Medical Dosimetry ■■ (2017) ■■–■■

Medical Dosimetry

journal homepage: www.meddos.org

Variations of target volume definition and daily target volume localization in stereotactic body radiotherapy for early-stage non–small cell lung cancer patients under abdominal compression

Chunhui Han, Ph.D., Sagus Sampath, M.D., Timothy E. Schultheisss, Ph.D., and Jeffrey Y.C. Wong, M.D.

Department of Radiation Oncology, City of Hope National Medical Center, Duarte, CA 91010

A R T I C L E   I N F O

Article history:
Received 24 February 2016
Received in revised form 22 October 2016
Accepted 29 January 2017

Keywords:
Non–small cell lung cancer
Abdominal compression
Stereotactic body radiotherapy

A B S T R A C T

We aimed to compare gross tumor volumes (GTV) in 3-dimensional computed tomography (3DCT) simulation and daily cone beam CT (CBCT) with the internal target volume (ITV) in 4-dimensional CT (4DCT) simulation in stereotactic body radiotherapy (SBRT) treatment of patients with early-stage non–small cell lung cancer (NSCLC) under abdominal compression. We retrospectively selected 10 patients with NSCLC who received image-guided SBRT treatments under abdominal compression with daily CBCT imaging. GTVs were contoured as visible gross tumor on the planning 3DCT and daily CBCT, and ITVs were contoured using maximum intensity projection (MIP) images of the planning 4DCT. Daily CBCTs were registered with 3DCT and MIP images by matching of bony landmarks in the thoracic region to evaluate interfractional GTV position variations. Relative to MIP-based ITVs, the average 3DCT-based GTV volume was 66.3 ± 17.1% (range: 37.5% to 92.0%) ($p < 0.01$ in paired t-test), and the average CBCT-based GTV volume was 90.0 ± 6.7% (daily range: 75.7% to 107.1%) ($p = 0.02$). Based on bony anatomy matching, the center-of-mass coordinates for CBCT-based GTVs had maximum absolute shift of 2.4 mm (left-right), 7.0 mm (anterior-posterior [AP]), and 5.2 mm (superior-inferior [SI]) relative to the MIP-based ITV. CBCT-based GTVs had average overlapping ratio of 81.3 ± 11.2% (range: 45.1% to 98.9%) with the MIP-based ITV, and 57.7 ± 13.7% (range: 35.1% to 83.2%) with the 3DCT-based GTV. Even with abdominal compression, both 3DCT simulations and daily CBCT scans significantly underestimated the full range of tumor motion. In daily image-guided patient setup corrections, automatic bony anatomy-based image registration could lead to target misalignment. Soft tissue-based image registration should be performed for accurate treatment delivery.

Introduction

Lung cancer is the leading cause of cancer death in the United States. More than 224,300 new lung cancer cases were diagnosed in 2016, and more than 85% of lung cancers are non–small cell lung cancer (NSCLC).[1] For patients with early-stage NSCLC, surgical ablation is the standard treatment with good long-term survival rate. However, up to one third of patients with early-stage NSCLC were not suitable for definitive surgery because of conditions that may include old age and cardiopulmonary complications.[2] For those patients, stereotactic body radiotherapy (SBRT) is an alternative noninvasive treatment modality that could lead to effective local control and long-term survival.[3,4]

Potential side effects from SBRT treatment include radiation-induced lung injuries. Because of the parallel structure of the lung, the severity of radiation-induced lung injuries depends on the volume of the normal lung that received high-dose radiation in SBRT treatment.[5] Precise target volume definition is essential in treatment planning for adequate tumor control while avoiding excessive lung irradiation. An internal target volume (ITV) is commonly defined in treatment planning to encompass the complete tumor motion during breathing.[6] Previous studies have shown that for lung tumors, because of respiratory motion during imaging, conventional 3-dimensional computed tomography (3DCT) simulations tend to underestimate the actual ITV volume.[7,8] Four-dimensional computed tomography (4DCT) is the preferred way to define the ITV for lung cancer patients.[8]

Abdominal compression is a technique aimed at reducing respiratory motion of the diaphragm, which has been shown to be able to significantly reduce organ and target motions in the

Part of this study was presented as a poster during the 2014 Annual Meeting of the American Society for Radiation Oncology (ASTRO).

Reprint requests to Chunhui Han, Ph.D., Department of Radiation Oncology, City of Hope National Medical Center, Duarte, CA 91010.
E-mail: chan@coh.org

http://dx.doi.org/10.1016/j.meddos.2017.01.008
0958-3947/

thoracic and abdominal regions.[9,10] Given significantly reduced respiratory lung motion with abdominal compression, we hypothesize that more efficient imaging techniques might be used for patient simulation as well as for daily image-guided patient setup process. Specifically, if target motion is sufficiently suppressed with abdominal compression, 4DCT-based simulation may be unnecessary, and during daily image-guided patient setup, bony alignment using existing automatic algorithms could be sufficient to align the target volume, which could improve simulation and daily setup efficiency significantly. Therefore, we carried out this study with 2 goals: (1) to evaluate whether 3DCT is sufficient to delineate the complete range of gross tumor volume (GTV) motion for patients with early-stage NSCLC under abdominal compression; and (2) to evaluate if automatic bony anatomy-based image registration is adequate for target alignment in daily image-guided patient setup for patients under abdominal compression.

Methods and Materials

In this institutional review board-approved study, we retrospectively selected 10 patients with early-stage NSCLC who received image-guided SBRT treatment in our institution in recent years. Each patient received a total dose of 50 to 60 Gy in 3 to 5 fractions. Table 1 lists the patient characteristics.

During CT simulation, each patient lay supine on a flat CT simulator table with both arms extended over the head holding 2 handles on a wing board. A stereotactic body immobilization system with a full-body vacuum bag on top of a carbon-fiber platform (Body Pro-Lok System, Civco Medical Solutions, Coralville, IA) was used to provide reproducible patient positioning during simulation and treatment. A flat abdominal plate (Respiratory Plate, Civco Medical Solutions) was placed inferior to the xiphoid process to press against the patient's abdomen. The back side of the abdominal plate was rigidly mounted to a rod, which was indexed to the patient immobilization platform with a support bridge. The force exerted by the plate was tailored to each individual patient so that maximum abdominal compression is achieved within patient tolerance. Once the degree of abdominal compression was determined, the plate rod was fixated to the support bridge, and the rod indexing to the bridge was recorded in the patient chart for use during treatment. Each patient received 1 helical 3DCT scan with 2.5-mm thickness and spacing, followed by 1 retrospective 4DCT scan on the same CT simulator (Optima PET/CT 560, GE Medical Systems, Waukesha, WI) in the thoracic region. During the 4DCT scan, a marker block was placed on the patient's abdomen to generate respiratory phase signals for a respiration tracking system (Varian Real-Time Position Management system, Varian Medical Systems, Inc., Palo Alto, CA). During both the 3DCT and the 4DCT scans, the patient was asked to breathe rhythmically under abdominal compression. The acquired CT images were sorted by image processing software (GE Advantage Workstation, General Electric, Fairfield, CT) to generate CT images at each of the 10 phases of the respiratory cycle. Maximum intensity projection (MIP) and average intensity projection (AveIP) images were subsequently generated by combining the CT images of the 10 phases. All the CT image sets from 4DCT scans, including MIP images, AveIP images, and CT images for each of the 10 breathing phases, were reconstructed with uniform thickness of 2.5 mm.

After the CT simulation, all the CT image sets were transferred to a treatment planning system (Eclipse Version 11, Varian Medical Systems) where contours of the target volumes and critical organs were drawn. The ITV was drawn in the MIP images as the complete visible GTV using the CT lung window setting, where the Hounsfield unit for the window width was 1250 and the Hounsfield unit for the window level is –375. Proper margins were added to the ITV to form the PTV for treatment planning. The ITV and PTV contours were copied to the AveIP images, which were used in the treatment planning system to generate SBRT plans.

All the patients were treated on a linear accelerator (TrueBeam, Varian Medical Systems) using the volumetric modulated arc therapy delivery technique. Before each treatment fraction, the patient lay supine on the treatment couch with the same patient immobilization platform as used during the CT simulation. Then, the abdominal plate was placed by indexing the plate rod on the support bridge to achieve the same degree of abdominal compression as during the CT simulation. The patient was first positioned on the treatment couch based on laser alignment, and then a cone beam CT (CBCT) scan was performed in the thoracic region for soft tissue-based image registration with the AveIP images from the planning 4DCT scan. Once the image registration was reviewed and deemed satisfactory by the radiation oncologist, treatment couch corrections were applied and the treatment was delivered. Each CBCT image set had a field-of-view dimension of 46 cm with 2-mm slice thickness and resolution of 512×512 pixels in the axial plane.

In this study, visible GTVs on planning 3DCT images and daily CBCT images were contoured to compare with the MIP-based ITV volumes. In contouring the GTV in the daily CBCT images and the planning 3DCT images, the same lung window setting as in MIP-based ITV contouring was used. The 3DCT images, 4DCT AveIP images, and 4DCT MIP images were automatically registered by intrinsic Digital Imaging and Communications in Medicine (DICOM) coordinates. To evaluate GTV positions in CBCT images compared with those in planning CT images, we first transferred daily CBCT images to the treatment planning system, and then applied an automatic bony anatomy-based image registration algorithm in the thoracic region to register the daily CBCT images with the 4DCT AveIP images. The registration results were reviewed to ensure good matching of the bony anatomy in the target region.

The following parameters for the GTV or ITV were analyzed for each image set: the volume, the length in each of the 3 orthogonal directions, and the center-of-mass (COM) coordinates. In this study, X, Y, and Z represent coordinates in the medial-lateral (ML), anterior-posterior (AP), and superior-inferior (SI) directions, respectively. In the analysis of COM differences between ITVs and GTVs, we also evaluated the absolute COM shift, defined as $\Delta L = \sqrt{\Delta X^2 + \Delta Y^2 + \Delta Z^2}$, where ΔX, ΔY, ΔZ are the COM coordinate differences between 2 volumes in the ML, AP, and SI directions, respectively.

In the analysis of image registration quality, we used the overlapping ratio to evaluate the degree of GTV-ITV volume matching in registered CBCT and MIP images. The overlapping ratio is defined as $OR = \frac{V_{CBCT} \cap V_{MIP}}{V_{CBCT}}$, where V_{CBCT} and V_{MIP} are the CBCT-based GTV volume and the MIP-based ITV volume, respectively, and $V_{CBCT} \cap V_{MIP}$ denotes the partial GTV volume in CBCT that overlaps with the ITV in the MIP images.

Results

Table 2 lists ITV and GTV volumes with each CT modality for each patient. Relative to the MIP-based ITV volume, the 3DCT-based GTV showed an average relative volume of $66.3 \pm 17.1\%$ (range: 37.5% to 92.0%). The 3DCT-based GTV volumes were significantly smaller than the MIP-based ITV volumes (the 2-tailed p-value < 0.01 in the paired t-test). Figure 1 shows the correlation between the relative 3DCT-based GTV volume and the distance from the COM of the MIP-based ITV to the top of the diaphragm (Pearson correlation coefficient = 0.86, with correlation significance p-value < 0.01). The dimension difference between the 3DCT-based GTVs and the MIP-based ITVs is shown in Table 3. Compared with the MIP-based ITV dimensions, the average GTV dimension in the 3DCT images was

Table 1
Patient characteristics

Patient index	Age (year)	Tumor location	ITV (cc)	Prescription (Gy)	Fractions
1	69	RUL	2.76	60	5
2	52	RLL	11.83	54	3
3	73	RUL	2.13	60	5
4	71	RUL	2.76	50	5
5	81	RUL	3.82	54	3
6	86	RLL	8.15	60	5
7	68	RLL	18.28	60	5
8	84	RUL	17.73	50	5
9	84	RLL	11.76	50	5
10	74	LLL	4.88	60	5

ITV, internal target volume; LLL, left lower lobe; RLL, right lower lobe; RUL, right upper lobe.

Table 2
GTV volumes in 3DCT and CBCT images compared with the MIP-based ITV volume for each patient

Patient	MIP-based ITV	3DCT-based GTV	Average CBCT-based GTV
1	2.76	2.15 (77.9%)	2.49 (90.0%)
2	11.83	6.57 (55.5%)	9.22 (77.9%)
3	2.13	1.77 (83.1%)	2.06 (94.6%)
4	2.76	2.54 (92.0%)	2.45 (88.9%)
5	3.82	2.87 (75.1%)	3.90 (103.2%)
6	8.15	4.00 (49.1%)	7.70 (95.1%)
7	18.28	9.7 (53.1%)	15.59 (84.3%)
8	17.73	11.58 (65.3%)	16.42 (89.0%)
9	11.76	4.41 (37.5%)	9.87 (90.5%)
10	4.88	3.61 (74.0%)	3.95 (86.4%)
Mean	8.4 ± 6.2	(66.3 ± 17.1%)	(90.0 ± 6.7%)

The percentage values are relative to the ITV volume in the 4DCT MIP images.