

Four-dimensional Cone Beam Computed Tomography-guided Radiotherapy for Lung Cancer Patients

a report by

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DOI: 10.17925/EOH.2006.0.1.27

External beam radiotherapy (RT) is the primary treatment modality for inoperable lung cancer patients. Substantial respiratory-induced geometrical uncertainties are associated with the radiotherapy treatment of lung cancer patient influencing the accuracy of imaging, treatment planning and treatment delivery. Generally, generous safety margins are applied around the target and optionally for organs at risk such that under- and over-treatment due to these geometrical uncertainties can be avoided with an acceptable probability (e.g. van Herk 2000). By reducing the inaccuracies, smaller margins can safely be applied, reducing exposure of nearby organs at risk and/or improving local control through dose escalation.

In order to reduce the uncertainties and artefacts induced by respiratory motion during computed tomography (CT) scanning, several groups have developed respiratory correlated acquisition techniques. By retrospectively sorting images obtained from an axial or helical CT scan using an external respiratory signal, a four-dimensional (4-D) CT dataset is obtained containing 3-D CT images at multiple phases of the respiratory cycle. 4-D CT reduces motion artefacts in CT images and provides respiratory motion information of tumours and organs at risk.

Image-guided RT

Any single 3-D or 4-D CT data set only represents the patient's anatomy at a specific moment in time. Using such a scan for treatment planning introduces substantial geometric uncertainties in the position of target and/or organs at risk between treatment planning and treatment delivery. To reduce these uncertainties, a variety of image-guided RT (IGRT) systems have been developed that allow verification and correction of the target position prior to each RT session.

The most common imaging modality used in radiotherapy to visualise soft tissue structures is CT. One approach to employ this technology for IGRT is to install a conventional CT scanner in the RT suite. A more recent development is a kilovoltage (kV) cone-beam CT (CBCT) scanner mounted on the

gantry of a linear accelerator, as shown in *Figure 1*. The advantages of this system compared with the spiral CT are compact design, the high isotropic resolution due to the fact that CBCT is not a slice-based imaging technology and the efficiency of obtaining patient images in the treatment position immediately before treatment without moving or touching the patient. These properties make CBCT very suitable for IGRT. The soft tissue contrast is inherently somewhat lower than fan beam CT at the same imaging dose but adequate for image-guided protocols. Currently, three CBCT-equipped linacs (Elekta Synergy 3.5, Elekta Oncology Systems Ltd, Crawley, West Sussex, UK) are installed in the Antoni van Leeuwenhoek Hospital, The Netherlands. Since 2004, the author and colleagues have conducted over 4,000 CBCT scans, imaging more than 400 patients for a variety of treatment sites for both bony anatomy and soft tissue-driven correction protocols.

Safety regulations limit the rotation speed of linear accelerators to one rotation per minute. Rotating around the patient multiple times as performed in axial and spiral fan beam CT scanners is therefore clinically not feasible. Linac-integrated CBCT scanners cope with this limitation by using 2-D detectors (amorphous silicon flat panel imagers) and a cone-shaped beam, acquiring a series of fluoroscopic 2-D images over a gantry sweep, which is then reconstructed into volumetric CBCT data. Consequently, however, the gantry rotation is slow compared with the breathing cycle in case of imaging of the thoracoabdominal region, such that data of acquired for multiple breathing cycles contribute to every voxel, giving rise to blurring of moving structures over their trajectory (see *Figure 2*). Slice selection procedures as employed by 4-D CT algorithms are therefore not suitable for such CBCT scanners, as there are no slices to select that correspond to a certain breathing phase. An alternative reconstruction algorithm was developed in order to make 4-D anatomical information accessible in the treatment room.

4-D CBCT Imaging

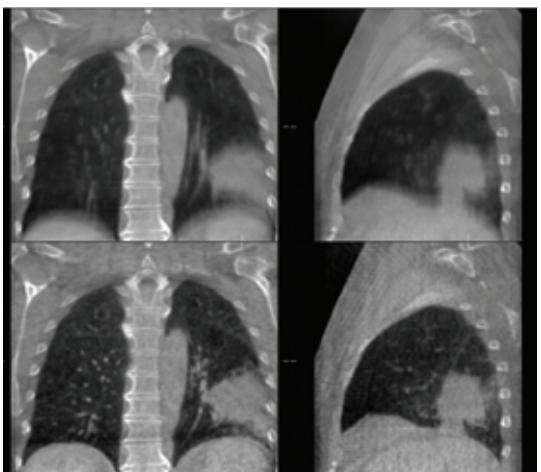
4-D CBCT scans can be obtained by retrospective

Figure 1: Cone Beam CT-guided Linear Accelerator (Elekta Synergy 3.5)



Orthogonal to the megavoltage (MV) treatment beam, a kV imaging system is mounted to the drum structure consisting of an X-ray source and an amorphous silicon flat panel detector.

Figure 2: Coronal (left column) and sagittal slices (right column), depicting a 3-D CBCT (upper row) and the exhale phase of a 4-D CBCT scan (lower row) reconstructed from a retrospectively sorted subset of the acquired fluoroscopic projection images (75 out of a total of 737).



Coronal (left column) and sagittal slices (right column), depicting a 3-D CBCT (upper row) and the exhale phase of a 4-D CBCT scan (lower row) reconstructed from a retrospectively sorted subset of the acquired fluoroscopic projection images (75 out of a total of 737).

sorting of the acquired projection images before reconstruction. That is, cone beam projections are snapshots recorded with very short X-ray pulses (e.g. 25ms), representing a certain respiratory phase, while different projections represent different respiratory phases. By sorting the breathing signal and the corresponding projections into several phase bins and subsequently feeding each subset of projections to the reconstruction algorithm, a 4-D CBCT dataset is generated. The number of projections used to

reconstruct each frame of the 4-D data set is inversely proportional to the width of each phase bin. As it is predominantly the number of breathing cycles imaged during the acquisition that determines the final image quality, the gantry rotation speed has to be adapted. In order to image 75 breathing cycles, with an average breathing cycle of 4s, a gantry rotation speed of about 0.11 revolutions per minute (one rotation per nine minutes) is required when using a half scanning protocol (rotating over an arc of 200°). The choice of respiratory correlated CBCT acquisition parameters involves a trade-off between imaging dose, scanning time, temporal resolution, spatial resolution and image quality. In the author's clinic the patient is scanned over four minutes, using an imaging dose of about 2cGy at the iso-centre.

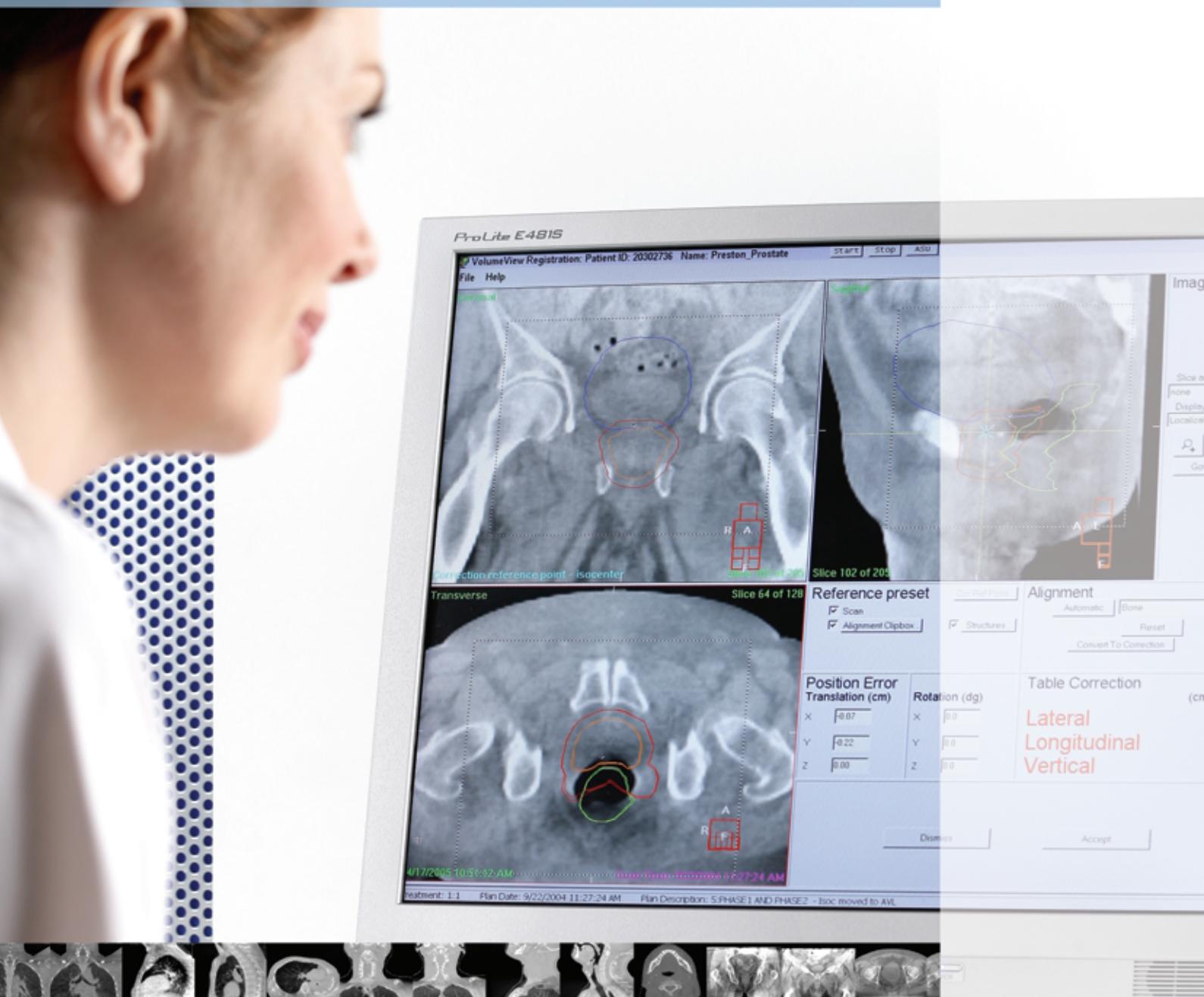
Figure 2 shows coronal and sagittal slices of a 3-D CBCT scan, as well as for the peak-exhale the 4-D CBCT scan of a lung cancer patient. The 4-D scans was reconstructed using about 75 projection images per breathing phase, on average corresponding to a 2.7° gantry angle increment per projection. Visual examination shows that the blurring of the moving objects is reduced considerably in the 4-D data such that the shape of the moving structures can be identified more easily and accurately. Furthermore, the 4-D data set provides information on the trajectory of these structures, absent in the 3-D data. Note, however, that 4-D CBCT imaging, similar to 4-D CT imaging, relies on a regular breathing pattern, while irregular breathing induces artefacts in 4-D reconstructions.

Breathing Signal Extraction

Any type of respiratory-correlated imaging needs a breathing signal to correlate the acquired data with the respiratory motion. Classically, a variety of external respiratory monitoring systems are used for this purpose, such as infrared reflecting makers, spirometry or stretching belts. A CBCT scanner acquires a series of 2-D projection data, showing the internal anatomy, including the position of moving structures, as a function of time. The breathing signal can be automatically obtained by tracking the position of the diaphragm from this series of projection data,⁹ eliminating the need for an additional respiratory monitor system. In short, this method enhances diaphragm-like features in the individual X-ray images, projects these features on the cranio-caudal axis, combines all successive 1-D projections to a 2-D image (see Figure 3) and extracts from this image the region with the most temporal variation. Finally, each 1-D signal is aligned to the next, resulting in a sequence of displacements which represents the respiratory signal. This method relies on the fact that frame-by-frame changes in the cranio-caudal direction

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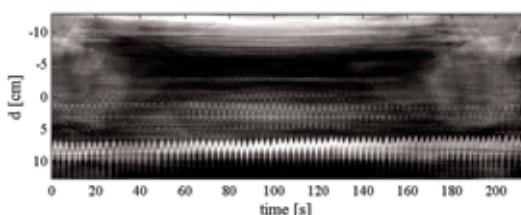
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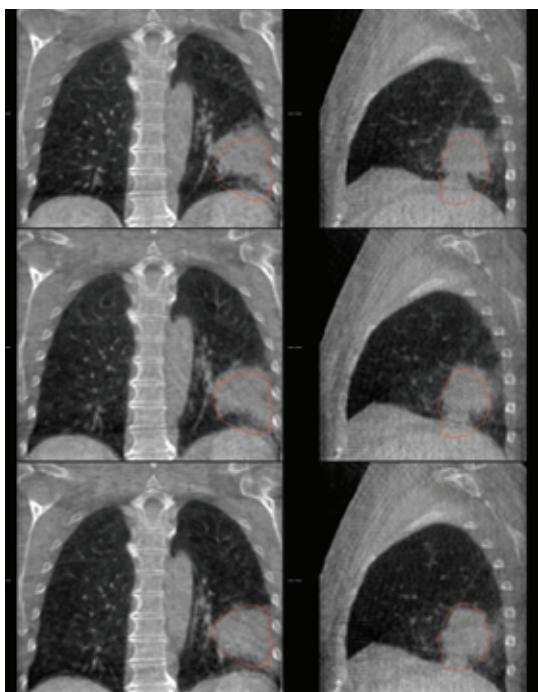
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Figure 3: The ‘Amsterdam Shroud’

Each column corresponds to a single projection image. The image clearly shows the rapid variation induced by the motion of the diaphragm and other structures compared to a slowly varying background due to the gantry rotation.

Figure 4: Coronal (left column) and sagittal slices (right column) depicting the peak-exhale (top row), mid-inhale (middle row) and peak-inhale phases (bottom row) of a 4-D CBCT scan. The red contour represents the GTV as delineated by the physician on the planning CT. Clearly, the planning target position does not represent the actual (average) target position in this case.



Coronal (left column) and sagittal slices (right column) depicting the peak-exhale (top row), mid-inhale (middle row) and peak-inhale phases (bottom row) of a 4-D cone-beam computed tomography (CBCT) scan. The red contour represents the GTV as delineated by the physician on the planning CT. Clearly, the planning target position does not represent the actual (average) target position in this case.

due to respiratory motion are considerably faster than changes due to gantry rotation.

Assessment of Geometrical Uncertainties

Given the ability to acquire a 4-D patient model just prior to treatment on the treatment machine, deviations of the target relative to the planning position can be easily assessed. *Figure 4* shows an example of a 4-D CBCT scan showing the peak-exhale, mid-inhale and peak-inhale phase. Clearly, the time-averaged mean position in the CBCT scan does not correspond

with position of the overlaid gross tumour volume (GTV) contour. The impact of uncertainties in the position of the mean position or baseline tend to dominate the uncertainties of the intra-fractional breathing motion. Therefore, the author and colleagues developed an infrastructure to measure and correct the baseline variations of the target over the course of treatment. In order to register the CBCT scan, the planning CT, the position of the isocentre and the delineated structures are imported as a reference through Digital Imaging and Communications in Medicine (DICOM)-RT. By registering a region of interest (expansion of the delineated GTV) defined in the planning CT with each phase of the 4-D-CBCT (about 30s execution time), the 3-D trajectory information of the target is obtained. Given the tumour position in each breathing phase, the peak-to-peak amplitude and mean tumour position are validated.

Corrections to accommodate for geometrical errors are currently limited to a single shift of the treatment couch, re-aligning the patient and/or the target relative to the treatment beam. Therefore, two correction protocols have been developed to correct for deviations of the mean tumour position relative to the planned position first an offline shrinking action level (SAL) correction protocol for conventional fractionation schemes limiting corrections of the target relative to the bony anatomy to the cranio-caudal direction; and second an online correction protocol for hypo-fractionated RT (3 x 20Gy) correcting the cranio-caudal and anterior-posterior deviations with an action level of 1mm.

Note that any correction to account for organ motion needs to be validated to check its impact on the dose constraints of the organs at risk.

Conclusions and Discussion

4-D CT permits generation of temporally varying (“4-D”) model of respiratory motion in patients from a single session of scanning. Even a 4-D CT scan, however, is just a snap shot movie loop of the patients respiratory cycle and needs to be validated over the course of treatment delivery. 4-D CBCT allows the validation of this model with the patient in the treatment position immediately before treatment. Correction strategies to account for discrepancies found between treatment and planning are currently limited to simple couch shifts. Future developments are focused on the development of more advanced correction strategies taking dosimetric consideration into account. ■

A version of this article containing references can be found in the Reference Section on the website supporting this briefing (www.touchoncologicaldisease.com).

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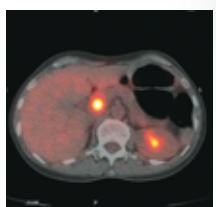
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