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Since the early 1980s, spurred by the introduction of supercomputing technologies, 4D radiation planning has been considered an affordable and elegant delivery option for radiation therapy. Newer advances prompted by computed tomography and 3D technology now allow views of tumors and their relationships to other vital structures. This enables physicians to generate a “beam’s eye view” of the target and surrounding structures from the perspective of the entering radiation beam. As a result, 3D views of the prescribed radiation dose cloud to the target and normal tissues can be optimized to further enhance the therapeutic ratio. Although 3D conformal radiation therapy (3D CRT) has revolutionized the oncolgy of use, its effectiveness is limited by respiratory motion and the impact that has on imaging and radiation treatment planning.23 Several researchers have shown that even with quiet respiration, lung tumors can move significantly, causing potential inaccuracies in treatment delivery.23,24 Without an adequate method to image and evaluate the consequences of respiration on tumor and nearby critical structures, advanced conformal radiation techniques such as intensity-modulated radiation therapy (IMRT) are not possible.

TARGET DEFINITION

As a general principle, the goal of CRT is to deliver the intended dose to the target with as little dose as possible leaking out to the surrounding normal structures. To complete this CME activity free of charge, please go to the accredited provider website www.mhreview.com/nra for post testing and Reader Evaluation. Estimated time to complete this activity should not exceed 1.0 hour.

LEARNING OBJECTIVES

• Describe the current state of radiation therapy for thoracic and abdominal tumors.
• Review the concepts of target definition in conformal radiation therapy planning.
• Explain the dosimetric impact of target and/or organ motion in radiation treatment planning.
• Review the early clinical experiences with 4D CT-based radiation treatment plans.

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ily on accurate delineation of the target
volume. The International Commission
on Radiation Units and Measurement has
provided guidelines on the definition of
target volumes used for treatment
planning.1 These volumes include the
gross tumor volume (GTV), the clinical
target volume (CTV), which accounts for
clinical microscopic extension of disease,
and a planning target volume (PTV),
which accounts for set-up uncertainties,
tumor motion, and dosimetric buildup of
radiation.

In fact, the greatest uncertainty in
thoracic radiotherapy is respiration-
synchronized motion of the target.1 It
is within the PTV that tumor motion—and
organ motion, for that matter—occurs.
Clear knowledge of the true kinematics of
these volumes of interest can significantly
improve radiation treatment planning by
providing a detailed map of trajectories throughout the respiratory or physiologic cycle.

In order to develop accurate planning
studies, it is critical that interobserver
toxicities such as radiation-induced transverse myelitis of the spinal cord.14

As described in the Clinical Practice
Panel Report,15 RTSTs are characterized by
4D CT-based radiation therapy treatments
that synchronize patient respiration with
image acquisition and during treatment.23

The process involves synchronization of
imaging acquired in temporal phases to
reflecting the respiratory cycle. These
prospective gating techniques of image
acquisition are triggered by a particular
respiratory phase. This approach to image
acquisition and delivery is also used for
other abdominal tumors.25-30

While a fairly crude (though effective)
method for minimizing motion, gating is
often encountered (Figure 1). These
toxicities occur as a result of the large
magnitude of these artifacts, which are
imposed on the target volume. 

One major challenge is to identify
when highly conformal radiation tech-
niques are feasible as an alternative to
conventional radiation techniques. For
this reason, the thorax and abdomen are
being targeted for radiation treatment
planning.

Many institutions are currently imple-
menting 4D CT-based radiation therapy
planning systems. A technology panel of
the American College of Radiology, the
American Society for Therapeutic Radiology and Oncology, the American Brachytherapy Society, and the American College of Radiation Physics has recommended that RTTs be readily available with this method, allowing for reductions in number, size, or duration of treatments23,24 for liver cancer. Several other authors have demonstrated the feasibility of using RTTs for the treatment of lung cancer, head and neck cancer, and other abdominal tumors.18,19

4D CT-based gated treatments 4D CT-
based techniques are more advanced
than 3D CRT, geometric and physiologic
motion, which may result from a PTV
dimensional accuracy and also
increased treatment time.23

Planning has historically been
expensive for these geometric and
respiratory-induced movements by
expanding the margins around a tumor to
minimize the risk of missing the disease,
the so-called “geographic miss.” In
contrast, the objective is to avoid
unnecessary irradiation to normal tissues.
Conventional radiation treatment planning has historically compensated for these geometric and respiratory-induced movements by
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surrounding tissues. This depends heavily on accurate delineation of the target volume. The International Commission on Radiation Units and Measurement has provided guidelines on the definition of target volumes used for treatment planning. These volumes include the gross tumor volume (GTV), the clinical target volume (CTV), which accounts for clinical microscopic extension of disease, and a planning target volume (PTV), which accounts for setup uncertainties, tumor motion, and dosimetric buildup of radiation.

In fact, the greatest uncertainty in thoracic radiotherapy is respiration-induced motion of the target. It is within the PTV that tumor motion—and organ motion, for that matter—influence the relationship between the target and surrounding normal tissues. The International Commission on Radiation Units and Measurement has provided guidelines on the definition of target volumes used for treatment planning. These volumes include the gross tumor volume (GTV), the clinical target volume (CTV), which accounts for clinical microscopic extension of disease, and a planning target volume (PTV), which accounts for setup uncertainties, tumor motion, and dosimetric buildup of radiation.

In the past, when motion was not considered explicitly by planning systems, normal tissues outside the target volume were subject to unintended but necessary irradiation, which resulted in undesirable acute and late effects. This is why modern radiation planning systems incorporate information on the respiratory motion of tumors.

Target volumes used for treatment planning free category 1 CME credit • Test code #713/4D CT-BASED RADIATION TREATMENT PLANNING CONSULTATIONS IN COMPUTED TOMOGRAPHY

Additionally, a marker system is necessary to temporally link the individual axial images of the 4D CT to a specific phase of the respiratory cycle. Various commercially available marker systems include implanted fiducial markers with radiographic visibility or external markers with optical CCD detection, such as the Real-Time Position Management radiation delivery system (RPM), from Varian Medical Systems of Palo Alto, CA (Figure 2). Unlike implanted fiducial markers, such external markers are designed to approach motion tracking noninvasively by correlating the movement of a marker block with internal organ motion linked to the respiratory cycle. These scans usually generate a large number of images (about 1500), which must be sorted. Consequently, a sufficiently fast imaging workstation is the third component necessary to efficiently process and sort for radiation treatment planning.

4D CT IN RADIATION TREATMENT PLANNING

Moving targets or organs can result in marked distortion in anatomic and functional imaging during data acquisition. Imaging modalities operated in a noncontiguous manner are likely to record a blurred image that is a summation of the object’s range of motion. More recently, gated CT scans have been developed to give a true representation of the tumor volume and its configuration, which accounts for setup uncertainties, tumor motion, and dosimetric buildup of radiation. Accordingly, several strategies have been developed in an attempt to control tumor motion by linking it to the clinical microscopic extension of disease. These strategies include the use of breathing control, abdominal compression, and sorting for radiation treatment planning.

MANAGING MOTION DURING TREATMENT

Several strategies have been developed in an attempt to control tumor motion by linking it to the clinical microscopic extension of disease. These strategies include the use of breathing control, abdominal compression, and sorting for radiation treatment planning.

Managing motion during treatment has historically been grouped into two main categories: breath-hold and continuous monitoring. Breath-hold techniques are based on the premise that tumor motion can be effectively stopped or slowed during treatment to allow for a single, unblemished, unblurred image of the target. As an example, respiratory gating is a technique that uses a gating system to capture a single image of the target volume. These techniques have been widely used in clinical practice, particularly for patients with tumors that are highly sensitive to radiation, such as lung cancer.

However, continuous monitoring techniques have also been developed to address the limitations of breath-hold techniques. These techniques rely on real-time monitoring of the patient’s respiratory motion to adjust the timing of radiation delivery. This can be accomplished using various techniques, such as implanted fiducial markers, respiratory waveform monitoring, or other methods. The advantage of continuous monitoring techniques is that they can capture the dynamic nature of tumor motion, which is crucial for ensuring accurate treatment delivery.

In conclusion, managing motion during radiation treatment is crucial for achieving optimal treatment outcomes. The combination of techniques, such as breath-hold and continuous monitoring, can help ensure that patients receive the most effective and personalized treatment possible.
abdomen. For abdominal tumors, the motion of the liver, spleen, and kidneys is predominantly in the superior-inferior direction with a average range of motion of approxi- mately 1.3 mm. Direct knowledge of these tumors has made it possible to deliver a novel program using whole abdominal IMRT (WAMRT). Both the dosimetric and clinical outcomes support this approach by improving local control and toxicities compared with conventional 2D and 3D approaches.

In early-stage non-small cell lung cancer with IMRT, which is made possible only by 4D CT’s ability to assess motion, we have found that the incidence of grade 3 esophagitis to be rare. Similarly, cases of grade 1 or 2 esophagitis were mostly resolved within two months of completing treatment. There were no patients with clinically evident radiation pneumonitis. There are clearly some limitations in the use of 4D CT in its current form. Regardless of acquisition mode, errors sometimes happen and manifest as the “mushroom” effect, where scalloping of the chest wall or diaphragm is seen. These occur when images are incorrectly matched to their respiratory phase and have to be manually removed from the data set. Additionally, there are errors in the imaging data set at the extremes of inspiration, expiration, and inspiration-expiration. As the technology advances, it is likely that these shortcomings will be resolved.

4D CT is capable of capturing a major advance in radiation therapy planning and is a powerful and precise tool for identifying and studying respiration-induced tumor and organ motion. This approach to treatment planning further individualizes patient assessment, identifying patient-specific tumor margins. As the tumor and organ kinetics are likely to be unique to each patient, the advanced treatment plans that can be generated with this modality will be inherently individualized for each patient. Seeing is truly believing.

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