The classic method for developing the beam geometry for radiation therapy planning is to use a conventional “simulator”, i.e. an R/F system that is geometrically equivalent to the linear accelerator used for treatment. The planning data include therapeutic beam angles, shapes and isocenters. The fluoroscopic imaging of a conventional simulator provides the physician with views of the patient’s internal anatomy, including respiratory motion, but due to limitations in soft-tissue visualization the tumor itself is often not shown.

With the advent of CT simulation the use of conventional simulators has diminished significantly. CT simulation can create synthetic X-ray projections from CT image volumes, referred to as Digitally Reconstructed Radiographs or DRRs. These enable the radiation oncologist to simulate treatment with the added benefit of better soft-tissue visualization. The CT volumetric data also facilitates planning the 3D distribution of the radiation dose. Furthermore, the new CT scanning protocols described below combine the benefit of soft-tissue visualization with the ability to show motion.

The main objective of external beam radiation therapy, including the more advanced 3D conformal radiation therapy, is to apply a local radiation dose, prescribed by a radiation oncologist, to a solid tumor within the planned treatment volume. In addition, the dose to nearby organs and critical structures must be minimized in order to mitigate treatment-related complications. In terms of the Dose Volume Histograms (DVH), the objectives are to:

- maximize the proportion (i.e. volume percentage) of the target tumor that receives the prescribed radiation dose
- minimize the proportion of critical structures, such as the heart, spinal cord or bowel, that receive any dose.

Respiratory motion, i.e. excursion, is one factor that adversely affects the objectives outlined above. This is especially true when targeting solid tumors in the lung and abdomen located near the diaphragm. Using very wide margins to ensure that tumor always remains in the treatment beam will result in unnecessary dose to other structures.

Multidetector-row CT (MD-CT) scans acquired in a single breath-hold can provide high-quality images with few motion artifacts. However, the breath-hold times required by the linear accelerator (linac) therapy machine far exceeds the capability of most patients.

Respiratory excursions of 1-3 cm have been observed in lung cancer patients. There are also many cases where respiratory motion is minimal. For effective treatment, it is desirable to identify the extent and direction of tumor movement during breathing. This will enable the linear accelerator jaws, multileaf collimator or blocks to be set to allow for tumor motion. In cases where tumor motion is extensive, the radiation oncologist will have the necessary data to apply gated treatment.
Materials and methods:

The multislice CT system used in this study is the Philips Brilliance CT Big Bore Oncology configuration (Figure 1). In addition to its unique 85 cm bore, this system provides several advanced features, including respiratory gating studies, integrated absolute marking and functional CT exams. The true 60 cm field of view enables clinicians to measure body mass, and allows more precise targeting. A coverage of 24 mm (16 x 1.5) mm with every rotation allows the user to isolate the area of treatment with few motion artifacts.

Philips’ CT Localization (CT L.O.C.) application is available directly on the console, so that the user can localize the tumor and mark the patient for therapy delivery without leaving the system. Special enhancements were added to this software in order to produce some of the images in this article.

Instead of simply estimating the margins needed to allow for respiratory excursion, the extent of the motion can be visualized and measured by respiratory gating during the CT, followed by on-line postprocessing for 4D CT, resulting in a significantly improved dose plan. The radiation oncologist can reduce the planned treatment volume and improve the dose volume histograms for the tumor and nearby organs and tissues. Furthermore, each phase of the breathing cycle can be visualized and compared. Particular phases can then be selected for treatment and specific beams can be planned for them.

During radiation therapy, the linac can typically be programmed and the beam can be shaped with a multileaf collimator to target high-intensity beams to the tumor. Most commercially available linacs have gating systems that can trigger radiation doses at selected phases of the respiratory cycle.

Procedure/workflow

The workflow for generating a 4D CT data set is shown in Figure 2. A respiratory sensor is integrated with the CT scanner’s reconstruction systems and databases to provide a seamless workflow. In this example, the respiratory sensor is an air bellows belt (Figure 2a) but an optical tracking device may also be used (see below). Prior to the CT planning scan, the respiratory sensor is placed on the patient’s chest or abdomen. The patient breathes in a normal, shallow pattern while his/her respiratory signal is recorded in conjunction with the scan. A typical respiratory waveform is shown in Figure 2b.

A spiral scan is planned for the anatomical region containing the tumor. The scan is acquired at a sufficiently low table speed (low pitch) for any scanned voxel to remain within the detector collimation throughout a complete breathing cycle. For example, on the Brilliance Big Bore CT the detector width is 24 mm (16 x 1.5): if the breathing cycle is 4 seconds, the table speed should be no greater than 6 mm per second.

After the scan, the source data and the respiratory signal are used to retrospectively reconstruct the images. Sets of images across many breathing cycles are reconstructed and sorted to produce some eight to ten 3D image volumes, each covering the entire scan field, corresponding to phases of the respiratory cycle [1]. For example, 3D image volumes can be reconstructed at maximum inspiration and maximum expiration (shown as points in Figure 2b).

Multiphasic visualization can be performed online on the Brilliance Big Bore CT console, or with the Extended Brilliance workstation.

Respiratory sensing devices

There are two commonly used devices for sensing respiratory movements. One is the air bellows sensor used in this study and the other is based on an optical tracking device.

The air bellows (Figure 2a) is an elastic belt positioned around the abdomen that expands and contracts with respiratory motion. It contains a pressure transducer, which converts the pressure waveform to a voltage signal, which is then digitized and transmitted to the CT-Scanner system. The pressure waveform is displayed on the scanner console with the local maxima identified with red dots (Figure 2b).
Figure 3. MPR views with the tumor contoured (red) for maximum inspiration (top row). The images for maximum expiration (lower row) show the movement of the tumor relative to these contours and the arrow in the coronal view (lower left).

The optical method uses an infrared video camera and a cube with reflective markers, placed on the patient’s chest. The video camera tracks the movement of the markers, which is recorded with a frame grabber for analysis on a PC.

Commercial software available with the device tracks the markers in correlation with the respiratory motion.

A set of reformatted or reprojected views, such as sagittal (lateral) or coronal (AP) [2], can be generated for each phase and stored as frames in a cine loop. These movies can be used to visualize the motion of the tumor and nearby structures. Figure 4 shows a temporal sequence of views projected from a “beam’s eye view”. This type of cine mode is similar to a fluoroscopic image acquired on a conventional simulator but

4D visualization
Postprocessing methods for using multiphasic (4D) data sets during radiation therapy planning (RTP) correspond to those used with a single image volume (image stack review, reformatting, re-projection etc.) but with additional methods for visualizing tumor motion.

For multiphasic axial image review, the oncologist can search through phases at a particular z-location or through z-locations at a particular respiratory phase. Image volumes associated with each respiratory phase can be reformatted or re-projected using visualization methods such as those in Table 1.

Figure 3 shows coronal (left column) and sagittal (right column) views for maximum inspiration (top row) and expiration phases (lower row). The tumor has been segmented and the resulting contours can be viewed in any respiratory phase to quantify tumor motion and its effect on the treatment plan. To illustrate this, the top row in Figure 3 shows tumor contours for the maximum inhalation phase and the lower row shows the same contours mapped to the maximum expiration phase.

Figure 4. Temporal phases of the breathing cycle projected as digitally reconstructed radiographs from the “beam’s eye view” (isocenter shown with yellow coordinate axis).
Figure 5. A contour delineates the tumor’s full range of motion in a coronal (AP) Multiphasic Maximum Intensity Projection (mMIP) over all the respiratory phases. The contour is used to set the geometry of the radiation therapy plan.

with the added benefit of CT, in that the soft tissue is clearly visible.

In addition to a cine view, a single (composite) view can be generated which shows the tumor’s entire range of movement (Figure 5). This multiphasic maximum intensity projection (mMIP) can be used to plan the geometric aspects of the radiation therapy treatment. Image volumes from each phase of the respiratory cycle are spatially projected to create a multiphasic set of MPR images. This set is then temporally projected by selecting the maximum voxel over each phase, computationally similar to the traditional spatial MIP of an image volume. Lung tumors usually have enhanced conspicuity in mMIP since they are generally surrounded by very low-density lung tissue. Furthermore, as shown in Figure 5, the mMIP can be used to segment the tumor’s excursion for planning blocks, multileaf collimation and other aspects of the radiation therapy plan.

Conclusion

New visualization methods have been developed for radiation therapy planning with respiratory gated, multiphasic CT data sets. The system enables the visualization of respiratory movements, helps to identify patients with minimal tumor movement, and reduces the tumor margins needed to keep the tumor in the treatment beam. Furthermore, respiratory-gated images are less prone to respiratory motion artifacts.

Respiratory sensors and reconstruction methods integrated into the Philips Brilliance Big Bore CT system provide a seamless workflow. 4D CT can facilitate pinpoint positioning and targeting accuracy, with the potential for better patient outcomes.

References

