White Paper

Elekta Unity
Comprehensive Motion Management—Explained

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The motion management process

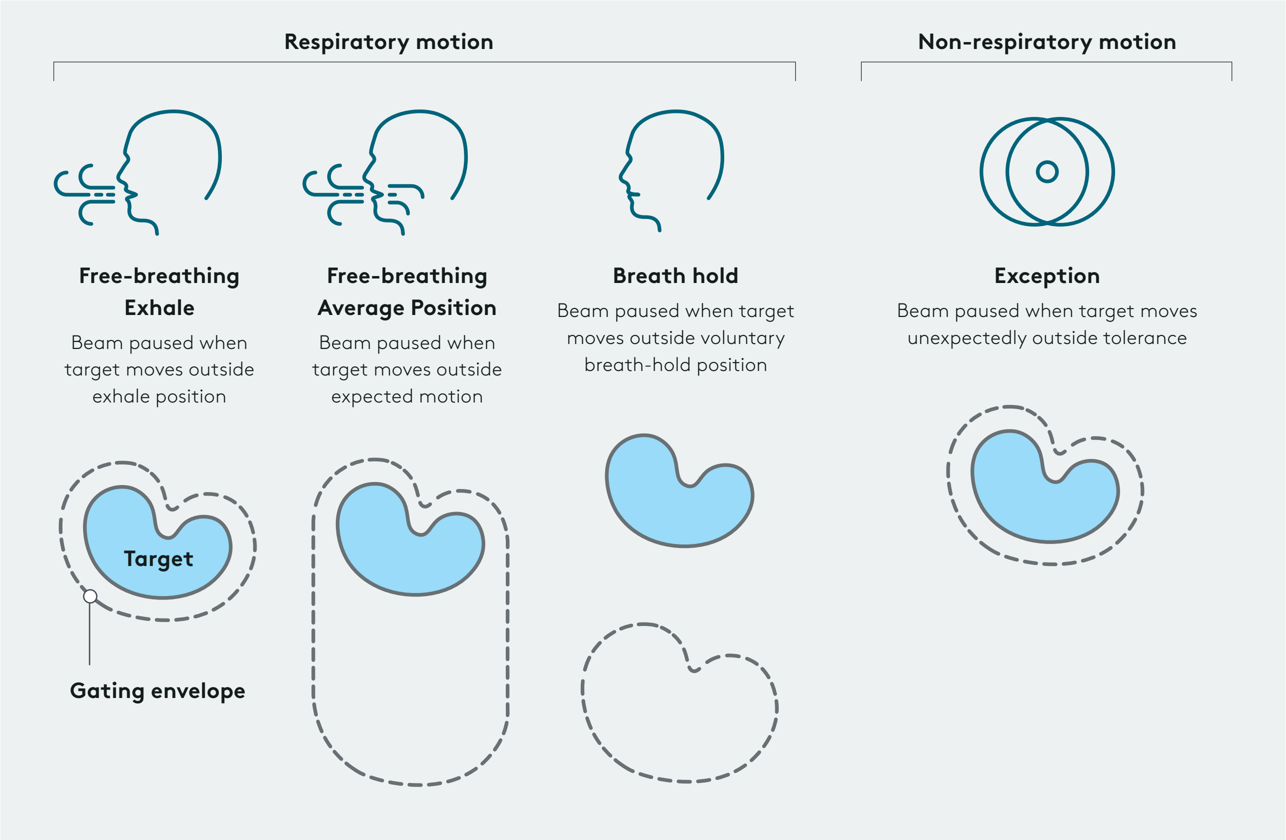
Elekta Unity provides anatomy-specific imaging sequences that exploit the capability of the 1.5T MR to optimize the visualization of the target and surrounding healthy tissue. These imaging sequences make some tissues appear bright while others make the same tissue dark—this is referred to as differing MR 'contrasts'. The 3D image contrasts available on Unity are T1, T2, Balanced, FLAIR and SPAIR. When using MR to monitor respiratory motion it becomes more important that the imaging is fast to minimize delays in detecting the target position, and to achieve this, we use balanced contrast imaging. When non-respiratory targets are being tracked, 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 and for the reasons just stated, this might have a different contrast to the cine image, making it challenging to identify the target on the cine images. This problem is solved by using two intermediate images called template images. The template images are automatically generated in a preparation phase from a short cine sequence. They are registered to the daily 3D MRI using an algorithm that is robust against the differing contrast. The user reviews this registration result and then we know where the target is in the template images. The cine images are then registered against the template images on the fly using a fast algorithm as the contrasts are identical. The combination of these two registration results indicates where the target is in real-time compared to the adapted plan and this position offset is used by the gating algorithm to enable and disable the radiation beam.

Motion management structures

In addition to the normal treatment planning structures, two new structures are introduced for motion management. These structures are produced from the reference plan to the daily MRI as part of the treatment workflow. The first structure is the registration structure. This defines the region of the image that is used by the registration algorithms. It's important that the motion of this region is representative of the motion of the target and that it contains sufficient anatomical detail for the registration algorithm to be robust. In some cases, it will simply be the GTV, possibly increased by a small margin, while in other cases it will be a local anatomical feature like vasculature. The other structure is the gating envelope. The structure includes the GTV and will likely be an auto-expansion of it. As the target moves the system calculates how much of the GTV remains within the gating envelope and if this value falls below a user-defined threshold, then the beam will be disabled.

Motion management strategies

There are many different situations in which we want to manage motion. As the MR is so capable Unity can provide four different motion management strategies. This enables you, the user, to choose the most relevant motion management strategy for your patient and their indication. There are three strategies to deal with respiratory motion and one non-respiratory strategy.



Free-breathing Exhale: Beam paused when target moves outside exhale position

Free-breathing Average Position: Beam paused when target moves outside expected motion

Breath hold: Beam paused when target moves outside voluntary breath-hold position

Exception: Beam paused when target moves unexpectedly outside tolerance

Respiratory motion

Free-breathing exhale

For this technique the patient is imaged and treated while breathing freely. However, the daily MRI image will only be acquired, and the radiation only delivered during the exhale phase. This is all done automatically without any action required by either the patient or the user, making this a very attractive technique.

The free breathing exhale technique could become the dominant motion management strategy going forward. It has the advantage of only turning on the beam when the target is within tolerance of the exhale position, allowing the user to reduce the planning ITV margin compared to the free breathing average technique. The fact that the patient is breathing freely, while the system does the work will make this particularly beneficial for sick and frail patients.

The free breathing exhale technique will extend the treatment time as the radiation is only enabled when the target is near the exhale phase of the respiratory cycle.

Free-breathing average

For this technique, the patient is imaged and treated continuously while they are breathing freely. The dose will be centered on the time-weighted average position of the target and an ITV margin will be used to ensure that the dose covers the expected motion. The target will be tracked continuously, and the beam will be paused if the target moves out of this planned expected motion i.e. only if something unexpected happens.

This strategy does not involve any complexity on the part of the patient or the user, it does not extend the treatment time and is like existing workflows in RT. It is more applicable to targets with small or modest motion. It should be noted that this motion management technique also manages the motion of other parts of the anatomy in the imaging Field of View. For example, a moving chest wall might cause artifacts in the image that obscure the target and then this motion management technique will be beneficial even if the target itself is barely moving.

It should also be noted that minor interventions can, in some circumstances, reduce the target motion sufficiently to make patients suitable for this strategy and avoid the increase in treatment time associated with gating the beam. These interventions include modest abdominal compression or continuous positive airway pressure (CPAP) and shallow breathing. These interventions might not be helpful if they hugely increase the treatment time.

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

Breath-hold

With 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 (18 seconds). Then, Elekta Unity Comprehensive Motion Management (CMM) True Tracking and Automatic Gating ensure that the treatment is delivered only during subsequent breath-holds.

The breath-hold technique is currently preferred by many clinicians. It has the advantage of minimal motion during a breath-hold. But it does require the patient to be able to understand the procedure and reproducibly hold their breath—this is challenging for some sick patients. A certain margin will be required to allow for variation between breath-holds. Breath-hold will be valuable when the increase in lung volume is beneficial dosimetrically e.g. moving the heart away from the target.

The treatment time will be extended by the time required to coach the patient to each breath-hold and for the recovery time between breath-holds. This extra time will be patient-specific, but this may be much longer than the time required for Free breathing exhale.

Non-respiratory motion

Exception

Unity True Tracking and Automatic Gating can be used for all patients with targets impacted by motion. Targets that are less impacted by respiratory motion can be subject to random motion. In this case—the exception gating strategy is used to track in real-time and the radiation is paused if it moves out of tolerance. This will ensure that the treatment is delivered correctly. All our normal imaging techniques can be used, and this is not expected to affect treatment time.

Treatment workflows

The treatment workflow is optimized for each strategy. This doesn't mean additional complexity for the user because this optimization is done by the system. All the user needs to do is select the appropriate strategy for the patient. This selection will likely be done at Simulation but must be done before the reference plan is created as this will depend on the strategy.

This section describes how the behavior of the system is optimized for each strategy and how this affects the workflow.

Free-breathing average

For this strategy, the patient is imaged and treated continuously while they are breathing freely. The dose will be centered on the time-weighted average position of the target and an ITV margin will be used to ensure that the dose covers the expected motion. The target will be tracked continuously, and the beam will be paused if the target moves out of this planned expected motion i.e. only if something unexpected happens.

Simulation and reference planning

The approach of using an ITV is well established. It is not expected that any changes will be needed from current practice. An example of an ITV approach is to define the target on all the phases of a 4D CT and define the ITV as the mathematical union of all these volumes. Alternatively, the extent of the motion might be quantified and the GTV expanded by the amplitude of the motion in each direction.

When the patient is treated for their first fraction on Unity, the clinical users will be able to assess the actual motion amplitude and compare this against what was used in Planning. This might cause an update to the reference plan.

If a 4D CT is used for reference planning, then the first fraction MRI might be selected as the reference image for following fractions.

Daily 3D imaging

This strategy uses a free-breathing imaging technique called 3D Vane XD to suppress motion artifacts. As the 3D Vane acquisition is over the entire respiratory cycle the resulting image is of the average target position. It will also have motion blur, meaning it's likely to be applicable for small and modest target motions.

3D Vane XD is available in four different contrasts for optimal target and OAR visualization. It is available in both T1 and balanced contrast. Both these contrasts are also available with the SPAIR fat suppression. Fat suppression takes away the brightness of the fat that can obscure the target. The brightness of the fat can be like trying to see some details when driving at night when the car coming towards you has got its headlights on. The glare from their headlights obscures what you're trying to look at.

The fat suppression turns off the headlights of the oncoming car and helps us to see the details in the patient more clearly. So, four different contrasts: T1, balanced and then both of those with fat suppression.

Template generation

The template will be automatically generated from the cine images that are in the middle of the respiratory range i.e. excluding the extreme inhale and exhale images. In this way, the template images are most likely to be representative of the treatment position.

Treatment and automatic gating

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

As the target is moving repetitively, target position prediction is used to eliminate system latency and there are no significant delays when either enabling or disabling the radiation beam. This will result in an accurate delivery of the treatment. The target prediction is based on a model of the recent respiratory motion of the patient and this motion model is continuously updated so systematic changes in the motion are included. The performance of the target position prediction is also continuously monitored and if this falls below a system-defined threshold the beam will be paused, and the user notified. This will likely be due to erratic breathing patterns and the clinical user should consider using a different strategy for this patient.

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. 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.

Free-breathing exhale

For this technique, the patient is imaged and treated while they are breathing freely. However, the daily MRI image will only be acquired, and the radiation only delivered during the exhale phase.

Simulation and reference planning

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

Daily 3D imaging

The imaging is performed using the 'T2 navigated technique'. The MR detects the exhale respiratory phase using a navigator channel which is placed on the diaphragm, this signal automatically triggers the acquisition of the 3D MRI. In this way, a T2 image is acquired in the exhale position with minimal motion blur. This is all done automatically by the MR without the need for respiratory belts or other techniques to detect the respiratory cycle. The acquisition time is extended due to it only occurring during the exhale phase. This can be compensated by using the Philips Compressed Sense function which acquires less data and still retains high image quality.

Template generation

The template will be automatically generated from the cine images that are at the exhale phase of the respiratory cycle. In this way, the template images are most likely to be representative of the treatment position.

Treatment and automatic gating

The Free breathing exhale technique will extend the treatment time as the radiation is only enabled when the target is in the desired position. As the current delivery technique is Step and Shoot and the gating duty cycle only affects the portion of the delivery for which the beam is on, it is expected to result in a modest change in the overall session time. For example, for an 8 Gy fraction dose we assume an 8-minute beam delivery time, during which the radiation is on for approximately 4 minutes. If we also assume that the gating duty cycle is 50% (most of the respiratory cycle is spent in exhale) then this 4-minute radiation-on time will become 8 minutes and the total beam delivery time will become 12 minutes i.e. an increase of 50%.

As the target is moving repetitively, target position prediction is used to eliminate the system latency and consequently there are no significant delays when either enabling or disabling the radiation beam. This will result in an accurate delivery of the treatment. The target prediction is based on a model of the recent respiratory motion of the patient; this motion model is continuously updated so systematic changes in the motion are included. The performance of the target position prediction is also continuously monitored and if this falls below a system-defined threshold the beam will be paused, and the user notified. This will likely be due to erratic breathing patterns and the clinical user should consider using a different strategy for this patient.

Intrafraction drift correction

If the average position of the target shifts during the fraction, then the duty cycle will be reduced, the beam will spend less time on, and the total treatment time will be prolonged.

The Intrafraction drift correction can be used to correct for this systematic shift and it will shift 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. This process should restore the original duty cycle.

Breath-hold

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

Simulation and reference planning

The image used for reference planning should be acquired using the same voluntary breath-hold technique as will be used during treatment. The simulation session might also be used as a training session to assess the patient's ability to hold their breath in a reproducible position. This image can be acquired on a CT or MR Sim. As the plan will be adapted on the daily breath-hold image on Unity, the reference image does not need to be the same as will be used on the day of treatment.

Daily 3D imaging

The 3D breath-hold images are all acquired in a single breath-hold (18 seconds) and are available in three different contrasts, T1, T2, and balanced to obtain optimal visualization of the target and OAR. The T2 contrast is quite challenging and therefore the spatial resolution is reduced.

Template generation
The template will be automatically generated from the cine images that are in a voluntary breath-hold. The images are registered to the Daily 3D breath-hold image so, while the two breath-holds should be similar, it is not critical that they are in the same position. In this way, the template images are most likely to be representative of the treatment position.

Treatment and automatic gating
As the intention is to treat the target while it is stationary during the breath-hold, no form of target position prediction can be used. Furthermore, we wish to ensure that the target is in a breath-hold not just passing through the breath-hold position, to this end, the tracked position of the target is checked to confirm that 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. Firstly, the user will not be expecting the beam to be enabled when the patient is not in a breath-hold. Secondly, the position of the anatomy is likely to be 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.

As the position of the breath-hold is in the control of the patient the Intrafraction drift correction does not apply to this strategy.

Non-respiratory

True tracking and automatic gating will also be used for targets that we do not expect to move. The target will be tracked in real-time and the radiation paused if it moves out of tolerance. This will ensure that the treatment is delivered correctly. All our normal imaging techniques can be used, and this is not expected to affect the treatment time.

Daily 3D imaging
All the normal imaging sequences can be used to obtain optimal visualization of the target and OAR.

Template generation
The template will be automatically generated from all the cine images. In this way, the template images are most likely to be representative of the treatment position.

Treatment and automatic gating
As the target is not expected to move, no form of target position prediction can be used, and the latency associated with pausing the beam will be a fraction of a second. This delay is not expected to significantly affect the accuracy of the treatment.

Intrafraction drift correction
If the target movement persists, then an Intrafraction drift correction can be used 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.

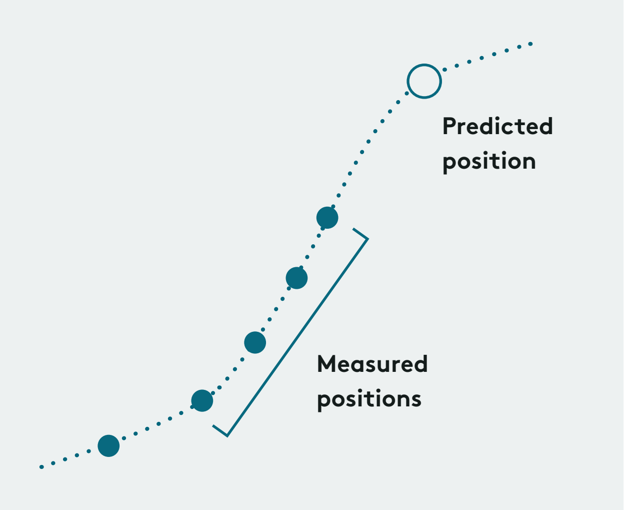
‘Under the hood’

Predictive algorithm

All systems have some inherent or system latency, that is the time delay between an event occurring and the response to that event. In the case of gating this is the delay between the target moving out of tolerance and the radiation beam being turned on or off, for some systems these two times are different. In radiation therapy, this latency can reduce the benefit from motion management techniques like gating.

The effect of the latency on radiation delivery is most significant for targets that are moving when the beam is turned on or off. This means that latency has less effect for non-respiratory targets or targets that are treated using a breath-hold technique. However, some patients will not be able to tolerate breath-hold techniques, or they might find free-breathing techniques simpler or easier to do. In the free breathing techniques compensating for this latency becomes more important.

Techniques to compensate for this system latency usually involve predicting the target position. Effectively, the system knows where the target has been in the recent past and it needs to predict where the target is now to be able to make a timely gating decision.



For these position prediction systems to work several factors need to be in place:

- The system needs to know how the target has been moving to enable the creation of a model of the motion.
- The system needs to know the ‘recent’ history to make this prediction. The AAPM Task Group 76 report recommends that this recent information is no older than 500 ms for reliable prediction.

Unity CMM uses a prediction model for both free-breathing techniques. The system builds a model from the motion of the target as measured by True Tracking.

One of the benefits of True Tracking continuously measuring the target position (this is not interrupted by Gantry moves as in other MR-Linacs) is that this enables us to continuously update the motion model to ensure that it most accurately represents the current target motion. The recent target positions are used together with the model to predict the current target position which is used to determine if the beam should be enabled or not.

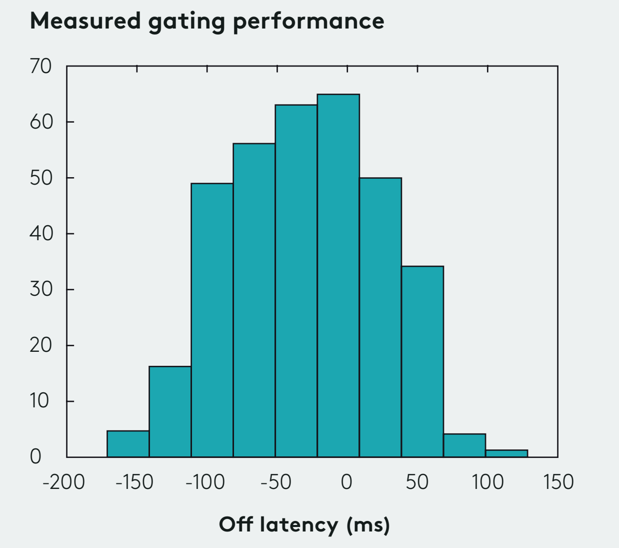
Unity has a low inherent system latency of nominally 300 ms; this includes the entire process of acquiring the cine image, analyzing the image, communicating the information, and enabling or disabling the beam (this delay is not significantly different between enabling and disabling). As this system latency is significantly less than 500 ms this enables the prediction to be reliable.

The accuracy of the prediction model is critically dependent on the regularity of the target motion which can often be improved by coaching the patient. If the target motion is particularly irregular, then it might not be possible to reliably predict the target position. To avoid this becoming a hazard, the system continuously checks the accuracy of the prediction by comparing the previously predicted values with the measured values as they become available. The mean and standard deviation of these errors are analyzed and if they are likely to cause a significant effect on the delivered dose then the beam will be inhibited and the user informed. If this occurs repeatedly the clinical user should consider an alternative motion management strategy for this patient.

The residual latency after this prediction has been applied has been measured, it has an average of 30 ms and a standard deviation of 50 ms, this is effectively zero.

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 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. Unity corrects for this cine plane curvature by incorporating it's effect into the mapping of the structures from the daily 3D MRI to the cine plane. In this way, Unity motion management 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.


Measured gating performance

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.

Hope for everyone dealing with cancer.

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Elekta Unity with Comprehensive Motion Management (CMM) has CE mark
and U.S. FDA 510(k) clearance. Not be available in all markets.