Abstract—Volumetric imaging and planning for 3-dimensional (3D) conformal radiotherapy and intensity-modulated radiotherapy (IMRT) have highlighted the need to the oncology community to better understand the geometric uncertainties inherent in the radiotherapy delivery process, including setup error (interfraction) as well as organ motion during treatment (intrafraction). This has ushered in the development of emerging technologies and clinical processes, collectively referred to as image-guided radiotherapy (IGRT). The goal of IGRT is to provide the tools needed to manage both inter- and intrafraction motion to improve the accuracy of treatment delivery. Like IMRT, IGRT is a process involving all steps in the radiotherapy treatment process, including patient immobilization, computed tomography (CT) simulation, treatment planning, plan verification, patient setup verification and correction, delivery, and quality assurance. The technology and capability of the Dynamic Targeting™ IGRT system developed by Varian Medical Systems is presented. The core of this system is a Clinac® or Trilogy™ accelerator equipped with a gantry-mounted imaging system known as the On-Board Imager™ (OBI). This includes a kilovoltage (kV) x-ray source, an amorphous silicon kV digital image detector, and 2 robotic arms that independently position the kV source and imager orthogonal to the treatment beam. A similar robotic arm positions the PortalVision™ megavoltage (MV) portal digital image detector, allowing both to be used in concert. The system is designed to support a variety of imaging modalities. The following applications and how they fit in the overall clinical process are described: kV and MV planar radiographic imaging for patient repositioning, kV volumetric cone beam CT imaging for patient repositioning, and kV planar fluoroscopic imaging for gating verification. Achieving image-guided motion management throughout the radiation oncology process requires not just a single product, but a suite of integrated products to manipulate all patient data, including images, efficiently and effectively. © 2006 American Association of Medical Dosimetrists.

Key Words: IGRT, Image-guided radiotherapy, CBCT, Cone beam CT, IMRT, Intensity modulated radiotherapy, OBI, On-Board Imager.

INTRODUCTION

Radiotherapy is one of the most effective treatment modalities for the majority of cancers and, with surgery, remains the most cost-effective way of curing many cancers.¹ Technical, academic, and clinical advances in radiotherapy have improved patient management and outcomes significantly. The development of more sophisticated approaches to radiotherapy treatment has been made possible by improvements in imaging techniques such as magnetic resonance (MR), computed tomography (CT), by 3-dimensional conformal and “inverse” treatment planning, better patient positioning, and more sophisticated linear accelerator technology. Radiation fields can now be shaped by means of computerized collimator systems and intensity-modulated radiotherapy (IMRT), including the use of multileaf collimators with up to 120 leaves for high-resolution IMRT. Considerable research has also been performed in defining the most appropriate fractionation schedules² with developments such as continuous hyperfractionated accelerated radiotherapy (CHART).³³

A review by Read⁴ describes clinical trials that demonstrate the benefits of conformal techniques. These have mostly been done in prostate cancer; however, the technology has similar benefits in other cancers, including head and neck. The rationale is that by conforming the target volume more accurately to the shape of the tumor, the consequent reduction in the volume irradiated will allow escalation of the radiation dose and hence an improvement in local control. Furthermore, diminishing the irradiation of adjacent normal tissues will reduce morbidity and toxicity. Conformal radiotherapy offers the greatest advantage at sites where existing local control is limited by the collateral dose to normal structures. The introduction of IMRT has further improved out-
comes by increasing organ sparing, providing better local control of disease, enhancing quality of life, and reducing treatment associated morbidity.\textsuperscript{5,6}

A fundamental tenet of radiotherapy is that successful outcomes require accurate alignment of the treatment field to the target volume.\textsuperscript{7–9} Reducing the field margin without compromising radiation dose to the clinical target volume (CTV) is particularly important in the proximity of organs at risk. However, tumors can move throughout a treatment regimen. Tumors are subject to interfraction motion; changes in position from day-to-day. Factors leading to setup uncertainties include the therapist’s skill in setting up the patient, variable filling of digestive or urinary organs, weight gain or loss, or even the patient’s cognitive state. In addition, tumors experience intrafraction motion; changes in position during a treatment session. The main contributors are normal respiratory, cardiac, and peristaltic organ motion, along with the patient’s voluntary movement. If the daily setup error including intrafraction motion is greater than the treatment-planning margin, the prescription dose to the target may not be achieved, or the tolerance dose to the normal tissues may be exceeded (Fig. 1).\textsuperscript{10–13}

\textbf{IMAGE-GUIDED MOTION MANAGEMENT IN THE RADIOTHERAPY PROCESS}

Varian Medical Systems (Palo Alto, CA) has introduced Dynamic Targeting IGRT\textsuperscript{TM}, a suite of tools for image-guided radiotherapy to provide means for effectively handling inter- and intrafraction motion. The dynamic targeting approach provides a suite of tools that work together to achieve better target localization across the clinical radiotherapy process. Dynamic targeting focuses on localizing and managing motion based on internal anatomy, not just on the conventional external marks or tattoos.

The steps of a typical clinical radiotherapy process include: imaging for staging, immobilization, imaging for planning, treatment planning, post-planning verification, treatment delivery, imaging for treatment verification, image and information management, and quality assurance. Effective strategies for image-guided motion management affect all of these stages. The suite of dynamic targeting tools—including the Exact\textsuperscript{TM}Couch with Indexed Immobilization\textsuperscript{TM}, the RPM\textsuperscript{TM} Respiratory Gating System, the Acuity\textsuperscript{TM} simulation system, the PortalVision\textsuperscript{TM} electronic portal imaging system, the SonArray\textsuperscript{TM} ultrasound imaging system, and the On-Board Imager\textsuperscript{TM}—are designed to incorporate motion management into the clinical process.

\textbf{OPTIMAL IMMOBILIZATION: PHYSICAL AND ELECTRONIC METHODS}

For accurate imaging and successful management of inter- and intrafraction motion, patients need to be consistently positioned. Variation in patient position can be minimized with the help of accurate patient positioning systems and rigid immobilization devices. Patients can be immobilized on a treatment couch, such as the Exact\textsuperscript{TM}Couch with Indexed Immobilization\textsuperscript{TM}, in the same position during all imaging, simulation, and treatment sessions (Fig. 2). Otherwise, systematic errors can be introduced, resulting in larger margins.\textsuperscript{14}

Management of tumor motion due to respiration has been achieved with both physical and electronic meth-

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\textbf{Fig. 1.} This sequence of MRI images shows the extent to which a reference point on the lung moves over a 2-second period due to respiratory motion (intrafraction motion).

\textbf{Fig. 2.} Exact\textsuperscript{TM}Couch with Indexed Immobilization\textsuperscript{TM}. 
ods. These include: voluntary breath hold,\textsuperscript{15} deep inspiration breath hold (DIBH),\textsuperscript{16,17} Active Breath Control (ABC),\textsuperscript{18} and physical restraint.\textsuperscript{19} These methods offer the advantage of being relatively simple to implement. However, they suffer from the disadvantage of limited patient compliance because they require momentary cessation or constraint of breathing by patients who typically already have limited respiratory capacity.

An alternative technique is called “gating,” an electronic method of limiting the effect of normal, intrafraction motion.\textsuperscript{20} Gating enables a radiation beam to selectively treat a moving target by electronically turning the beam on and off at specified intervals—effectively “freezing” the tumor in position, much like a strobe light can appear to freeze a moving object.\textsuperscript{21–24} For example, the RPM\textsuperscript{TM} Respiratory Gating System uses an infrared camera to track a passive marker block placed on the patient’s chest or abdomen. The system then processes the tracked motion to characterize the patient’s normal breathing pattern in the form of a respiratory waveform.

The data is typically gathered during CT simulation so that the respiratory motion can be synchronized with the CT image acquisition. The resulting CT images can then be used to create a treatment plan that delivers doses at the desired point in the respiratory cycle. During treatment, the system automatically gates the radiation beam on only when the tumor falls within the planned treatment field. Abnormal motion that deviates from the regular respiratory cycle is automatically filtered out. Throughout the simulation and treatment processes, the patient can breathe naturally and remain comfortable (Fig. 3).

**IMAGING AND TREATMENT PLANNING: THE ADVANTAGES OF GATED 4D CT**

Tumors and organs can move up to 3 cm with respiration; therefore, CT data for planning must target the tumor position where it would be during treatment. Traditional CT images show respiratory motion as artifacts. Consequently, target volumes based on these images may be distorted and larger than necessary. To
account for and to visualize tumor motion, information is needed from a fourth dimension—time. The capabilities of 3D CT are extended through 4-dimensional (4D) CT technology, which allows clinicians to view volumetric CT images changing over time. The acquisition of 4D-CT data can be synchronized with a respiratory phase signal, such as that provided by the RPM™ Respiratory Gating System. The system sorts, or bins, the images based on the point in the respiratory cycle at which they were acquired. Using the binned images, the system can reconstruct volumetric CT images that minimize the motion artifacts appearing in the traditional CT images (Fig. 4).25,26

There are 2 different approaches to 4D-CT image acquisition: prospective and retrospective. During a prospective 4D-CT simulation, the CT scanner collects images only at one phase, or portion, of a patient’s normal respiratory cycle. Instead of scanning continuously, the system takes a series of snapshots at the proper phase, moves the couch to the next position, takes more snapshots, and so on. Basically, prospective 4D-CT results in one volumetric CT image collected at a specific phase of the respiratory cycle.

In contrast, retrospective 4D-CT produces multiple volumetric CT images, each representing one phase of the respiratory cycle. The system collects images continually during all phases, while the couch remains stationary. Each acquired image has a phase stamp so that after collecting the images, the system can bin them based on the phase of the respiratory cycle and the position of the imaging couch in which they were collected. Each phase can then be separately reconstructed. Meanwhile, the couch moves to the next position and more images are collected continuously. This process is repeated until the entire volume of interest is scanned and reconstructed (Fig. 5).

In the steps of the clinical radiotherapy process that lead up to treatment planning, imaging is performed with the intent of clearly visualizing the target volume. The payoff of using image-guided motion management comes in the treatment planning stage, because target volumes and critical structures can be contoured with individual margins that account for the actual motion rather than population-based margins. Some of the individual margins may be smaller than the population-based margins, while some may actually be larger. The key point is that they represent target motion of the individual patient.

POST-PLANNING VERIFICATION: INTEGRATED SIMULATION AND VERIFICATION

Before treatment, clinicians can use the Acuity™ system to help ensure that treatment plans will achieve the intended results. Acuity™ integrates verification software tools for dynamically tracking tumor motion during the verification process. It produces high-resolution, radiographic and fluoroscopic digital images of patients in their treatment positions. Clinicians can then evaluate the treatment plan by observing the patient’s position and respiratory motion with the overlaid fields and determining whether that motion will remain within the treatment field margins. Any necessary adjustments to the plan can be made and re-verified quickly.27,28

REVIEW OF IMAGING IN THE TREATMENT ROOM

The latest advances in imaging technology can help clinicians obtain more information about the target volume position and correct for changes in its position at the time of treatment. Using image-guided motion management during 3DCRT and IMRT, clinicians can more accurately control the dose delivered to the tumor while reducing exposure to the surrounding healthy tissue.

Early studies based on port films indicated the benefits of portal verification.29,30 Numerous subsequent studies have characterized the magnitude and nature of setup errors for a variety of clinical conditions. Weekly port films are the routine clinical standard for ensuring accurate targeting of external beam radiotherapy.31 Random and systematic errors of up to 6 mm (σ) have been reported in such studies.32 The modern era of electronic
portal imaging devices (EPIDs) began in the early 1980s with the demonstration of a fluoroscopic system to acquire megavoltage transmission images. The introduction of the scanning liquid ionization chamber system in 1990 was quickly followed by the introduction of camera-based fluoroscopic EPIDs from other manufacturers. The importance of geometric accuracy has driven the development of digital imagers that can monitor treatment accuracy more effectively than weekly port filming with minimal increase in workload. An EPID can acquire images automatically with near real-time display, store them digitally, and provide quantitative analysis tools. Studies have shown that increased portal imaging frequency can reveal daily variations in patient alignment that are not observed with weekly filming. Furthermore, an EPID can provide immediate patient alignment information, without the delay involved in processing a film. Instant-image availability enables the development of on-line correction protocols and daily targeting adjustments. In addition to aiding acquisition, the digital nature of EPIDs can be exploited to enhance the portal review process. Studies have examined the process of subjective portal image evaluation by clinicians and have found a wide variation among reviewers in reporting setup deviations in portal images. Many EPID systems offer computer-assisted image review with anatomy-matching routines and quantitative alignment analysis.

Investigations of internal organ motion have demonstrated that, for many sites, substantial reductions in geometric uncertainty require the visualization of internal structures in the reference frame of the treatment machine. The development of volumetric imaging systems for online image guidance has been a major focus of research in the past 5 years. Many investigators have examined the use of the treatment beam to perform megavoltage computed tomography (MV-CT) of the patient in the treatment position. This was first demonstrated in 1983 by Swindell et al. and was extended to cone-beam implementations by Brahme et al. proposed the development of MV CT based on the 50-MV scanning photon beam of the racetrack micro-

Fig. 5. (a) Beam’s-eye views of non-gated (left) and gated (right) treatment volumes and (b) corresponding dose-volume histograms in the Eclipse™ treatment planning system. Images courtesy AZ Sint Augustinus, Wilrijk, Belgium.
tron\textsuperscript{50}; this approach offers elevated contrast due to the increased pair-production cross-section. Many investigators have been evaluating MV CT for radiotherapy verification.\textsuperscript{51–53} Although utilization of the MV source for imaging seems to offer an elegant solution in terms of imaging and delivery with the same source, it faces the enormous challenge posed by the low inherent soft tissue contrast and poor detection efficiency of x-ray detectors in the MV energy range.\textsuperscript{54} The low efficiency results in poor signal-to-noise performance for clinically acceptable doses. Furthermore, the increased radiation transport in the x-ray detector reduces the spatial resolution that can be expected at these energies.

Introducing kilovoltage-imaging technologies into the therapy setting is another alternative. The clear value of integrated imaging and delivery compelled Uematsu \textit{et al.} to install a conventional CT scanner and a conventional simulation unit in the radiotherapy suite.\textsuperscript{55} This approach offers volumetric CT, real-time fluoroscopy and radiographic imaging in the treatment room. Reference between the 3 is maintained through a single, pivoting table that can dock to each system. This approach has been employed in a variety of anatomic sites, demonstrating the many advantages of integrated imaging and delivery.

**THE PORTALVISION\textsuperscript{TM} MEGAVOLTAGE IMAGING SYSTEM**

The PortalVision\textsuperscript{TM} electronic portal imaging system creates high-resolution, 2D electronic images using the megavoltage treatment beam, and compares them to the digitally-reconstructed radiographs (DRRs) from the treatment planning system or the digital images from the Acuity simulator. This comparison is done for 2 purposes: verification of the patient setup and verification of individual field placements. Electronic portal imaging systems are in routine clinical use at many institutions and are increasingly being used to measure setup errors.\textsuperscript{56} The introduction of amorphous silicon flat-panel imagers has been demonstrated to produce better portal images using less dose.\textsuperscript{57} The improvement in image quality has also enabled the practical use of implanted radiopaque markers for on-line corrective positioning.\textsuperscript{58}

Also, the dosimetric capabilities of PortalVision\textsuperscript{TM} allow clinicians to convert the electronic image into a dose distribution and then compare the acquired portal dose to the predicted portal dose from the planning system. Quantitative comparisons can be performed for machine quality assurance (QA), for verifying monitor unit calculations\textsuperscript{59} or for pretreatment verification of IMRT fluence distributions (Fig. 6).\textsuperscript{60}

**THE SONARRAY\textsuperscript{TM} OPTICALLY-GUIDED ULTRASOUND**

The SonArray\textsuperscript{TM} system produces 3D ultrasound data sets through optical tracking of freehand-acquired 2D ultrasound data. The therapist holds the ultrasound probe and manipulates it over the anatomic region of interest, commonly the prostate. The position and angulation of the ultrasound probe is determined by an array of infrared light-emitting diodes (IRLEDs) attached to the probe. An optical camera system, usually attached to the treatment room ceiling or wall, is used to determine the positions of the IRLEDs in 3D space. The position of the ultrasound probe is determined by the IRLEDs, and an ultrasound volume can be reconstructed by coupling the position information with the raw 2D ultrasound data.\textsuperscript{51–63}

In addition to building the 3D ultrasound image volume, optical guidance is used to determine the absolute position of the ultrasound volume in the treatment room. Because the position of the 3D ultrasound volume is fixed relative to the ultrasound probe, knowledge of the probe position in the treatment room is sufficient to determine the position of the 3D ultrasound image volume relative to the linac isocenter.

On the day of the treatment, a 3D ultrasound volume is acquired while the patient is in the treatment position. Treatment planning contours viewed on the axial, sagittal, and coronal 3D ultrasound images are compared side by side to the planning CT, in relation to the isocenter. The contours determined from the CT scans are then manipulated until they align with the anatomic structures on the ultrasound images, the necessary couch corrections are calculated, and the couch is repositioned prior to treatment.

**THE ON-BOARD IMAGER\textsuperscript{TM} KILOVOLTAGE IMAGING SYSTEM**

The On-Board Imager\textsuperscript{TM} (OBI) is designed to improve the accuracy and effectiveness of cancer treatments by providing tools to target and track tumors more accurately. The OBI enables clinicians to obtain high-
By rotating the gantry 90°, 2 coherent kV images can be used of the patient position used in treatment planning. Rapid manual or automated image matching to reference tissue detail. Software tools are incorporated that allow landmarks with a high degree of spatial accuracy and soft tissue yield digital images showing internal anatomic structures. They be used in concert with one another. Thus the 2 imagers are in a "bi-plane" geometry and can be used in quick succession without rotating the gantry. The robotic arms also allow the imager to be retracted out of the way when necessary, and to complete treatment delivery, all within the standard daily treatment appointment.

Varian’s approach is to integrate a kV x-ray source and large-area flat-panel digital detector on either the Clinac® or Trilogy™ medical linear accelerators for radiography, volumetric cone-beam CT, or fluoroscopy. In this highly integrated form, the control system orchestrates the interplay of the imaging and delivery components in a single machine. Such an approach offers the flexibility to employ a treatment-procedure-specific imaging strategy, whether real-time fluoroscopy, radiography, cone-beam CT, or an appropriate combination of all 3. Integration allows image-guided procedures to be performed within the tight time constraints found in the radiotherapy setting (Fig. 7).

The OBI is mounted on the treatment machine gantry via 2 robotically-controlled arms; each operate along 3 axes of motion, so that they can be positioned optimally for the best possible imaging of the target volume or the motion of other internal structures some distance away. The robotic arms also allow the imager to be quickly and automatically retracted out of the way when not in use. The kV imaging system operates in a plane orthogonal to the megavoltage treatment beam and its associated amorphous silicon PortalVision™ imager. Thus the 2 imagers are in a “bi-plane” geometry and can be used in concert with one another.

The amorphous silicon flat-panel x-ray image detectors yield digital images showing internal anatomic landmarks with a high degree of spatial accuracy and soft tissue detail. Software tools are incorporated that allow rapid manual or automated image matching to reference images of the patient position used in treatment planning. By rotating the gantry 90°, 2 coherent kV images can be quickly acquired. Alternatively, the image pair can consist of a kV image and orthogonal MV image acquired in rapid succession without rotating the gantry. The imaging software then registers that image pair against a corresponding reference image pair. The reference images can be radiographs acquired on a simulator or they can be DRR images computed from the volumetric CT data set used in treatment planning. The image registration software takes advantage of common or coherent information in each image pair to search for the position and angular correction needed to minimize the difference in mutual information contained within the reference image set and the daily image set. This in-plane mutual information matching can be restricted to a user specified region of interest if desired. The result from this 2D + 2D anatomical matching is a computed offset with 5 degrees-of-freedom (5DOF). The needed x, y, and z translations plus the in-plane rotations (pitch and yaw) are automatically computed. The matched image sets are then overlaid with suitable tools for visual verification and confirmation. Once the match is accepted, the corrected position offsets are automatically downloaded so that the treatment couch can be repositioned remotely from outside the treatment vault (Fig. 8).

In addition to anatomic matching, the MarkerMatch™ automated software tools are provided for matching the position of implanted radiopaque fiducial markers using similar kV image pairs. The planning volumetric CT data set is acquired after implanting suitable fiducial markers. The MarkerMatch™ software is used to quickly search the 3D treatment planning CT data to locate the marker positions corresponding to the PTV. Each treatment day, a pair of kV radiographic images is acquired as described above. The MarkerMatch™ software automatically locates the markers in each of those 2 images and registers those locations against the corresponding 3D coordinates of the same markers in the treatment planning CT data set. From this volumetric match, a full 6 degrees-of-freedom (6DOF) correction vector is computed. Again, after review and verification of the match, the couch position can be automatically repositioned from outside the room. In this way, soft tissue structures or target volumes such as the prostate can be quickly targeted using low-dose radiographic imaging on a daily basis.

Possibly the most powerful imaging modality this system incorporates is cone beam CT (CBCT). In this mode, an entire volumetric CT data set is reconstructed with a single gantry rotation, while the patient and treatment couch remain stationary. The system takes full advantage of the Varian PaxScan 4030CB amorphous silicon flat panel digital imager that utilizes unique technology to provide the high dynamic range, sensitivity, and frame rates needed for these applications, and a unique Varian 150 kVp x-ray tube designed specifically for this application.
The overall CBCT process is very similar to the radiographic repositioning technique, except 3D CBCT images, rather than a pair of radiographs, are acquired. The CBCT operating mode is preferred when direct visualization of 3D soft-tissue detail is important for patient repositioning prior to treatment, e.g., prostate. CBCT imaging can also be used when small targets are being treated without fiducial markers (image-guided radiosurgery), when a small number of treatment fractions are being used (hypofractionation), or when adaptive planning is desired. Image acquisition, image registration, image match verification, and automatic remote repositioning of the treatment couch are all done in the OBI system to optimize efficiency. After the treatment, the CBCT images can be imported into the Eclipse™ treatment planning system for fusion with the planning CT. Dose distributions for each day’s treatment can then be calculated, allowing changes in the clinical target volume to be monitored during the treatment course. In an example of the process known as dynamic adaptive radiotherapy (DART)™, the plan can be re-optimized for future fractions to account for changes (Fig. 9).

Operating in the fluoroscopic mode, the OBI system can display real-time anatomic motion and thus provide a clear indication of how a tumor will move during treatment due to respiration or other normal physiological processes. This modality can be used in concert with the real-time position management (RPM)™ respiratory gating system to confirm the intended beam gating periods and the resulting margins immediately prior to each treatment. This may be a useful tool as part of an extracranial radiosurgery or radio-ablation program. Real-time tracking algorithms have been demonstrated that are anticipated to be useful in directly providing respiratory gating or tracking information from internal anatomic motion (Fig. 10).

A LOOK AHEAD

So far, the imaging techniques discussed have focused on assuring the patient is in the proper position prior to treatment, so individual treatment margins can be used, rather than population-based margins. However, the use of functional imaging can influence the way in which clinicians define the target volume itself. Clinical researchers at the Memorial Sloan-Kettering Cancer Center have developed the concept of a biological, or functional, target volume that is derived from biological images and used to guide customized dose delivery to various parts of the treatment volume.64 Functional imaging techniques, such as magnetic resonance spectroscopy (MRS), positron emission tomography (PET), and single photon emission computed tomography (SPECT), provide metabolic, or other functional data indicating the location, size, and aggressiveness of disease. These techniques may help clinicians...
Fig. 9. Each of the CBCT images shown here were acquired in 1 minute and use nominally 660 projections to maximize image quality. Reconstruction field-of-views (FOVs) are nominally 25 cm (head) and 45 cm (body) in diameter. (a) Cone-beam CT images of a patient being treated for prostate cancer. Note the excellent contrast of the prostate in the axial slice. Slice thickness was 1.5 mm. Images courtesy of Henry Ford Hospital, Detroit, MI. (b) Cone-beam CT of a patient with head-and-neck cancer using 1-mm slices. Note the excellent delineation of the cervical spine and the good soft tissue contrast. Swelling on the right side of the axial scan is visible where the lesion is located. Images courtesy of Duke University Medical Center, Durham, NC. (c) Cone-beam CT images of a patient with nasopharyngeal carcinoma. The images were acquired on the first (f) and tenth (g) days of treatment. The change in the target volume is clear, e.g., examine how the fit of the immobilization mask changes between the first and second images. Images courtesy of Stanford University, Palo Alto, CA.
observe functional changes so that they can create targeted treatment plans that deliver escalated doses to the most metabolically active parts of a tumor.

For example, Fig. 11 shows a PET and CT image of a head-and-neck cancer case. Based on the combined functional PET image and the anatomical CT image, clinicians may localize cancerous regions even before they are physically evident. Then, by using motion management techniques, they can treat the small lesions with a higher dose. Likewise, clinicians may use SPECT or MRI to identify functional lesions of interest, and then differentially dose the lesions with IMRT based on that functional information.

Motion artifacts in PET images caused by respiration are an important factor in degrading PET image quality and quantification. Motion artifacts lead to 2 major effects: first, they affect the accuracy of quantification, producing a reduction of the measured standard uptake value (SUV). Second, the apparent lesion volume is overestimated. Both impact upon the usage of PET images for radiotherapy treatment planning. The first affects the visibility, or contrast, of the lesion. The second results in an increase in the planning target volume, and consequently a greater radiation dose to the normal tissues. One way to compensate for this effect is by acquiring the PET data in synchronization with the respiratory motion.

The combination of IMRT and IGRT has the potential to achieve both unparalleled tumor control and normal tissue sparing. The desire to confidently administer highly conformal radiotherapy to complex 3D volumes, has lead to DART™, the natural convergence of IMRT, IGRT, and dose guidance. DART™ can occur daily (online), during treatment (real time), or it can occur between fractions (offline), depending on the nature and timing of new patient information. Offline adaptation takes place between treatment fractions based on new information that can be used to

Figure 10. OBI screen capture showing the pretreatment fluoro mode being used to verify a lung field prior to treatment. The treatment aperture is green, indicating that the RPM™-gating system would automatically gate the treatment beam on at this phase of the respiration cycle.
adapt treatments for gradual changes in patient anatomy, physiology, or adjuvant therapy. Real-time adaptation involves the RPM™ respiratory gating system to gate the beam during treatment to account for internal organ motion. Treatment machine parameters are adapted in real time to conform to the patient anatomy in real time. Online adaptation is updating the treatment parameters based on new daily information to account for variations in patient anatomy or physiology for which repositioning the patient alone cannot correct. Online adaptation ensures that the treatment objectives are continuously met despite these changes in the patient.

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