White Paper

Elekta Unity
Comprehensive Motion Management—Explained

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Introduction

Elekta Unity's Comprehensive Motion Management (CMM) with True Tracking and Automatic Gating combines Unity's diagnostic quality imaging capabilities with powerful algorithms and technology to quantify movement and correct for it automatically, as it happens—ensuring precise and accurate treatment delivery.

Leveraging the power of the 1.5 T MR, anatomy-specific imaging sequences optimize the visualization of the target and surrounding healthy tissue. These sequences utilize varying 'MR contrasts' to differentiate tissues, making some appear bright while others appear dark, thereby enhancing the clarity and precision of imaging. The 3D image MR contrasts available on Elekta Unity are T1, T2, Balanced, FLAIR and SPAIR.

When using MR to monitor and track targets impacted by respiratory motion it's crucial that imaging is fast to minimize delays in detecting the target position. To achieve this, we utilize Balanced contrast imaging. For tracking target less impacted by respiratory motion (non-respiratory targets), a slower T2 cine can be used, which improves the visibility of certain tissue boundaries.

The shape and position of the target are defined on the daily 3D MRI. Due to differing contrasts, identifying the target on cine imagines can be challenging. This issue is solved by using two intermediate images called template images. The template images are automatically generated during a preparation phase from a short cine sequence and are registered to the daily 3D MRI using an algorithm that is robust against the differing contrast.

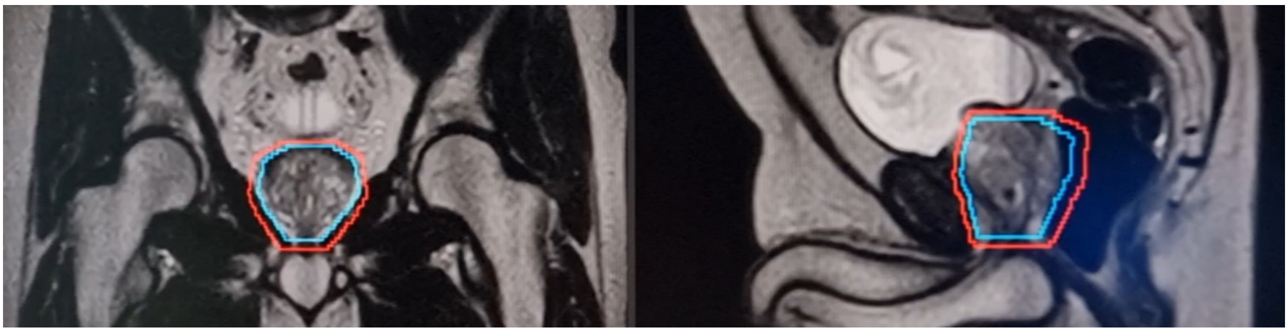
The user reviews this registration result to confirm the target's location in the template images. Subsequently, the cine images are registered against the template images in real-time using a fast algorithm as the contrasts are identical. The combination of these two registration results provides the targets position in real-time compared to the adapted plan. This position offset is used by the gating algorithm to enable and disable the radiation beam accordingly.

Motion management structures

In addition to the standard treatment planning structures, two new structures are introduced for motion management, see figure 1. These structures are derived from the reference plan to the daily MRI as part of the treatment workflow.

The first structure is the **registration structure**, which defines the region of the image used by the registration algorithms. It's important that the motion of this region accurately represents the motion of the target and contains sufficient anatomical detail for the registration algorithm to be robust. In some cases, it may simply be the **target structure** e.g. Gross Tumor Volume (GTV), possibly with a small margin increase, while in other cases, it may be a local anatomical feature like vasculature.

The second structure is the **gating envelope**. This structure includes the target structure e.g. GTV and will likely be an auto-expansion of it. As the target moves the system calculates how much of the target remains within the gating envelope. If this value falls below a userdefined threshold, the beam will be disabled.



Registration structure   Gating envelope

Figure 1 Courtesy of Dr. Michele Rigo Advanced Radiation Oncology Department (ARO), IRCCS Ospedale "Sacro Cuore – don Calabria", Negrar (VR), Italy.

Four motion management strategies

Effective motion management is crucial in various clinical scenarios. Elekta Unity's advanced MR capabilities offer four distinct motion management strategies, providing the flexibility to select the most appropriate approach for each patient. Three of these strategies are designed to manage respiratory motion, while the fourth focuses on non-respiratory motion. This section details each of these strategies.

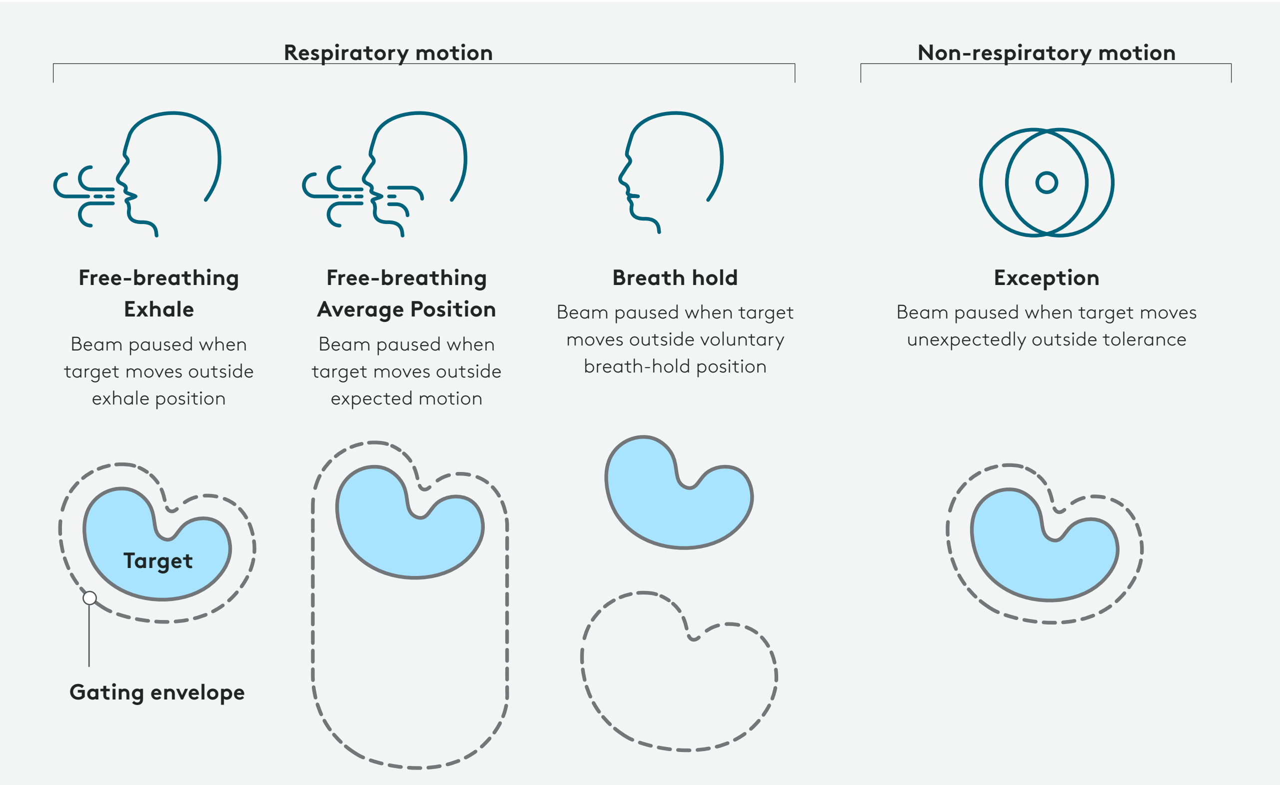
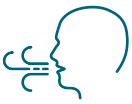


Figure 2 Four motion management strategies available on Elekta Unity.



1. Respiratory motion—Free-breathing, average position

In this technique, the patient is continuously imaged and treated while breathing freely. The dose is centered on the time-weighted average position of the target, with an ITV (Internal Target Volume) margin used to ensure the dose covers the expected motion. The target is tracked continuously, and the beam is paused only if the target moves outside the planned expected motion, i.e., if something unexpected occurs.

This strategy is straightforward for both the patient and the user, doesn't extend treatment time, and is similar to existing respiratory motion management workflows in radiotherapy. It's particularly suitable for targets with small or modest motion. Additionally, this technique manages the motion of other anatomical parts within the imaging field of view.

For instance, a moving chest wall might cause artifacts that obscure the target, making this technique beneficial even if the target itself has minimal movement.

Minor interventions can sometimes be used to reduce target motion sufficiently to make patients suitable for this strategy, avoiding the increased treatment time associated with gating the beam. These interventions include modest abdominal compression, continuous positive airway pressure (CPAP), and shallow breathing. However, these interventions may not be beneficial if they significantly increase treatment time.

For the free-breathing average position technique, radiation is not expected to be paused during treatment, ensuring that the treatment time is not extended.

2. Respiratory motion—Free-breathing, exhale

In this technique, the patient is imaged and treated while breathing freely. However, the daily MR image is acquired, and radiation is delivered only during the exhale phase. This process is fully automated, requiring no action from either the patient or the user, making it a highly attractive option.

The free-breathing exhale technique has the potential to become the dominant motion management strategy. It offers the advantage of activating the beam only when the target is within the tolerance of the exhale position, allowing for a reduced planning ITV margin compared to the free-breathing average technique. The fact that the patient breathes freely while the system manages the process is particularly beneficial for sick and frail patients. However, this technique may extend the treatment time, as radiation is enabled only when the target is near the exhale phase of the respiratory cycle.

3. Respiratory motion—Breath-hold

In this technique, the patient is imaged and treated during a voluntary breath-hold. The patient is coached to hold their breath, and the system acquires the daily 3D MR in a single breath-hold (approximately 18 seconds). Elekta Unity CMM then ensures that treatment is delivered only during subsequent breath-holds.

The breath-hold technique is currently favored by many clinicians due to its advantage of minimal motion during the breath-hold.

However, it requires the patient to understand the procedure and consistently hold their breath, which can be challenging for some sick patients. A margin is necessary to account for variations between breath-holds. This technique is particularly valuable when an increase in lung volume is beneficial dosimetrically, such as moving the heart away from the target.

The treatment time will be extended due to the time needed to coach the patient for each breath-hold and the recovery time between breath-holds. This additional time is patient-specific and may be significantly longer than the time required for the free-breathing exhale technique.

4. Non-Respiratory motion—Exception

Elekta Unity CMM can also be utilized for all patients with targets affected by motion. For targets less impacted by respiratory motion but subject to random motion, the exception gating strategy is employed. This strategy tracks the target in real-time and pauses radiation if the target moves out of tolerance, ensuring accurate treatment delivery.

All standard imaging techniques can be used with this strategy, and it's not expected to extend treatment time.

Treating with Comprehensive Motion Management

The treatment workflow is optimized for each motion management strategy, ensuring efficiency without adding complexity for the user. The system handles this optimization automatically. The user simply needs to select the appropriate strategy for the patient. This selection is typically made during the simulation phase and creation of the reference plan. This is important to ensure the reference pan is created with the anatomy in the correct phase of the breathing cycle for the chosen strategy.

This section outlines the workflow, and how the system is optimized for each motion management strategy.

1. Respiratory motion—Free-breathing, average position

In this strategy, the patient is continuously imaged and treated while breathing freely. The dose is centered on the time-weighted average position of the target, with an ITV margin ensuring the dose covers the expected motion. The target is tracked continuously, and the beam is paused only if the target moves outside the planned expected motion, i.e., if something unexpected occurs

Simulation and reference planning

The use of an ITV is a well-established approach, and no changes are expected from current practice. One method involves defining the target across all phases of a 4D CT scan and determining the ITV as the mathematical union of these volumes. Alternatively, the extent of motion can be quantified, and the GTV expanded by the amplitude of motion in each direction. When the patient undergoes their first treatment fraction on Elekta Unity, clinical users can assess the actual motion amplitude and compare it to the planning data. This may necessitate an update to the reference plan. If a 4D CT is used for reference planning, the first fraction MRI might be selected as the reference data set for subsequent fractions.

Daily 3D imaging

This strategy employs a free-breathing imaging technique called 3D Vane XD to suppress motion artifacts. Since the 3D Vane acquisition spans the entire respiratory cycle, the resulting image represents the average target position and may exhibit motion blur, making it suitable for small and modest target motions.

3D Vane XD is available in four different contrasts for optimal visualization of the target and organs at risk (OAR). These contrasts include T1 and Balanced, both of which are also available with SPAIR fat suppression. Fat suppression reduces the brightness of fat that can obscure the target, similar to how turning off the headlights of an oncoming car improves visibility at night.

Thus, four different contrasts are available: T1, Balanced, and both with fat suppression.

Template generation

The template is automatically generated from cine images captured in the middle of the respiratory range, excluding extreme inhale and exhale images. This ensures that the template images are most representative of the treatment position.

Treatment and automatic gating

For the free-breathing average position technique, radiation is not expected to be paused during treatment, thus the treatment time will not be extended.

As the target moves repetitively, target position prediction is employed to eliminate system latency, ensuring there are no significant delays when enabling or disabling the radiation beam. This results in accurate treatment delivery. The target prediction is based on a model of the patient's recent respiratory motion, which is continuously updated to account for systematic changes.

The performance of the target position prediction is also continuously monitored. If it falls below a system-defined threshold, the beam will be paused, and the user notified. This is likely due to erratic breathing patterns, and the clinical user should consider using a different strategy for such patients.

Intrafraction drift correction

If the average position of the target shifts during the fraction, then the beam will be paused more frequently, and the total treatment time will be longer. Elekta Unity CMM Intrafraction drift correction can be used to correct for this systematic shift, and it will shift the dose distribution to the new average target position. The True Tracking imaging planes and Gating Envelope will also be shifted to the new position. This process should restore the target motion to be within the Gating Envelope.

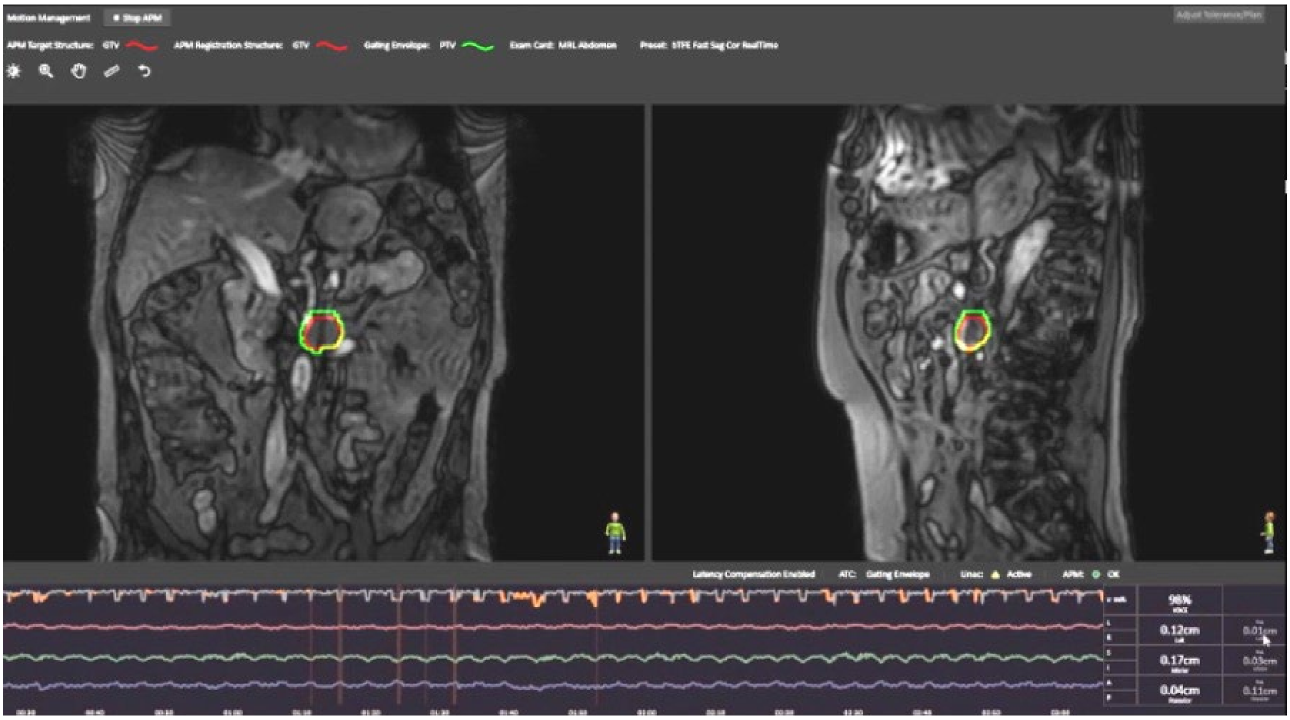


Figure 3 Courtesy of Prof Intven UMCU Utrecht. Patient treated with Elekta Unity CMM – Free breathing - Exhale Motion management strategy.

2. Respiratory motion— Free-breathing, exhale

In this technique, the patient is imaged and treated while breathing freely. However, the daily MR image is acquired, and radiation is delivered only during the exhale phase.

Simulation and reference planning

The reference plan should be created using an exhale phase image. This can be achieved by selecting the exhale phase of a 4D CT scan or using a T2 Navigated technique on MR Sim.
If a 4D CT is used for reference planning, the first fraction T2 Navigated MRI might be selected as the reference image for subsequent fractions.

Daily 3D imaging

Imaging is performed using the T2 Navigated technique. The MR system detects the exhale respiratory phase using a navigator channel placed on the diaphragm, which automatically triggers the acquisition of the 3D MR. This results in a T2 image acquired in the exhale position with minimal motion blur. This process is fully automated by the MR system, eliminating the need for respiratory belts or other techniques to detect the respiratory cycle. Although the acquisition time is extended due to imaging only during the exhale phase, this can be compensated by using the Philips Compressed SENSE acceleration technique which speeds up image acquisition without compromising image quality.

Template generation

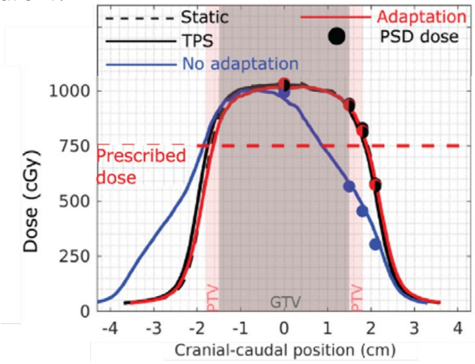
The template is automatically generated from cine images captured at the exhale phase of the respiratory cycle. This ensures that the template images are most representative of the treatment position.

Treatment and automatic gating

The free-breathing exhale technique extends treatment time as radiation is enabled only when the target is in the desired position. With the current Step and Shoot delivery technique, the gating duty cycle affects only the portion of the delivery when the beam is on, resulting in a modest increase in overall session time. For example, for an 8 Gy fraction dose with an assumed 8-minute beam delivery time (4 minutes of radiation-on time), if the gating duty cycle is 50% (most of the respiratory cycle is spent in exhale) , the radiation-on time will become 8 minutes, and the total beam delivery time will be 12 minutes, representing a 50% increase.

As the target moves repetitively, target position prediction is used to eliminate system latency, ensuring no significant delays when enabling or disabling the radiation beam. This results in accurate treatment delivery. The target prediction is based on a model of the patient's recent respiratory motion, which is continuously updated to account for systematic changes. The performance of the target position prediction is also continuously monitored. If it falls below a system-defined threshold, the beam will be paused, and the user notified. This is likely due to erratic breathing patterns, and the clinical user should consider using different strategies for such patients.

Uijtewaal P et al. (2023) evaluated the spatial and dosimetric performance of target tracking and automatic gating using a motion platform equipped with high spatial resolution radiochromic film. The real time gating was tested with both a Lujan CC motion (cos4, A peak-to-peak = 20 mm, T = 4 s) and patient-derived respiratory CC motion (A peak–to–peak = 18 mm, T = 5 s, drift = 0.01 mm/min). They found that for both respiratory patterns studied, the dose delivered to the moving phantom with gating was comparable to that with no motion, achieving a 100% gamma pass rate at 3%/3mm. Even with a stricter tolerance of 1%/1mm, the pass rate only decreased from 90% for static delivery to 80% for gated delivery, see figure 4.



Gamma pass-rate (3%/3 mm)	No gating	Gating
Lujan (cos4) motion	31	100
Respiratory motion	26	100

Figure 4. Gamma pass-rate with and without gating, and the dose profile for 'Gating' extracted from the measured film dose

Intrafraction drift correction

If the average position of the target shifts during the fraction, the duty cycle will be reduced, resulting in less beam-on time and prolonged total treatment time. Intrafraction drift correction can be used to adjust for this systematic shift, shifting the delivered dose distribution to the new average target position. The True Tracking imaging planes and Gating Envelope will also be adjusted to the new position, restoring the original duty cycle.

3. Respiratory motion—Breath-hold

In this technique, the patient is imaged and treated during a voluntary breath-hold.

Simulation and reference planning

The reference planning image should be acquired using the same voluntary breath-hold technique that will be used during treatment. The simulation session can also serve as a training session to assess the patient's ability to hold their breath consistently. This image can be acquired using either a CT or MR Sim. Since the plan will be adapted based on the daily breath-hold image on Elekta Unity, the reference image does not need to be the same as the one used on the day of treatment.

Daily 3D imaging

The 3D breath-hold images are acquired in a single breath-hold (approximately 18 seconds) and are available in three different contrasts: T1, T2, and Balanced. These contrasts provide optimal visualization of the target and organs at risk (OAR). The T2 contrast is quite challenging, so the spatial resolution is reduced.

Template generation

The template is automatically generated from cine images taken during a voluntary breath-hold. These images are registered to the daily 3D breath-hold image. While the two breath-holds should be similar, it is not critical that they are in the exact same position. This ensures that the template images are most representative of the treatment position.

Treatment and automatic gating

The goal is to treat the target while it is stationary during the breath-hold, so no form of target position prediction is used. To ensure the target is in a breath-hold and not just passing through the breath-hold position, the tracked position of the target is checked to confirm it is stationary before the beam is enabled. This results in a short delay at the start of each breath-hold.

It is important to check that the target is stationary for two reasons: first, the user does not expect the beam to be enabled when the patient is not in a breath-hold; second, the position of the anatomy is likely different when the patient is in a breath-hold compared to when the target is moving and momentarily within tolerance. This delay should improve the accuracy of the treatment. Since the breath-hold position is controlled by the patient, intrafraction drift correction does not apply to this strategy.

4. Non-respiratory—Exception

Elekta Unity CMM with True Tracking and Automatic Gating are also employed for targets that are not expected to move. The target is tracked in real-time, and radiation is paused if it moves out of tolerance, ensuring accurate treatment delivery. All standard imaging techniques can be used, and this is not expected to affect treatment time.

Daily 3D Imaging

All standard imaging sequences can be utilized to achieve optimal visualization of the target and organs at risk (OAR).

Template generation

The template is automatically generated from all cine images, ensuring that the template images are most representative of the treatment position.

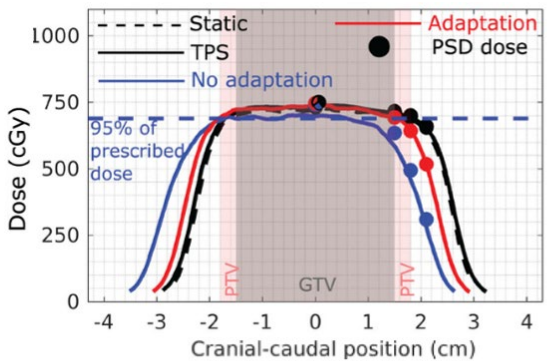
Treatment and automatic Gating

Since the target is not expected to move, no target position prediction is used. The latency associated with pausing the beam is minimal, typically a fraction of a second, and is not expected to significantly impact treatment accuracy.

Intrafraction drift correction

If target movement persists, intrafraction drift correction can be applied to shift the delivered dose to the new average target position. The True Tracking imaging planes and Gating Envelope will also be adjusted to the new position.

Uijtewaal P et al. (2023) evaluated the spatial and dosimetric performance of target tracking and intrafraction drift correction ('trailing') using high spatial resolution radiochromic film. They found that 'trailing' enhanced the 3%/3-mm local gamma pass-rates from 80% to 97% compared to the static dose, see figure 5.



Gamma pass-rate (3%/3 mm)	No trailing	Trailing
Artificial drift motion	37	95
Prostate motion	80	97

Figure 5 Gamma pass rate with and without 'Trailing, and the dose profile for 'Trailing' as extracted from the measured film dose

'Under the hood'

Predictive algorithm

All systems exhibit some degree of inherent latency, which is the time delay between an event occurring and the system's response to that event. In the context of gating, this refers to the delay between a target moving out of tolerance and the radiation beam being turned on or off. For some systems, these two times may differ. In radiation therapy, this latency can diminish the effectiveness of motion management techniques such as gating.

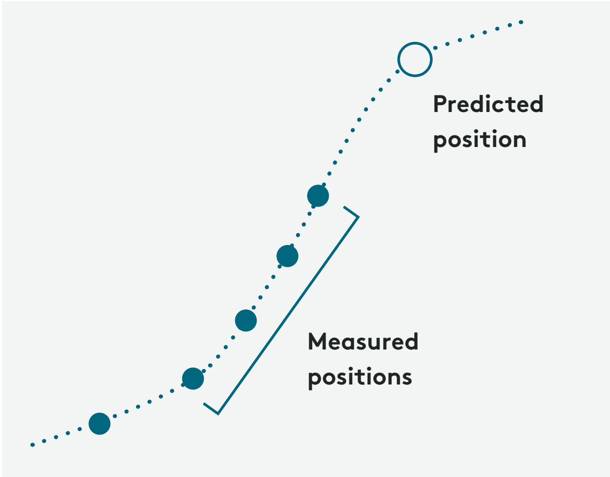


Figure 6 Position prediction

The impact of latency on radiation delivery is most pronounced for targets that are in motion when the beam is activated or deactivated. Consequently, latency has a reduced effect on non-respiratory targets or those treated using a breath-hold technique. However, some patients may not be able to tolerate breath-hold techniques, or they might find free-breathing techniques simpler or more comfortable. In such cases, compensating for latency in free-breathing techniques becomes crucial.

Techniques to compensate for system latency typically involve predicting the target's position. Essentially, the system uses recent data on the target's past positions to predict its current location, enabling timely gating decisions.

For these position prediction systems to function effectively, several factors must be considered:

- The system must understand the target's movement patterns to create an accurate motion model.
- The system requires recent historical data to make reliable predictions. According to the AAPM Task Group 76 report, this data should be no older than 500 milliseconds.

Elekta Unity CMM employs a prediction model for both free-breathing techniques. This system constructs a model based on the target's motion as measured by True Tracking. One significant advantage of True Tracking is its ability to continuously measure the target position without interruption from Gantry movements, unlike other MR-Linacs. This continuous measurement allows for ongoing updates to the motion model, ensuring it accurately reflects the current target motion. The recent target positions, combined with the model, are used to predict the current target position, determining whether the beam should be enabled or not, see figure 6.

Elekta Unity has a low inherent system latency of approximately 300 milliseconds. This latency encompasses the entire process of acquiring the cine image, analyzing it, communicating the information, and enabling or disabling the beam, with minimal difference between enabling and disabling. As the system latency is significantly less than 500 milliseconds, the prediction is reliable.

The accuracy of the prediction model heavily depends on the regularity of the target motion, which can often be improved through patient coaching. If the target motion is particularly irregular, reliable prediction may not be possible. To mitigate his risk, the system continuously verifies the accuracy of the prediction by comparing previously predicted values with measured values as they become available. The mean and standard deviation of these errors are analyzed, and if they are likely to significantly affect the delivered dose, the beam will be inhibited, and the user will be informed. If the issue occurs repeatedly, the clinical user should consider an alternative motion management strategy for the patient.

The residual latency after applying this prediction has been measured using a plastic scintillation dosimeter (PSD). Uijtewaal P et al. (2023) See figure 7.

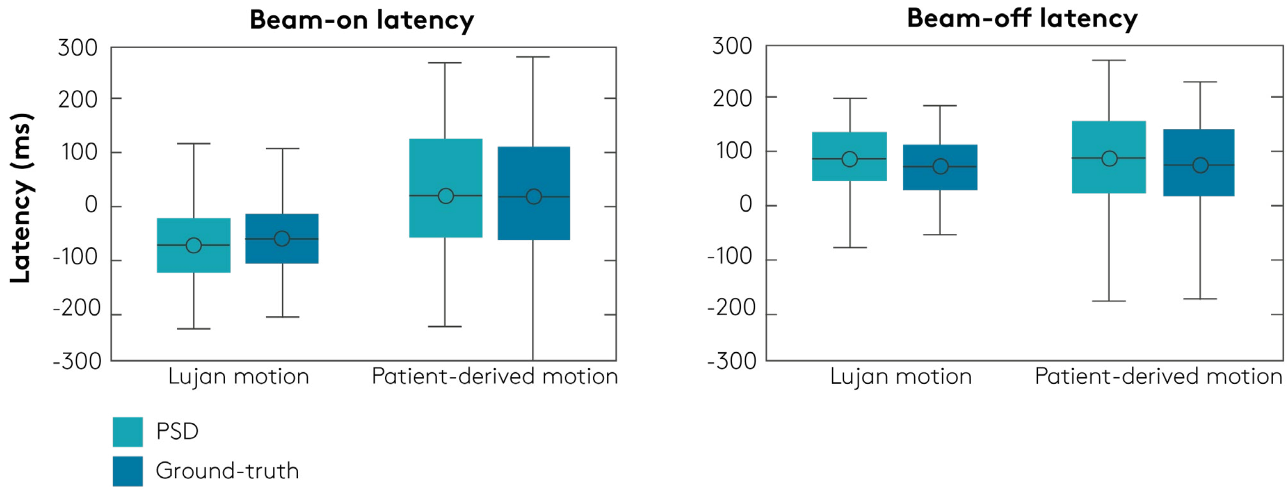


Figure 7 Beam gating latency based on the MRI 4D scintillator cassette's PSDs and based on the beam pulses.

	Beam-on latency	Beam-off latency
Lujan motion	-74.6±77.9 ms	80.0±71.2 ms
Patient-derived motion	20.5±129.5 ms	82.7±103.3 ms

Distortion correction

All MR systems have known non-linear characteristics, and this causes the underlying information to be distorted. It is standard practice for these distortions to be corrected. For 3D images, this correction can be done in every direction and as a result, the daily images on Elekta Unity have very low distortion. For 2D cine images, it's simple to correct for the distortion within the plane, but it is more challenging to correct for the fact that the plane is curved. Elekta Unity corrects for this cine plane curvature by incorporating it's effect into the mapping of the structures from the daily 3D MR to the cine plane. In this way, Elekta Unity CMM is fully distortion corrected in all directions. This feature, combined with the large lateral field coverage of the Unity MLC, makes it possible to precisely treat targets that are not near the isocentre.

Conclusion

The unique integration of a diagnostic quality MRI and state-of-the-art radiation therapy system in Elekta Unity allows continuous real-time, anatomy-specific MR imaging, even during gantry rotation. This high-quality imaging allows the position of the target to be continuously tracked with low latency. The Target Tracking and gating is optimized for the four motion management strategies and their strategy specific imaging sequences, meaning more patients than ever can benefit from precision treatment in the presence of motion. Elekta Unity provides the ability to see and treat like never before.

More than Confident—certain

1. Uijtewaal P, Borman P, Cote B, et al. Performance characterization of a novel hybrid dosimetry insert for simultaneous spatial, temporal, and motion-included dosimetry for MR-linac. Med Phys. 2023

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Hope for everyone dealing with cancer.

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