



Tracking versus Gating in the Treatment of Moving Targets

a report by

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Image-guided radiation therapy (IGRT) and intensity-modulated radiation therapy (IMRT) can deliver a highly conformal radiation dose to the target while avoiding nearby critical structures. However, organ motion, especially respiratory motion, introduces a technical challenge to IGRT/IMRT planning and delivery of radiation. The movement of the target typically results in either the target receiving less than the prescribed dose or the critical structures receiving an additional, unnecessary dose. Beyond this practical problem, the challenge is that we do not have a good indicator to tell us where the target is at any given time. Current approaches to answering this question can be classified into three categories:

- wait for the target;
- follow the target; or
- predict the target.

Organ motion, especially respiratory motion, introduces a technical challenge to image-guided radiation therapy/intensity-modulated radiation therapy planning and delivery of radiation.

Wait for the Target

This concept means that we can expect the target to be at a certain position during a specific interval of the respiratory cycle. The exact portion of the respiratory cycle is determined at the time of computed tomography (CT) imaging. The same interval is used for the delivery of radiation, thus ensuring a reproducible position for the target. The assumption for this method is that the target will be at the same or similar location if the breathing cycle of the patient can be reproduced. In order to reproduce the patient's breathing cycle, internal or external markers should be positioned on the patient's body; the signal from the motion of the marker is then recorded and correlated to the motion of the target. A portion of the breathing cycle can be selected as a 'gate' for imaging the patient and for treatment delivery. This method is also known as 'gating'.

Follow the Target

Different imaging modalities are used to determine the target location in realtime and redirect the beam to follow the target. This method is also called 'tracking' since the beam is locked on the target and follows it as it moves.

Predict the Target

This category uses a mathematical model of the breathing pattern that is derived from the patient's imaging studies. This model is then used to predict the target's location at any time.

Categories one and two have been clinically implemented in one form or another. Category three is still considered a research method. In this paper, we will review the clinical applications of the first two categories, and discuss recent developments of category three. A comparison of these three methods will be presented, along with a discussion on the pros and cons of each approach.

Gating Method

Category one, or the 'gating' method, was first presented almost 20 years ago.¹ The gated signal was generated using gold markers implanted in the target, and the signal was used to control the linear accelerator systems in realtime. Later on, at the University of California-Davis, signals from a video camera were used to control a linear accelerator.² This system is currently being marketed as the Real-Time Position Management (RPM) Respiratory Gating System by the Varian Corporation.

Figure 1 shows the gating loop using an RPM system. A plastic box is placed on top of the patient's chest wall or abdomen. Two white dots on the localisation box reflect light, which is captured by an infrared camera. When the infrared camera captures the signal, a breathing pattern is generated. Typically, the breathing pattern will resemble a sinusoidal curve. A threshold can be applied to define a gating window on the respiratory signal. The gating can be based on phase or amplitude criteria, both of which have their respective problems.

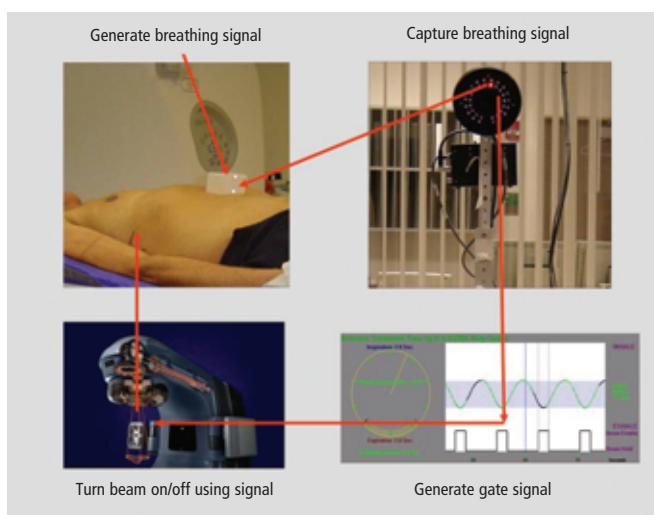


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Figure 1: Gating Loop for Computed Tomography Scan or Treatment



Top-left: a crystal box is placed on top of a patient's abdomen to generate breathing signal. Top-right: an infrared camera captures the breathing signal. Bottom-right: breathing signal is converted into 'gate' signal. Bottom-right: the 'gate' signal is used to control beam on/off for computed tomography scan or treatment.

However, what is critical is to define a gating window for a period of time where the motion of the target is minimal. Typically, this is during the expiration part of the respiratory cycle. The gating signal is then used to turn the CT scanner beam on and off during the patient-imaging

Patient co-operation is necessary for all gating techniques, and some of the proposed techniques may cause patient discomfort.

study. Once a treatment plan is developed, the same gating window is used to control the linear accelerator's beam on and off for the delivery of the treatment.

Another option is to gate the patient at a specific breathing phase. For example, a self-breath-holding (SBH) method was proposed by Onishi et al.^{3,4} In this method, a switch connected to the radiation console allows a patient to control the delivery of radiation. The patient is irradiated immediately following CT scanning to reduce the set-up error. The patient is trained in SBH. The patient finds an optimal position in a breathing cycle to start the irradiation. This method is easy to implement, is affordable, is controlled fully by the patient and was reported to be accurate.⁴

Another proposed method was termed active breathing control (ABC).^{5,6} The patient's breathing is monitored continuously with an ABC apparatus. At a pre-set lung volume, during either inspiration or expiration, the airflow of the patient is temporarily blocked, thereby suppressing breathing motion. Radiation is turned on only during this period. This method is known for its simplicity of use and high precision.⁵

However, an ABC device is needed for its implementation.

The deep inspiration breath-hold (DIBH) technique was used at Memorial Sloan-Kettering Cancer Center (MSKCC).⁷ The DIBH technique involves coaching the patient, encouraging him or her to breathe at a reproducible deep inspiration breath-hold level. Patient breathing is monitored through a spirometer with a custom computer interface during simulation, verification and treatment. The reproducibility of the DIBH manoeuvre for each patient is validated again during fluoroscopy over multiple breath-holds. Tumour motion is estimated by comparing a free-breathing CT scan and a DIBH CT scan. The estimated tumour motion range can be used to determine the spirometer action levels for treatment. By linking the isocenter to the diaphragm measured from the DIBH digitally reconstructed radiographs (DRR) to the distance measured on the portal films, the patient lung inflation can be verified over the course of the treatment. Commercial spirometry products are now available, such as the VMAX Spectra 20C (VIASYS Healthcare Inc., Yorba Linda, California) or the SpiroDyn'RX (Dyn'R, Muret, France), which can be used for the implementation of this method.

Some efforts have been put into limiting patient breathing⁸ using a stereotactic body frame with a flexible plate to press against the patient's abdomen. In comparison with data for patients without compression, the tumour motion was reduced from 0.8–2cm (mean 1.2cm) to 0.2–1.1cm (mean 0.7cm).⁹ Common to all gated delivery techniques is the increased treatment time, since only part of the breathing cycle is used for the delivery of radiation. It is typical to use one-quarter to one-third of the cycle when the beam is on, making this method relatively inefficient. Patient co-operation is necessary for all gating techniques, and some of the proposed techniques may cause patient discomfort. Finally, the gating signal may not exactly reflect the real position of the target.^{10,11}

Tracking Method

Since gated treatment has the disadvantage of longer treatment time, researchers are investigating the possibility of tracking the target in

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realtime and getting the same treatment effect while shortening the treatment time. Target tracking requires two steps:

- localising the target; and
- following the target.

There are several methods to localise the target in realtime. X-ray imaging systems provide a practical solution to this problem. The in-room imaging approaches by CyberKnife and Brain Lab offer similar implementations, whereby two X-ray systems are paired with two imaging plates. Other manufacturers of linacs use an on-board imager

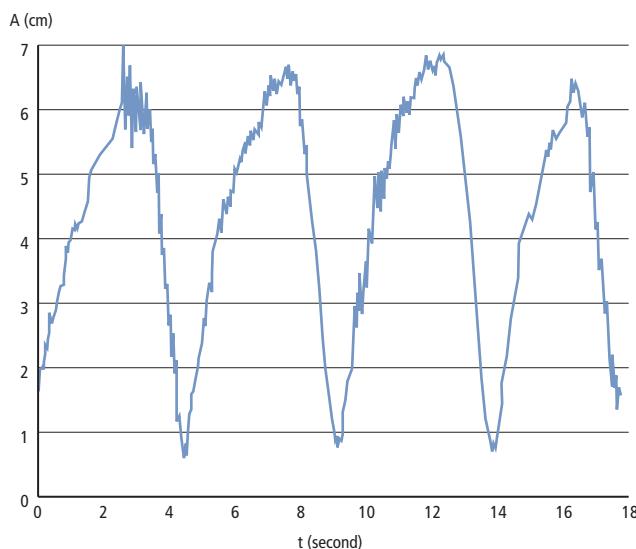
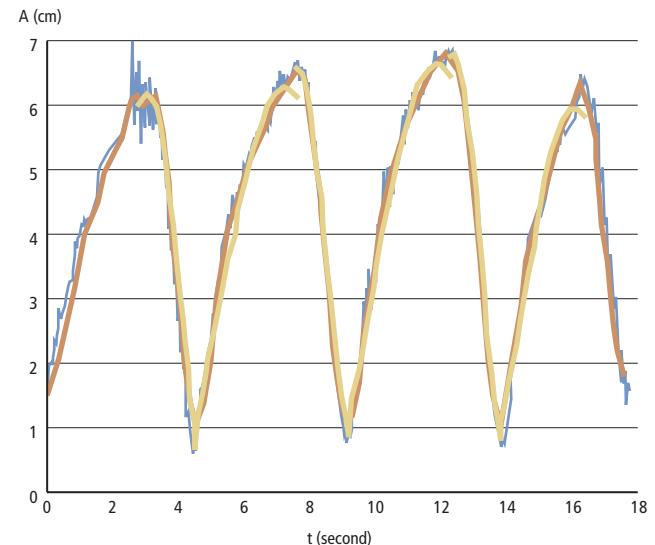
Figure 2: Real Patient Breathing Cycle Curve

Figure 2 shows the breathing curves of a real patient. In Figure 3 the orange line shows the de-noised curve for Figure 2, and the yellow line shows the prediction curve using the Kalman Filter.

(OBI) capable of acquiring cone beam CT data. The X-ray imaging system can track the implanted fiducial markers in the target and, through a feedback loop, instruct the linac where to deliver the

Figure 3: Predicting the Breathing Curve Using the Kalman Filter

not be enough to represent the real target.^{20,21} Another major problem with following the tumour is time latency. Finally, sensitive tracking failure detection methods should be employed for any tracking technique to ensure proper radiation delivery.

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radiation. Non-ionising tracking methods were also developed using a radiofrequency coil (RF) coil,¹² wireless electromagnetic transponder¹³ or three-dimensional ultrasound.¹⁴

To follow the tumour in realtime, Murphy¹⁵ summarised four approaches:

- move the couch;
- move the beam;
- move the linear accelerator; or
- move the dynamic multileaf collimator (DMLC).

Since DMLC is available in most clinical centres, moving the DMLC to follow the tumour may be the most appropriate approach, although all methods should be equivalent when properly applied. Several research groups have investigated this matter and developed algorithms to optimally move the DMLC.¹⁶⁻¹⁹

Even though different techniques for localising and tracking the tumour have been developed, the implementation of this technique continues to be challenging. One major problem with localisation algorithms is whether the real target is being localised. Both internal and external features (such as markers or tumour shape) for localising the target may

Predicting Method

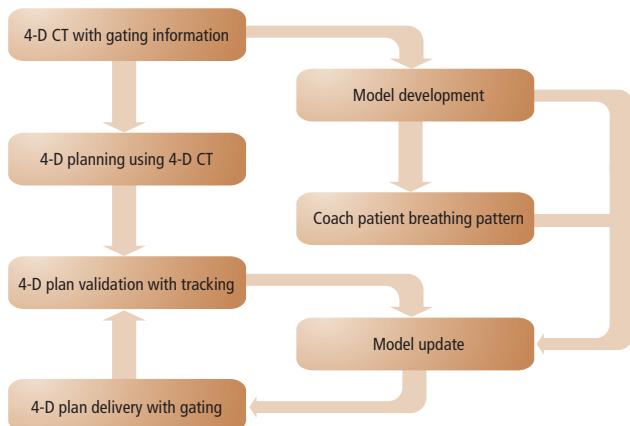
The feedback time latency problem of the tracking method could be overcome if there was a way to forecast the position of the target. This technique is called the predicting method. The main difference between tracking and predicting is that, for the latter, a model is needed to predict the location of the target. There are three basic steps for the predicting method: predicting, verifying and delivering.

The predicting model can be built using either the breathing curves of the patient or four-dimensional (4D) CT images to identify the target movement range.

No matter how accurate and precise the model is, when introducing it into clinical use the model must be verified and adjusted according to the patient's current breathing pattern.

Other filters for prediction have also been studied.²² Other approaches such as using a sine or cosine function for predicting the breathing curves were also investigated.^{23,24} Low et al.²⁵ also hypothesised that the motion of lung and lung tumour tissues could be a function of degrees of freedom: the position of the tissues at a user-specified reference breathing phase, tidal volume and its temporal derivative airflow (tidal volume phase space) and where time is an implicit variable in the model. No matter how accurate and precise the model is, when introducing it into

Figure 4: A Proposed Respiratory Motion-control Flow Chart



clinical use the model must be verified and adjusted according to the patient's current breathing pattern. A good model should be able to adjust its parameters easily and quickly based on several initial inputs from the patient. The model has to be robust enough to handle breathing noise such as coughing. Verifying and quickly adapting the model to the patient's realtime breathing pattern is a challenge. Once the model is verified, the beam can be adjusted to engage the target without the time delay that is present in the tracking methods. Time delay is not a problem for the predicting method, since the model can estimate the target location in advance.

Since no reproducibly generalised pattern of respiratory behaviour exists for any particular patient,³⁰ the choice of an accurate predictive model is still an area of investigation. The ultimate management of respiratory-related motion may end up being a mixture of currently available technologies. A potential solution for controlling the respiratory motion is illustrated in *Figure 4*. The patient is scanned using

4-D CT with synchronous acquisition of the respiratory signal. A model is constructed based on 4-D CT information and the patient is coached in order to minimise the breathing pattern difference between imaging and plan delivery. After a 4-D plan is developed, it is validated using a tracking technique and the model is updated if necessary. The 4-D plan will be delivered with gating technology; however, multiple gates may be selected for shortening the delivery time and to increase efficiency of delivery. A closed loop exists to validate, track, predict and deliver the 4-D plan.

Summary

In this review paper, we have summarised the methods for managing the respiratory motion as it relates to the delivery of radiation therapy. Respiratory motion continues to be a challenging problem; however, since the introduction of 4-D CT we can account explicitly for respiration-related motion during the imaging of the patient. For treatment planning, there are several problems to overcome, including target

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motion and target/organ deformation. The optimal delivery of the treatment, which is the final step in the process, is an active area of investigation. Several strategies have been proposed, but none so far can reproducibly and globally address the problem. In the meantime, there are methods that, although less efficient, enable us to deliver radiation to a moving target, thereby reducing the beam margins and minimising the dose to the surrounding healthy tissue. ■

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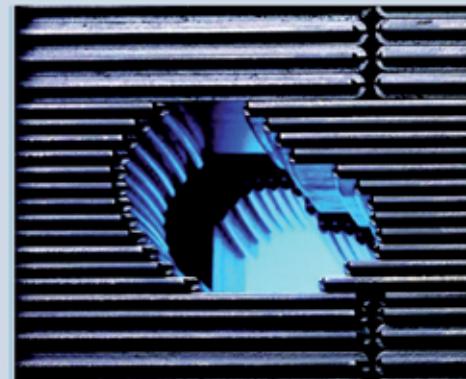


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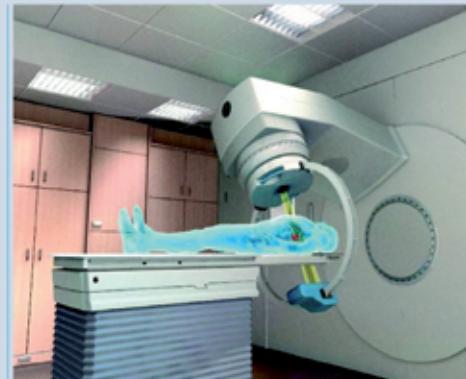


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MV IGRT for Real-Time Tumor Tracking