**Introduction**

Respiratory motion presents a number of challenges in the delivery of radiotherapy to certain thoracic (e.g., lung, breast) or abdominal (e.g., liver) tumors. During the acquisition of planning images, free breathing can cause artifacts that may affect the delineation of tumors and organs-at-risk, thereby potentially impacting the accuracy of dose calculation.\(^1\) In treatment planning, tumor movement during respiration may require the addition of margins (internal target volume: ITV) around the clinical target volume (CTV), which increases the volume of healthy tissue exposed to high doses. Since this exposure increases the risk of treatment-related complications,\(^2,3\) there is a limit to the dose that can be delivered to the target.\(^1\) In addition, during treatment delivery, the averaging of the dose distribution across the path of tumor motion can cause variations between the intended dose and the actual dose delivered. These variations may average out over the course of conventional multiple field or multiple fraction treatments but they may be an issue, particularly with hypofractionated regimens.\(^1\)

Respiratory motion management is extremely important during the delivery of modern radiation treatment techniques, such as stereotactic body radiotherapy (SBRT). There are several techniques currently used to reduce or manage respiratory motion such that margins can be reduced and to enable dose escalation. The choice of method will depend on the amount of tumor motion and the needs of individual patients.
Elekta offers a suite of respiratory motion management solutions, including products for:

- **Diaphragm control (BodyFIX® patient immobilization)** - Stable patient positioning and abdominal compression reduce diaphragm movement and target motion in the thorax and abdomen caused by respiratory motion.

- **Volumetric visualization (Symmetry™ 4D image guidance)** - Unique, anatomically correlated 4D image guidance allows target motion to be visualized over time during treatment delivery and without the need for external markers. The ability to account for baseline shifts supports the reduction of margins for free breathing and ensures complete confidence in the delivery of dose distributions to moving targets.

- **Gated treatment delivery (Response gating interface)** - Treatment can be delivered during a predetermined phase of the respiratory cycle, either during free breathing or during a voluntary or assisted breath hold. The beam is “on” while the breathing cycle is within the treatment window (or gate) and “off” during the rest of the cycle.

**Respiratory gating**

Respiratory gating is used routinely in the treatment of tumors in the lung, left-sided breast, liver and pancreas to reduce dose to healthy tissues and critical structures.

Free breathing gated delivery is well tolerated by patients, but there is a trade-off between accuracy and efficiency. It has been proposed that the reduction of margins in respiratory gated radiotherapy requires accounting for respiratory baseline shifts and variations in external/internal motion correlation, which can be achieved using 4D imaging. Guckenberger et al (2011) found that, for pulmonary targets with motion amplitudes greater than 10-15 mm, the combination of gating and imaging – to determine mean target position (MTP) – allowed both smaller safety margins and longer duty cycles.

Relatively few patients have pulmonary target motion amplitudes of greater than 15 mm. For example, in a recent lung radiotherapy study involving 409 patients, less than 10% had a respiratory excursion exceeding 15 mm. Therefore, using the aforementioned recommendations, moderate gating will be beneficial for a small group of patients when combined with MTP and, for the vast majority of pulmonary targets, the use of MTP – as measured using Symmetry – provides equivalent benefit to gating, yet is more efficient.

Another gating technique, breath hold gating, can be used to increase the distance between the target and critical structures (Figure 1) and/or to reduce lung volume (and therefore healthy tissue irradiation) during radiation delivery. With breath hold gating techniques, the target is held in a stationary position during beam delivery, which allows margins to be reduced (Figure 2) and results in significant sparing of healthy tissue. Since patients must hold their breath in a predictable and reproducible fashion, this method may not be suitable for patients with compromised breathing.
Assisted breath hold, using Active Breathing Coordinator™ (Elekta) combined with Symmetry 4D image guidance or XVI VolumeView™ (Elekta), allows breath hold gated CBCT image acquisition that is consistent with the treatment gating window. This ensures that image acquisition is consistent with the anatomical treatment position, facilitating accurate registration and treatment delivery.

The gating signal

Respiratory gating can be manual, with the radiation beam controlled by the operator (and sometimes the patient), or it can be automatic, in which the beam is controlled by a signal generated by a motion management solution, such as spirometry (Active Breathing Coordinator), external markers, imaging (Symmetry and XVI) or surface mapping (C-RAD Catalyst™).

In Elekta digital linear accelerators, Response provides an integral, seamless interface that supports automated gated treatment delivery for a range of delivery techniques, from 3D conformal (3D CRT) to IMRT and VMAT. In keeping with the Elekta open systems philosophy, Response can be triggered by a variety of gating sources, allowing use of a gating technique that is most appropriate to the needs of the patient.
Response supports three types of gating: breath hold, exception and free breathing.

- **Breath hold gating**

Supporting a range of automated breath hold gated techniques, such as deep inspiration breath hold (DIBH) with Active Breathing Coordinator, Response works with the digital linear accelerator to deliver radiation to the immobilized target. The beam is enabled when the patient is in the required breath hold and is held off while the patient is breathing/recovering. Typically, the beam is enabled for 15 to 20 seconds and “off” for 30 to 60 seconds.

- **Exception gating**

Unintended gross patient movement can cause exposure to surrounding healthy tissues and critical structures. Managing this scenario and preventing unwanted dose delivery, Response supports the use of exception gated treatments; inhibiting radiation when movement detected by an external gating device exceeds a specified threshold. The beam is held off if the patient’s breathing pattern falls outside of the normal range and is re-enabled when the breathing returns to normal range. Similarly, the beam is held off if the patient contour falls outside of a certain tolerance from set up and is re-enabled if it moves back within tolerance. Beam “hold off” is exceptional and typically lasts for just a few seconds.

- **Free breathing gating**

Connecting the Elekta digital linear accelerator via Response to an external gating device to monitor patient respiratory motion – either directly or via a surrogate – allows radiation to be delivered only when breathing motion is within a predefined window. Outside of this window, radiation is inhibited. Maximum gating is suggested to be 25% (once every four seconds).

The following explanation describes how Response allows Elekta digital linear accelerators to deliver accurate gated delivery.

**How Response gating interface works**

In Elekta linear accelerators, a radiation beam is produced by the application of a High Tension (HT) pulse to the magnetron and simultaneously to the electron gun. This pulse causes electrons to be accelerated into the waveguide, while causing the magnetron to produce the accelerating radio frequency (RF) wave that accelerates the electrons along the waveguide to produce the radiation beam.

The HT pulses (triggered by the thyratron) are totally independent of each other, enabling the system to produce a variable number of pulses per second (pps), up to a maximum of 400 pps. The average frequency of pulses is called
the Pulse Repetition Frequency (PRF). Since the dose delivered in each pulse is nominally constant, the dose rate is effectively proportional to the pulse rate.

The signal (PRF signal) to switch the thyratron “on” (PRF Enable) is initiated from the digital linac control system, but is controlled by physical relays in the PRF interlock chain. If any of the relays is open, for example, if a parameter is out of tolerance, the pulse cannot be produced and radiation is paused (see Figure 3).

With Response automatic gating, an additional relay module is inserted into the PRF interlock chain which, when triggered to open, stops the generation of the HT Pulse and therefore turns the radiation beam off. In this way, the beam can be turned on or off at defined points within the breathing cycle or when the target is located within a defined area.

**Controlling the electron beam**

For accurate beam production, the magnetron must be at the correct frequency and the electron gun current must be at the correct operating level.

The operating frequency of the magnetron is affected by its temperature, which is primarily influenced by the mean RF power. This, in turn, is proportional to the PRF. For example, when the RF is initially turned on, the magnetron heats up and its frequency changes. This change is compensated for by the movement of a physical tuner. Elekta linear accelerators use a uniquely designed, fast tuning magnetron that enables the physical tuner to correct for frequency changes faster than any temperature effect. This means that, during normal operation, the magnetron remains at the correct frequency at all times.

The electron gun is kept at a standby level when radiation is not being delivered. At the start of radiation delivery, elevating the electron gun from this relatively cool state to its operating level takes less than one second.

The most significant change in operating conditions for the magnetron and the electron gun occurs when radiation is first turned on from “cold” (i.e. at the start of a beam). The initial RF pulses are used to enable the magnetron to tune to the required operating frequency. Once the magnetron operating frequency is within the required threshold, the electron gun current is switched from the standby level to the higher operating level. Electrons are then emitted and accelerated by the RF pulse, which produces the radiation beam. The fast tuning magnetron enables initial startup times of just four seconds.\(^\text{10}\)

The conditions during a momentary pause in radiation (for example, during a step-and-shoot IMRT delivery) are quite different. The PRF signal is disabled (paused) until the MLC leaves have moved to the next shape. Typically, this pause is short enough to allow the electron gun current to be held at its nominal operating level and for the magnetron to stay at the correct frequency. Then, when the PRF is re-enabled, the beam restarts immediately.

This mechanism of pausing and restarting the radiation is also used whenever a geometric parameter goes momentarily out of tolerance during a dynamic delivery.
The flexible design of the Elekta digital linear accelerator allows the period during which the electron gun is held at its operating level to be programmed as part of the machine set up. Prior to the release of the gating function, this period was set to one second. However, studies have shown that it is possible to extend the holding period to 6.5 seconds without significant impact on the dosimetric delivery of the beam.\cite{11-12} Therefore, when the gating function is enabled, it is recommended that this period be set at 6.5 seconds. Then, for short beam holds, the electron gun current is held at its operating level and the magnetron remains at the correct frequency. As a result, beam start-up is significantly quicker, ensuring accurate and reliable beam generation. This applies to gated treatment deliveries as well as other beam segments, such as step-and-shoot IMRT.

It is recommended that users optimize Elekta digital machine parameters according to the “setting to work” instructions,\cite{13} to enable gated treatment plans to be delivered at various dose rates in an accurate, stable and efficient manner.

**Evidence**

In a recent evaluation of Response on an Elekta Synergy® digital linear accelerator, the delivery efficiency and dosimetric accuracy of gated VMAT deliveries for lung SBRT treatment plans were examined. The gating signal was generated by the C-RAD Catalyst system and surface motion, as a surrogate for breathing motion, was simulated using a moving chest plate.\cite{11-12}

Two gating windows, 77% and 66% around the end of exhalation, were used for the gated deliveries. Dosimetric accuracy was evaluated by comparing measured and planned coronal dose distributions using gamma index analyses (with pass rate criteria of 3 mm/3%). The total delivery times, number of beam interruptions and gamma index pass rates were compared between deliveries with a continuously variable dose rate (CVDR) and a binned dose rate (non-CVDR).\cite{11-12}

This study demonstrated that respiratory gated VMAT can be delivered accurately and efficiently on an Elekta digital accelerator. For lung SBRT plans delivered with CVDR, compared to binned dose rate, delivery times were reduced and high dosimetric accuracy was achieved during VMAT arc delivery with frequent beam interruptions due to respiratory gating. This demonstrates that Elekta digital accelerators can accurately deliver gated radiotherapy, even for complex delivery techniques such as VMAT.\cite{11-12}

**Conclusion**

The Response gating interface allows accurate and efficient respiratory gating to be performed on Elekta digital linear accelerators and provides the flexibility to select the most appropriate gating technique depending on tumor motion and individual patient requirements. It can be used in combination with intrafraction image guidance (including Symmetry 4D imaging) and Active Breathing Coordinator as well as numerous third party motion management solutions.

For further information about any of the products mentioned in this paper, visit www.elekta.com.
References


* Treatment strategies referenced from clinical papers are not an endorsement by Elekta of a respiratory gating strategy.
ABOUT ELEKTA

Elekta’s purpose is to invent and develop effective solutions for the treatment of cancer and brain disorders. Our goal is to help our customers deliver the best care for every patient. Our oncology and neurosurgery tools and treatment planning systems are used in more than 6,000 hospitals worldwide. They help treat over 100,000 patients every day.

The company was founded in 1974 by Professor Lars Leksell, a physician. Today, with its headquarters in Stockholm, Sweden, Elekta employs around 4,000 people in more than 30 offices across 24 countries. The company is listed on NASDAQ OMX Stockholm.