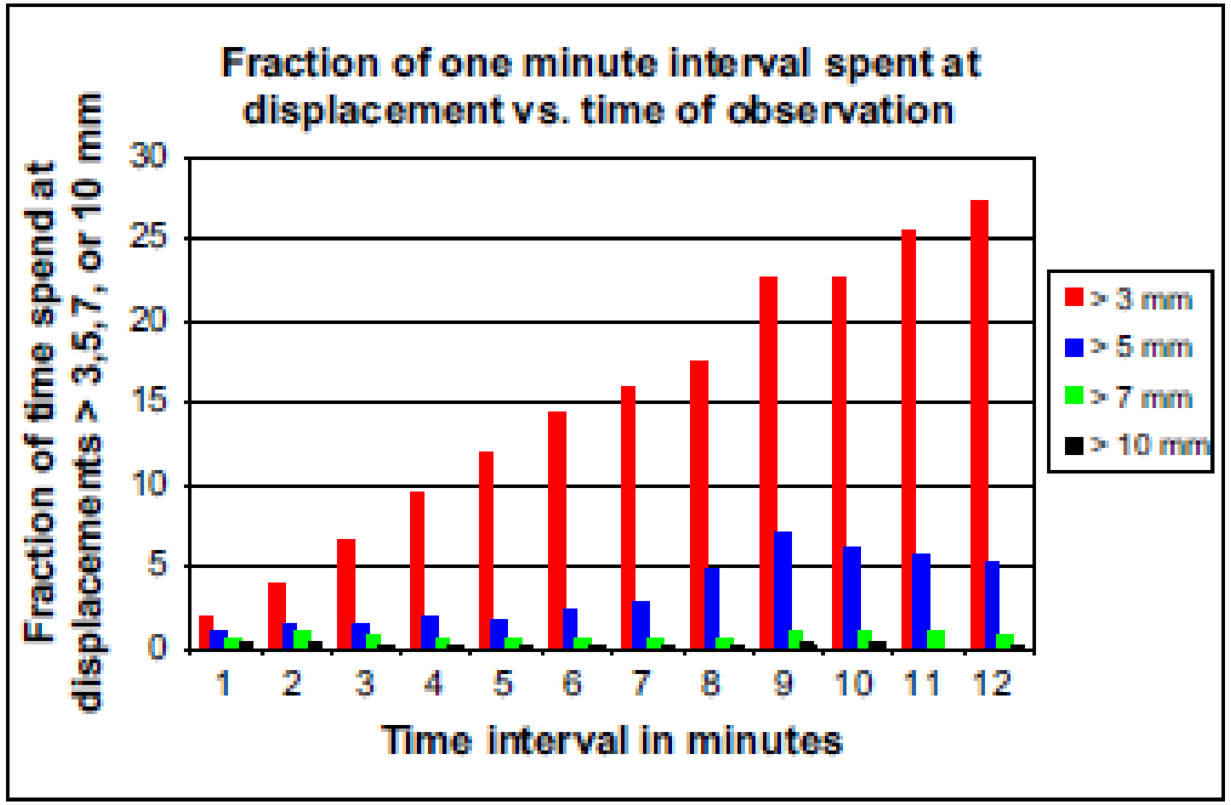


Fig. 4. Fraction of time that certain displacements were observed plotted vs. time of observations. For this plot, all first, second, and so forth, minutes from all tracking sessions were analyzed separately for prostate displacement. Likelihood of prostate displacement clearly increased with time elapsed after patient positioning.

Study Parameters

Analysis of electromagnetic fiducial marker tracking data from 17 patients across 550 treatment fractions provided robust statistical characterization of real-world prostate motion during conventional radiotherapy delivery.

Key Finding

The prostate was displaced by more than 3 mm for an average of 14% of total treatment time, highlighting the substantial temporal burden of clinically significant intrafraction motion.

Langen KM et al. Observations on real-time prostate gland motion using electromagnetic tracking. Int J Radiat Oncol Biol Phys. 2008;71(4):1084-90.

Kron 2010: Pre/Post Treatment Imaging Analysis

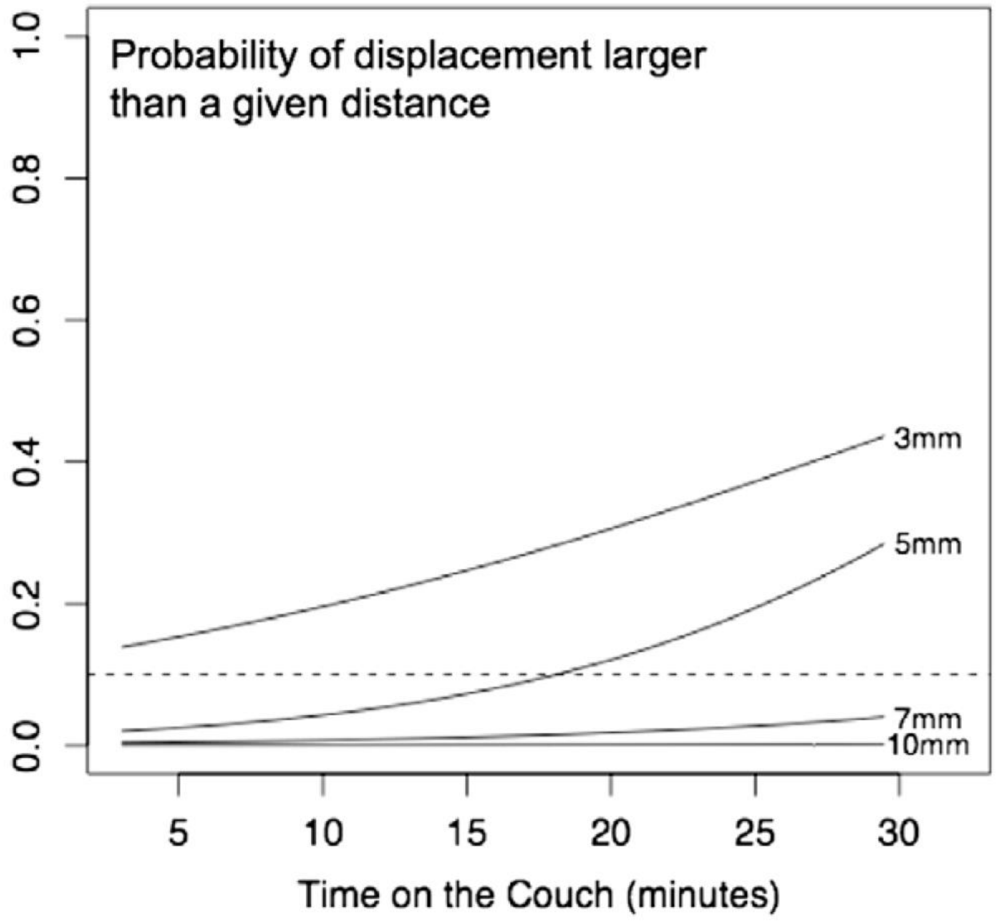


Fig. 3. Probability of prostate displacement larger than a given distance as a function of time.

Pre- and post-treatment kV imaging of implanted fiducials provided snapshot assessment of intrafraction motion, revealing time-dependent displacement patterns that supported the case for real-time monitoring.

Mean 3D Displacement

1.7 mm average shift between pre- and post-treatment imaging

Maximum Observed

25 mm displacement in extreme cases, demonstrating substantial inter-patient variability

Time Correlation

Positive correlation between treatment duration and displacement magnitude

Kron T et al. Intra-fraction prostate displacement in radiotherapy estimated from pre- and post-treatment imaging. Radiother Oncol. 2010;95(2):191-197.

Motion Limiting Strategies: Endorectal Balloons

Endorectal balloons physically stabilize the prostate through posterior compression and rectal immobilization, reducing gas-related motion and creating a more predictable geometric relationship between target and rectum.

Balloons can be inflated with either water or air depending on treatment modality. Air-filled balloons provide improved tissue contrast for photon-based imaging, while water-filled balloons minimize proton range uncertainties.

Motion Limiting Strategies?: Hydrogel Spacers

Su 2021: Proton Therapy Comparison

Study compared 190 proton patients treated with rectal balloons versus hydrogel spacers. Pre/post fiducial imaging revealed slightly larger PTV margins required for hydrogel cohort: +0.5 mm left-right, +0.2 mm superior-inferior.

Sawayanagi 2022: VMAT SBRT Study

Comparison of 8 hydrogel spacer patients versus 30 control patients treated with VMAT SBRT. 4D ultrasound monitoring detected increased intrafraction motion with spacers: +0.5 mm superior, +0.7 mm anterior directions.

While hydrogel spacers provide excellent rectal dose reduction through physical separation, they may introduce slightly larger motion components compared to endorectal balloons, particularly in superior and anterior directions.

Su Z, Henderson R, Nichols R, et al. A comparative study of prostate PTV margins for patients using hydrogel spacer or rectal balloon in proton therapy. *Physica Medica*. 2021/01/01/ 2021;81:47-51. doi:https://doi.org/10.1016/j.ejmp.2020.11.033
Sawayanagi S, Yamashita H, Ogita M, et al. Injection of hydrogel spacer increased maximal intrafractional prostate motion in anterior and superior directions during volumetric modulated arc therapy-stereotactic body radiation therapy for prostate cancer. *Radiat Oncol*. Feb 23 2022;17(1):41. doi:10.1186/s13014-022-02008-3

Gating Technologies Overview

Real-time motion detection systems enable treatment beam gating—automatic beam interruption when displacement exceeds predefined thresholds—across multiple technology platforms.

Radiofrequency Tracking

Calypso and Raypilot systems use electromagnetic transponders for high-frequency position monitoring and automated beam gating.

Fiducial Tracking

Marker Match and ExacTrac platforms perform kV radiographic imaging of implanted markers, triggering beam holds when displacement exceeds tolerance.

Cine MRI Tracking

MRIdian and Unity MR-Linac systems utilize continuous MRI acquisition for direct soft tissue visualization and real-time gating without fiducials.

Ultrasound Tracking

Clarity system utilizes ultrasound to continuously determine the prostate position and pause delivery if the detected position is outside of specified tolerance levels.

Clinical Impact of Gating: Lovelock Study

Approximately 10% of patients would have failed to meet clinical dosimetric goals (PTV D95 >90%) without motion tracking and repositioning interventions, even with conventional 5 mm radial / 3 mm posterior PTV margins.

Critical Time-Dependency Finding: "If the posterior margin were designed such that, on average, 95% of the dose had to be delivered with the prostate within the posterior PTV margin, this margin would have to be increased by approximately 2 mm every 5 minutes after the final imaging procedure used for setup."

Continuous Monitoring and Intrafraction Target Position Correction During Treatment Improves Target Coverage for Patients Undergoing SBRT Prostate Therapy
Lovelock, D. Michael et al.
International Journal of Radiation Oncology, Biology, Physics, Volume 91, Issue 3, 588 - 594

Motion Compensation: CyberKnife Synchrony

CyberKnife delivery distributes dose across multiple discrete node points throughout the target volume using a compact 6 MV linear accelerator mounted on a robotic arm.

Stereoscopic planar kV imaging detects implanted fiducials during treatment delivery, calculating real-time positional offsets relative to planned coordinates.

Treatment node positions dynamically adjust to account for measured displacement, ensuring accurate dose delivery despite target motion. The robotic arm repositions between each beam-on segment to maintain geometric accuracy.

Motion Compensation: Radixact Tomotherapy

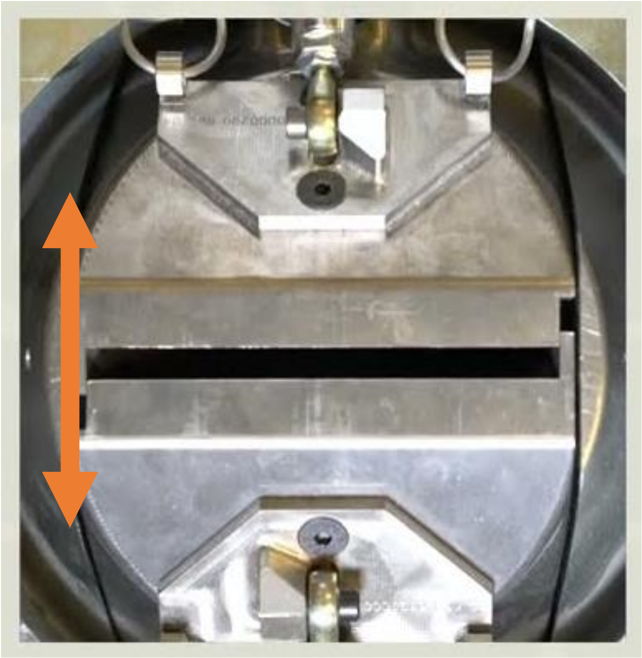
Thin radiation slice (1.0, or 2.5 cm field widths required for Synchrony) delivered during continuous gantry rotation and couch translation

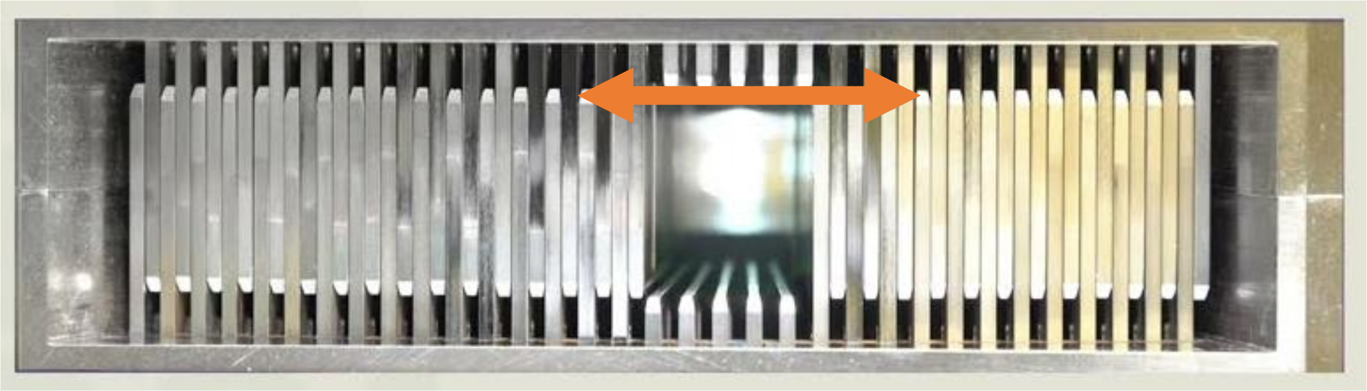
kV images are acquired as the gantry rotates before and during treatment, these kV images are used to calculate target offset position

2 - 6 images are acquired per gantry rotation

Target motion in the longitudinal (sup/inf) direction is compensated for via jaw tracking

Transverse motion in the axial plane is compensated for via MLC offset





Motion Adaptation Models: Quasi-Static Approach

1. **Image Acquisition**
   Stereoscopic kV projections detect current fiducial positions
2. **Position Calculation**
   3D displacement computed relative to planned coordinates
3. **Mechanical Adjustment**
   Jaws and MLCs shift to compensate for measured offset
4. **Iterative Updates**
   Process repeats continuously throughout delivery

The Quasi-Static Model (QSM) assumes target position remains relatively constant between imaging updates, making it ideal for slowly drifting targets like prostate. Lu et al. demonstrated adequate PTV coverage with 2-second imaging intervals for 1 cm jaws, while 4-6 second intervals sufficed for 2.5 cm jaw settings across various motion patterns.

https://pmc.ncbi.nlm.nih.gov/articles/PMC9868108/

Motion Compensation: C-Arm Linac MLC Tracking

1

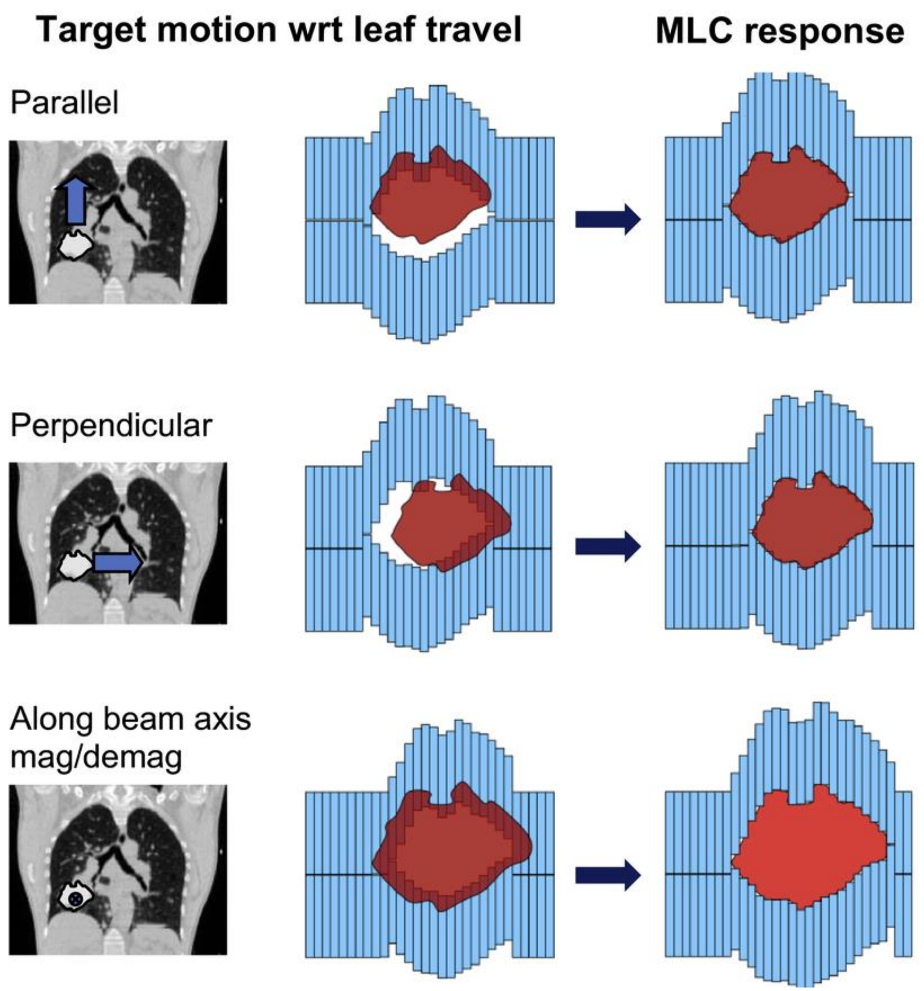
Keall 2014: First Implementation

Pioneering study utilized real-time electromagnetic transponder signals to modify dynamic MLC positions during conventional fractionated radiotherapy, establishing proof-of-concept for MLC tracking.

2

Keall 2018: Clinical Trial Results

Prospective clinical trial enrolled 28 patients treated with hypofractionated regimens (2-13.75 Gy per fraction), demonstrating feasibility and safety of EM-guided MLC tracking for prostate cancer.

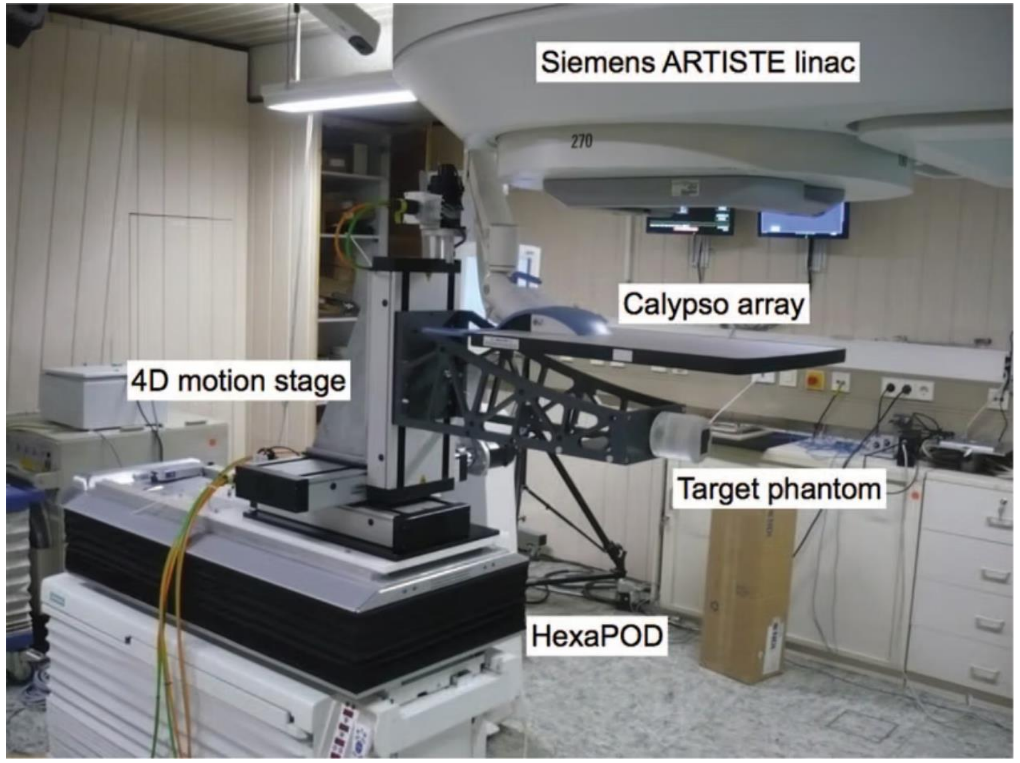


MLC tracking represents an elegant solution for C-arm linacs, requiring no robotic couch or specialized delivery system—only real-time position feedback and dynamic leaf sequencing modifications.

Keall PJ, Colvill E, O'Brien R, et al. The first clinical implementation of electromagnetic transponder-guided MLC tracking. *Med Phys*. 2014;41(2):020702. doi:10.1118/1.4862509

Keall PJ, Colvill E, O'Brien R, et al. Electromagnetic-Guided MLC Tracking Radiation Therapy for Prostate Cancer Patients: Prospective Clinical Trial Results. *Int J Radiat Oncol Biol Phys*. 2018;101(2):387-395. doi:10.1016/j.ijrobp.2018.01.098

Motion Compensation: Treatment Couch Tracking



Alternative Compensation Strategy

Rather than modifying beam delivery geometry, robotic treatment couches can maintain constant target position within the beam coordinate system by dynamically adjusting patient position in response to detected motion.

Comparative Performance

Multiple studies have demonstrated dosimetrically equivalent results between couch tracking and MLC tracking approaches. Couch tracking offers simpler implementation on conventional linacs but requires specialized robotic couches with sufficient speed and precision.

Menten, M.J., Guckenberger, M., Herrmann, C., Krauß, A., Nill, S., Oelfke, U. and Wilbert, J. (2012), Comparison of a multileaf collimator tracking system and a robotic treatment couch tracking system for organ motion compensation during radiotherapy. Med. Phys., 39: 7032-7041. https://doi.org/10.1118/1.4761868
Jöhl A, Ehrbar S, Guckenberger M, Klöck S, Mack A, Meboldt M, Zeilinger M, Tanadini-Lang S, Schmid Daners M. The ideal couch tracking system-Requirements and evaluation of current systems. J Appl Clin Med Phys. 2019 Oct;20(10):152-159. doi: 10.1002/acm2.12731. Epub 2019 Sep 19. PMID: 31535782; PMCID: PMC6806475.

Clinical Trials Establishing Reduced Margins

PACE-B Trial: Standard Margins

Landmark randomized trial comparing conventional RT to SBRT established 5 mm radial / 3 mm posterior margins as acceptable for SBRT delivery on either conventional linacs or CyberKnife platforms.

MIRAGE Trial: Motion-Managed Reduction

Prospective trial directly compared margin requirements between platforms: 4 mm uniform margins for conventional linac SBRT versus 2 mm uniform margins for cine MRI-gated delivery on MR-Linac systems.

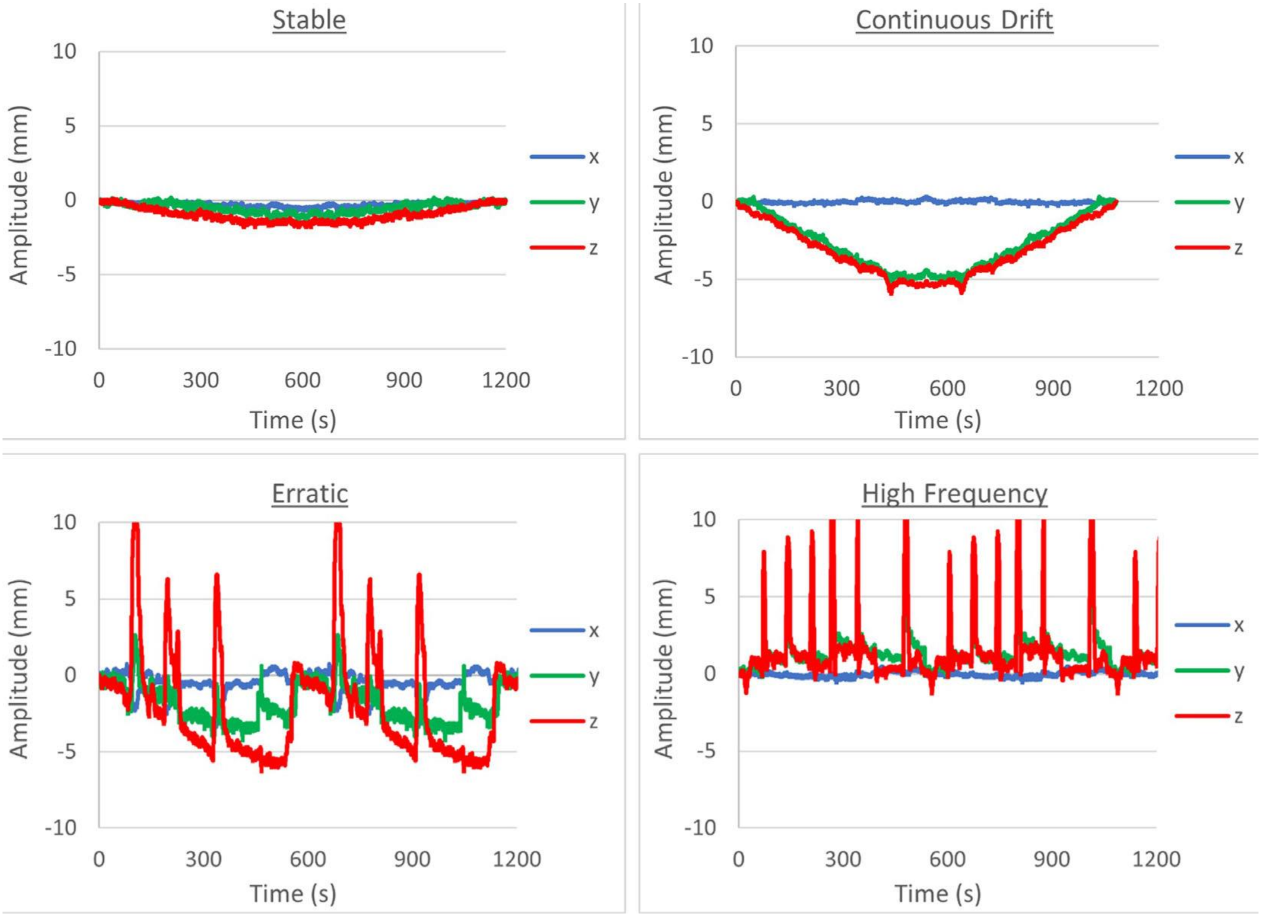
These trials established evidence-based margin reductions achievable with motion compensation technologies, providing clinical validation for adopting advanced motion management strategies.

Goddard et. Al. 2023: PTV Margin Reduction

Five patient plans were delivered to a phantom capable of 3D motions
Phantom diode and gafchromic film placed in 3 planes within the PTV
Stationary and four motion types
3 fiducials located within the PTV
TrueBeam marker match
- 2 mm gating radius
- 10 s imaging period

Radixact Synchrony
- 4 images per gantry rotation
- 7.2 – 9.0 s imaging period

2 mm uniform PTV margin



Goddard, L., Jeong, K., Tang, J., Garg, M., & Tomé, W. A. (2023). Reducing PTV margins for prostate SBRT with motion compensation and gating techniques. *Journal of applied clinical medical physics*, *24*(4), e13861. https://doi.org/10.1002/acm2.13861

Dosimetric Results: Target Coverage

TABLE 4 Average gamma pass rates for Gafchromic film measurements using a gamma criteria of 3%, 2 mm, 80% threshold dose for uncorrected and corrected/gated measurements with the Radixact and Truebeam systems respectively

	Radixact synchrony		Truebeam marker match	
Motion type	**Uncorrected (St. Dev)**	**Corrected (St. Dev)**	**Uncorrected (St. Dev)**	**Gated (St. Dev)**
Stable	98.6% (1.2%)	98.9% (0.9%)	93.7% (12.2%)	99.7% (0.2%)
Drifting	70.2% (9.2%)	95.4% (2.7%)	85.2% (11.2%)	87.7% (14.8%)
Erratic	73.2% (6.4%)	95.4% (2.1%)	92.1% (5.1%)	94.2% (11.0%)
High frequency	80.1% (4.8%)	94.3% (2.9%)	88.4% (9.6%)	97.6% (2.4%)

TABLE 5 Average gamma pass rates for Delta4 diode measurements using a gamma criteria of 3%, 2 mm, 10% threshold dose for uncorrected and corrected/gated measurements with the Radixact and Truebeam systems, respectively

	Radixact Synchrony		Truebeam Marker Match	
Motion type	**Uncorrected (St. Dev)**	**Corrected (St. Dev)**	**Uncorrected (St. Dev)**	**Gated (St. Dev)**
Stable	99.7% (0.2%)	100.0% (0.1%)	99.9% (0.2%)	99.8% (0.5%)
Drifting	73.5% (6.1%)	90.0% (4.7%)	81.7% (5.5%)	99.7% (0.4%)
Erratic	77.9% (2.5%)	95.3% (1.7%)	87.1% (4.2%)	98.0% (1.9%)
High frequency	84.1% (3.2%)	93.7% (3.8%)	80.1% (4.8%)	90.2% (5.8%)

Both motion compensation platforms maintained adequate PTV coverage across all motion scenarios with 2 mm uniform margins. Diode and film measurements confirmed minimal deviation from planned dose distributions, validating the feasibility of further margin reduction when coupled with real-time motion management.

OAR Dose Reduction with Margin Reductions

TABLE 3 Organ at risk and PTV overlap volume

Organ at risk	Original PTV Overlap Volume (cm^3)	Reduced PTV Overlap Volume (cm^3)	Volume reduction
Bladder	5.5	1.6	74%
Neurovascular bundle	1.8	0.7	63%
Rectum	0.3	0.0	96%
SpaceOAR	3.1	1.3	61%

Transitioning from standard margins (5 mm radial / 3 mm posterior) to motion-compensated 2 mm uniform expansion produces dramatic reductions in OAR overlap, directly translating to decreased toxicity risk without compromising target coverage.

Online Adaptive RT: The Next Frontier

Enhanced Image Quality

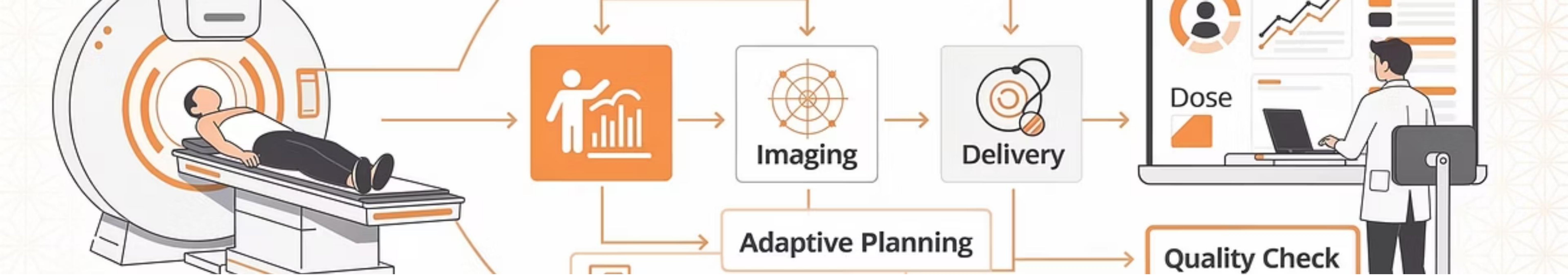
Advanced imaging platforms (MR-Linac, ClearRT CBCT) enable accurate auto-contouring algorithms and real-time anatomy assessment.

Computational Advances

GPU-accelerated dose calculation and optimization algorithms enable treatment plan generation within clinically acceptable timeframes at the treatment unit.

Daily Adaptation

Online adaptive planning accounts for daily variations in target geometry and OAR positions, ensuring optimal dose distributions despite anatomical changes.



Synergy: Adaptive Planning + Motion Compensation

Complementary Technologies

Online adaptive planning addresses interfraction anatomical variations occurring between treatment sessions. Motion compensation manages intrafraction displacement during individual treatment deliveries.

Neither technology alone provides complete motion management—true precision requires both strategies working in concert.

Temporal Limitations

Even sophisticated adaptive workflows require finite time between setup imaging and treatment delivery. Target motion occurring during this interval remains unaddressed without real-time compensation.

Optimal workflow combines daily adaptation to current anatomy with continuous motion tracking throughout beam delivery.

Summary: Motion Management Essentials

Motion is Inevitable

Prostate intrafraction motion is clinically significant and must be explicitly addressed in SBRT protocols

Compensation Enables Precision

Real-time motion tracking and compensation technologies enable substantial PTV margin reduction below conventional standards

Toxicity Reduction

Reduced PTV margins translate directly to decreased OAR overlap and lower treatment toxicity risk

Adaptive Integration

Maximum benefit requires combining online adaptive planning with intrafraction motion compensation strategies

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The future of prostate SBRT lies in intelligent integration of multiple precision technologies—adaptive planning for interfraction changes, real-time compensation for intrafraction motion, and advanced imaging for continuous verification. Together, these innovations enable unprecedented geometric accuracy and therapeutic ratio optimization.