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Original Article

Variation in Lung Tumour Breathing Motion between Planning Four-dimensional Computed Tomography and Stereotactic Ablative Radiotherapy Delivery and its Dosimetric Implications: Any Role for Four-dimensional Set-up Verification?

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Abstract

Aims: To investigate variation in tumour breathing motion (TBM) between the planning four-dimensional computed tomograph (4DCT) and treatment itself for primary or secondary lung tumours undergoing stereotactic ablative radiotherapy (SABR).

Materials and methods: Sixteen consecutive patients underwent planning 4DCT at least 1 week after implantation of a fiducial marker. The maximal extent of breathing motion of the intra-tumoural fiducial was measured at 4DCT and again at delivery of each SABR fraction on the linac using stereoscopic kilovoltage imaging. Displacements of the fiducial beyond planned limits were measured in three dimensions and represented as vectors. Variation in breathing motion between the planning 4DCT and treatment, and between individual SABR fractions was analysed.

Results: Although TBM at treatment exceeded planned tumour motion limits for at least part of the course for all patients, 31% of patients remained consistently within 1 mm, 50% within 2 mm and 69% consistently within 3 mm of planned parameters. However, 19% of patients experienced TBM variation 5 mm or more beyond planned limits for at least one fraction. For all patients, the median displacement vector at treatment beyond the planned motion envelope was 1.0 mm (mean 2.0 mm, range 0–12.7 mm). Variation in TBM at treatment from 4DCT correlated neither with the magnitude of TBM at 4DCT nor with planning target volume size ($r_s = 0.13$, $P = 0.62$; $r_s = 0.02$, $P = 0.94$, respectively). Nor was TBM variation related to tumour type or lobar position ($P = 0.35$, $P = 0.06$, respectively). Inter-fraction TBM variation was modest, with an average standard deviation of 1.7 mm (0.3–8.7 mm).

Conclusions: TBM variation between 4DCT and treatment and between SABR fractions was modest for most patients. However, 19% of patients experienced significant TBM variation that could be clinically relevant for those most severely affected. It seems prudent to carry out on-couch assessment of TBM at each SABR fraction to identify such patients who might benefit from respiratory gating or adaptive radiotherapy to maintain tumour motion within the planned limits.

Key words: Breathing motion; breathing movement; respiratory motion; SABR; stereotactic ablative radiotherapy

Introduction

The precise targeting of lung tumours with respect to set-up error and breathing movement facilitates minimisation of target volumes, which in turn allows the delivery of ablative radiation doses using stereotactic ablative radiotherapy (SABR). This process requires knowledge of the pattern and extent of tumour movement throughout the breathing cycle. Such information is most reliably achieved through four-dimensional computed tomography (4DCT) [1–5]. Modern SABR protocols mandate a 4DCT-based expansion of gross tumour volume (GTV) to account for tumour motion, but to minimise the volume of healthy lung irradiated, prophylactic expansion to a clinical target volume (CTV) is prohibited, and planning tumour volume (PTV) expansion is limited to ~5 mm [6–8]. As margins are so tight and doses so high with SABR, image guidance is

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imperative for set-up verification to avoid geometric miss with resultant tumour under-dosage and excessive irradiation of normal tissue.

Although current practice thus verifies patient and tumour position before each fraction - and usually during each fraction too - it is reliant on the premise that the extent and direction of tumour breathing motion (TBM) at treatment is the same as it was at planning 4DCT, and that it remains consistent throughout the entire treatment course. Although literature exists on intra- and inter-fraction tumour motion variation [9–12], to our knowledge only a single study of 12 assessable patients reported the consistency of breathing motion between planning 4DCT and treatment for patients receiving lung SABR [13].

To confirm the available data and the validity of the current approach to SABR planning and treatment, we assessed the variation between TBM on planning 4DCT compared with TBM at the time of treatment, as well as inter-fraction variation. We then considered the dosimetric effect of such variation and its implications for tumour control probability.

Materials and Methods

We analysed the first 16 consecutive patients receiving lung SABR for primary or secondary tumours. A risk-adapted dosing schedule was used for treatment. Thus patients received between three and eight SABR fractions with a single patient receiving 10 fractions. Ethics approval was obtained from our institutional review panel before extracting identifying data.

A 1 cm Visicoil gold marker (IBA, Schwarzenbruck, Germany) was implanted intra-tumourally at least 1 week before 4DCT. 4DCT was carried out on a Lightspeed four-slice computed tomography scanner (GE, Waukesha, WI, USA) with patients immobilised in a vacuum pillow with arms raised. 1.25 mm helical scans were obtained. Infrared surface detection (VisionRT, London, UK) was used for four-dimensional information and 10 respiratory bins were created for each respiratory cycle. Audible breath coaching during both 4DCT and treatment was used for all patients. The maximum tumour breathing movement vectors in three dimensions, represented by the furthest tip of the implanted fiducial marker, were measured on 4DCT using the measurement tool.

Contouring and planning was carried out using iPlan v4.5.1 using Monte-Carlo algorithm (Brainlab, Heimstetten, Germany). A GTV was contoured on all 10 respiratory bins to account for TBM and expanded 5 mm to create the PTV. Patients were treated on a Novalis Classic with exactrac kilovoltage imagers (Brainlab). An infrared camera was used to track the respiratory cycle using chest and abdominal markers. Once patients had settled into a regular breathing pattern, stereoscopic kilovoltage imaging localised the tumour and isocentre based on the intra-tumoural fiducial. To measure the maximal extent of TBM, a set of images was obtained at maximal inspiration and expiration. These points were auto-detected by Brainlab software and hence actually lie just before the true peak/nadir immediately before the graph of breathing amplitude becomes horizontal. Maximal vector displacements of the fiducial marker at the extremes of breathing were compared with planning 4DCT. Statistical calculations were carried out using SPSS v22.0 (Armonk, NY, USA).

As 4DCT slice thickness was 1.25 mm, the inherent insensitivity of the study method for superoinferior measurement is half this distance or 0.625 mm. Thus, superoinferior breathing motion of up to 0.63 mm beyond the 4DCT limits was considered ‘within tolerance’. Our results thus represent minimum possible displacements; actual superoinferior values could have been up to 0.63 mm greater.

Results

The median PTV was 40.0 cm^3 (mean = 47.1 cm^3). Pathology was primary lung cancer in nine patients and metastasis in seven. Eleven tumours were in the upper lobes, one in the middle and four in the lower lobes. Measurements were available for 92 of the 95 fractions delivered.

There was no patient for whom the TBM vectors remained completely within 4DCT limits throughout the treatment course. However, about one-third of patients had tumours that never moved >1 mm beyond the 4DCT limits, half remained constantly within 2 mm thereof and two-thirds remained consistently within 3 mm thereof (Figure 1). Only three of the 16 patients (19%) exhibited TBM of 5 mm or more beyond the planned tolerance for part of their treatment. Further details are provided in Table 1.

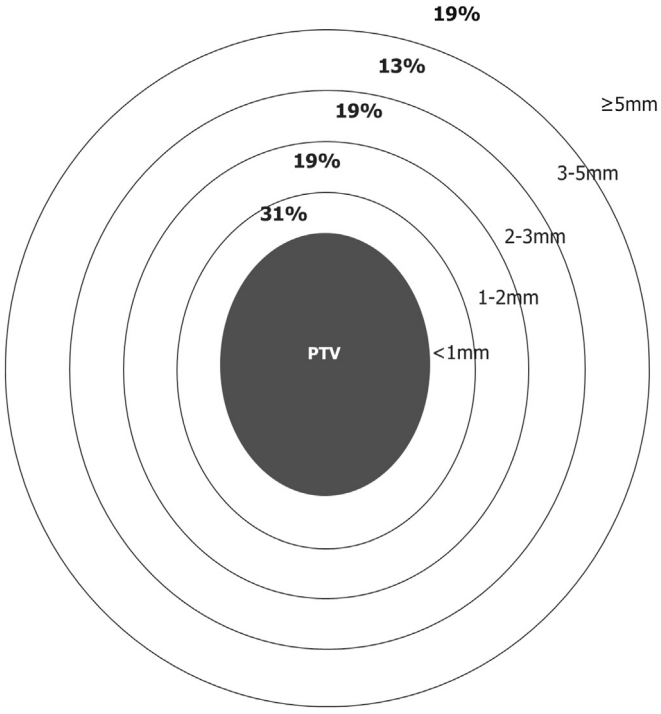

Fig 1. Maximal breathing motion variation beyond 4DCT limits at any time during treatment.