Dosimetric Consequences of 3D Versus 4D PET/CT for Target Delineation of Lung Stereotactic Radiotherapy

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Introduction: Lung tumor delineation is frequently performed using 3D positron emission tomography (PET)/computed tomography (CT), particularly in the radiotherapy treatment planning position, by generating an internal target volume (ITV) from the slow acquisition PET. We investigate the dosimetric consequences of stereotactic ablative body radiotherapy (SABR) planning on 3D PET/CT in comparison with gated (4D) PET/CT.

Methods: In a prospective clinical trial, patients with lung metastases were prescribed 26 Gy single-fraction SABR to the covering isodose. Contemporaneous 3D PET/CT and 4D PET/CT was performed in the same patient position. An ITV was generated from each data set, with the planning target volume (PTV) being a 5-mm isotropic expansion. Dosimetric parameters from the SABR plan derived using the 3D volumes were evaluated against the same plan applied to 4D volumes.

Results: Ten lung targets were evaluated. All 3D plans were successfully optimized to cover 99% of the PTV by the 26 Gy prescription. In all cases, the calculated dose delivered to the 4D target was less than the expected dose to the PTV based on 3D planning. Coverage of the 4D-PTV by the prescription isodose ranged from 74.48% to 98.58% (mean of 90.05%). The minimum dose to the 4D-ITV derived by the 3D treatment plan (mean = 93.11%) was significantly lower than the expected dose to ITV based on 3D PET/CT calculation (mean = 111.28%), $p < 0.01$. In all but one case, the planned prescription dose did not cover the 4D-PET/CT derived ITV.

Conclusions: Target delineation using 3D PET/CT without additional respiratory compensation techniques results in significant target underdosing in the context of SABR.

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Respiratory motion is known to introduce a potential risk of inadequate target coverage in the setting of radiotherapy for lung tumors. To mitigate this risk, the use of respiratory-gated (4D) computed tomography (CT) is increasingly prevalent to account for respiratory-induced tumor excursion.[1] More recently, the use of simulation positron emission tomography (PET)/CT in the radiotherapy treatment planning position has enabled more accurate delineation of thoracic malignancies by overcoming registration errors normally introduced when planning using a simulation CT scan fused to a separately captured diagnostic.[2] In many centers, PET/CT scans acquired in the radiotherapy treatment position are performed without compensating for respiration on the assumption that this slow acquisition scan, which can take up to 30 minutes to acquire, may adequately capture respiratory induced tumor excursion across many breathing cycles. However, the intensity of the PET signal varies according to the ventilatory pattern and may underestimate the range of tumor excursion depending on patient specific breathing patterns.[3]

Stereotactic ablative body radiotherapy (SABR) is a high precision radiotherapy technique characterized by sharp dose gradients and tight tumor margins. In the context of SABR, it is plausible that inaccurate target delineation may result in significant reduction in dose delivered to the tumor. The hypothesis of this study is that target delineation using slow acquisition 3D PET/CT when compared with 4D PET/CT will result in an increased risk of geographic miss using SABR. The primary aim is to assess the dosimetric impact of radiotherapy planning using conventional 3D PET/CT in comparison with 4D PET/CT.

MATERIALS AND METHODS

As part of an independent ethics board approved prospective clinical trial (Universal Trial Number U1111-1145-0751), consecutive patients with peripheral lung metastasis were enrolled. Eligibility was defined as patients with no more

than 1 to 2 ^{18}F-FDG-PET avid pulmonary metastases with a maximum tumor diameter of less than 5 cm. Tumors were peripherally located beyond the exclusion envelope of 2 cm from central airways as defined by Timmerman et al.[4]

PET/CT Acquisition

Patients sequentially completed both a standard whole body PET/CT and a 4D PET/CT scan in a default radiotherapy planning position using the radiotherapy palette and head rest with their arms raised. Patients were not given any breathing coaching. All trial-related PET scans were performed on a GE-Discovery 690 PET/CT scanner (GE Medical Systems Milwaukee, WI). A free-breathing PET/CT scan was acquired first and took approximately 20 minutes. Immediately after the completion, a 4D-CT scan was acquired centered over the lesion of interest. Ventilation was allowed to stabilize and recorded using the Varian Real-Time Patient Monitoring (RPM) system (Palo Alto, CA). A step and shoot 4D-CT scan was performed and followed by a 10-minute list-mode PET acquisition while recording the patient breathing trace. The GE automatic phase matching software was used to process the 4D-PET/CT scan into 10 bins based on a percentage of the respiratory cycle (i.e., 0%, 10%, 20%, etc.). A representative example of sequential 3D and 4D PET/CT acquisition is given in Figure 1. From the respiratory correlated CT data, a maximum intensity projection (MIP) CT data set was produced by the GE motion match software. Using the MIM Maestro software (MIM 5.4.4, MIM Software Inc., Cleveland, OH), an equivalent PET MIP data set was reconstructed from the respiratory correlated PET data.[5] This PET (MIP) image demonstrates the maximum PET avidity of each voxel across the respiratory cycle. A CT average (AVG) data set was reconstructed from the 4D-PET/CT data, in which the density of each voxel is represented as the average density of that voxel across all respiratory phases. All PET and CT data were reconstructed with a slice thickness of 3.75 mm.

Target Delineation

Image sets were imported in CMS Focal for the purpose of target volume and critical structure delineation. A single experienced thoracic radiation oncologist (D.L.B.) independently delineated both 3D and 4D targets at separate sittings. Manual contouring was performed using a protocol found to be highly reproducible for target delineation as previously published.[6] In delineating target volumes, the internal target volume (ITV) concept was used. A 3D-ITV was delineated using 3D-CT and 3D-PET data sets. For the purposes of planning, the 3D-PET/CT was assumed to produce a target volume inclusive of respiratory motion, because of the long acquisition time of the PET component. A 4D-ITV was delineated using 4D-CT (MIP) and 4D-PET (MIP). Standardized lung window/level settings (1700 ± 300) were used for the CT data sets. After target delineation, the 3D-CT and 4D-CT (MIP) were fused to 4D-PET/CT (AVG). As the 3D and 4D data sets were acquired sequentially without patient repositioning, the fusion was based on the shared DICOM origin of the data sets and verified through visual assessment. After image fusion, the 3D-ITVs and 4D-ITVs were copied from their respective

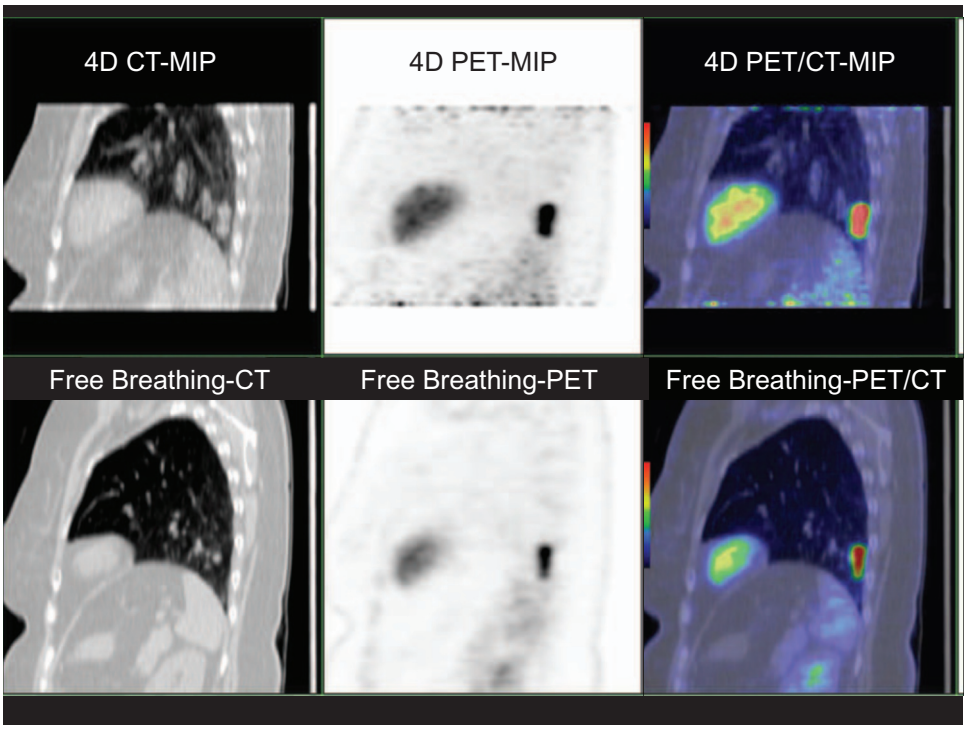

FIGURE 1. The 4D positron emission tomography (PET)/computed tomography (CT) acquisition (above) and 3D PET/CT acquisition (below) in a patient with a lower lobe tumor, demonstrating CT images (left), PET images (middle), and coregistered PET/CT images (right).