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# Four-dimensional planning for motion synchronized dose delivery in lung stereotactic body radiation therapy

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ABSTRACT

*Background and purpose:* To investigate a weighted four-dimensional (W-4D) treatment planning strategy based on the greater clinical advantage of the conformal over the intensity-modulated technique in lung stereotactic body radiotherapy (SBRT).
*Material and methods:* Two planning strategies (individual-phase 4D [IP-4D] and W-4D) were evaluated in eighteen lung SBRT patients. The IP-4D plan can deliver a constant fluence during whole respiratory phases. The W-4D plan's key concept was to escalate (or reduce) fluence using a 4D optimization algorithm when the tumour target was out-of-line (or in-line) with an organ-at-risk. The fluence was converted to a dynamic multi-leaf collimator leaf sequence for deliverable 4D irradiation.
*Results:* In all patients, the W-4D plan enabled planning tumour volume conformity comparable to the IP-4D plan. The W-4D plan yielded a significantly lower maximum dose than the IP-4D plan for the spinal cord (−11%; $p < 0.01$), oesophagus (−14%; $p < 0.01$), heart (−22%; $p = 0.01$) and stomach (−23%; $p = 0.07$), and a lower mean dose to liver (−19%; $p = 0.18$) while maintaining the mean dose to lung (−1%; $p = 0.23$).
*Conclusions:* W-4D is a robust, practical planning approach that achieves significant dose sparing relative to non-time-resolved tracking; it may be of greater clinical benefit in radiotherapy than the spatially intensity-modulated 4D approach.


Respiratory motion causes significant geometric and, therefore, dosimetric uncertainties in lung cancer radiotherapy [1,2]. The impact of such uncertainties is amplified in hypofractionated regimens such as lung stereotactic body radiotherapy (SBRT). A variety of techniques for respiratory motion management have been described in the literature [3]. These include defining motion-inclusive margins, target immobilization, respiratory gating and real-time motion tracking. A common theme among these approaches is to treat motion as a hindrance and try to mitigate its effect. The aim of the present study was to present a novel 4D (3D + time) treatment planning approach that uses respiratory motion to our advantage, as an additional degree of freedom rather than as a constraint.

Investigations regarding 4D planning for multi-leaf collimator (MLC) tracking have been reported by several groups. A number of studies have reported the design and development of a deliverable 4D intensity-modulated radiation therapy (IMRT) planning method [4–6]. Several concepts have been proposed for 4D-volumetric modulated arc therapy (4D-VMAT) planning [7,8]. However, these approaches for 4D-IMRT and 4D-VMAT were not time-resolved. They only considered leaf constraints and accounts of translation and deformation of the tumour target over the respiratory phases. This was because dose optimization was performed using only a representative peak-exhale phase 4DCT, and generated one MLC sequence for the phase. Subsequently the MLC motion sequencer modified the other phase MLC sequences to fit the tumour translation and deformation. Nohadani et al. described a time-resolved 4D IMRT optimization where the fluence map is optimized across all four dimensions simultaneously [9]. However, the deliverability of this method was not verified, i.e., whether it is practically possible to achieve a sequence that can deliver the calculated fluence. In addition, if the complex 4D-MLC sequence can be computed, relative to conformal radiotherapy (CRT) the technique is susceptible to the unexpected event of irregular breathing because of the inherent weakness of intensity modulation. In a comparative study involving CRT, IMRT and VMAT for lung SBRT, CRT showed the best dose sparing for lung and spinal cord, with comparable target coverage for a tumour measuring <70 $cm^3$ [10]. Regarding practical 4D irradiation, the CRT technique is robust and can provide more sparing of Organs at risk (OARs) while maintaining target dose coverage.

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In the present study, we present a novel practical weighted-4D (W-4D) planning technique for conformal lung radiotherapy, developed around a commercial treatment planning system (TPS).

## Materials and methods

### *Patient cohort*

Eighteen lung SBRT patients treated at our institution between July 2008 and December 2012 were chosen based on their residual motion (⩾5 mm after immobilization and/or abdominal compression) as assessed from 4DCT. There were fourteen patients with and four without abdominal compression. All patients were treated with three fractions of 18 Gy to a total dose of 54 Gy. Fig. 1 shows the characteristics regarding Planning Target Volume (PTV) location, tumour target volume and residual motion for all 18 patients. The mean volume was 60 $cm^3$ (6–211 $cm^3$), and the average amplitude of tumour motion was 1 cm (0.3–1.6 cm).

### *Planning with 4DCT simulation*

All patients underwent 4DCT simulation acquired on a sixteen-slice Brilliance CT Big Bore helical scanner in conjunction with the Bellows abdominal pressure belt system (Philips Healthcare, Andover, MA, USA). The ten individual-phase 4DCT datasets were sent to a dedicated workstation running the Eclipse TPS.

Photon beams (6 MV) directed from nine to thirteen fields were used to create two types of treatment plans, an equally weighted IP-4D and W-4D. All plans were normalized such that 100% of the dose covered 95% of the PTV.

### *IP-4D and W-4D methods*

The two methods had several steps in common and are therefore discussed together. In each method, the gross tumour volume (GTV) was contoured on each of the ten phases of the 4DCT. For each phase, the PTV was defined as a 5-mm uniform expansion of the GTV. The 50% respiratory phase, corresponding to peak exhalation, was chosen as the reference phase on which normal structures were contoured. For each patient, ten separate plans were generated using the Eclipse TPS corresponding to the ten respiratory phases. For each plan, the number of beams and the beam angles were transferred from the corresponding clinically approved plan generated using the common internal target volume-based method. To minimize errors and/or beam holds caused by finite leaf velocity, the collimator angle for each field was set such that MLC leaf travel was parallel to the principal component of tumour motion in the beam's eye view (BEV) [11,12]. The MLC aperture for each field was determined by adding a uniform 5-mm margin to the PTV as seen in the BEV to achieve better conformity and heterogeneity for the PTV at each phase. For each patient, a total of $P \times J$ separate 3D dose distributions were calculated using an anisotropic analytical algorithm, version

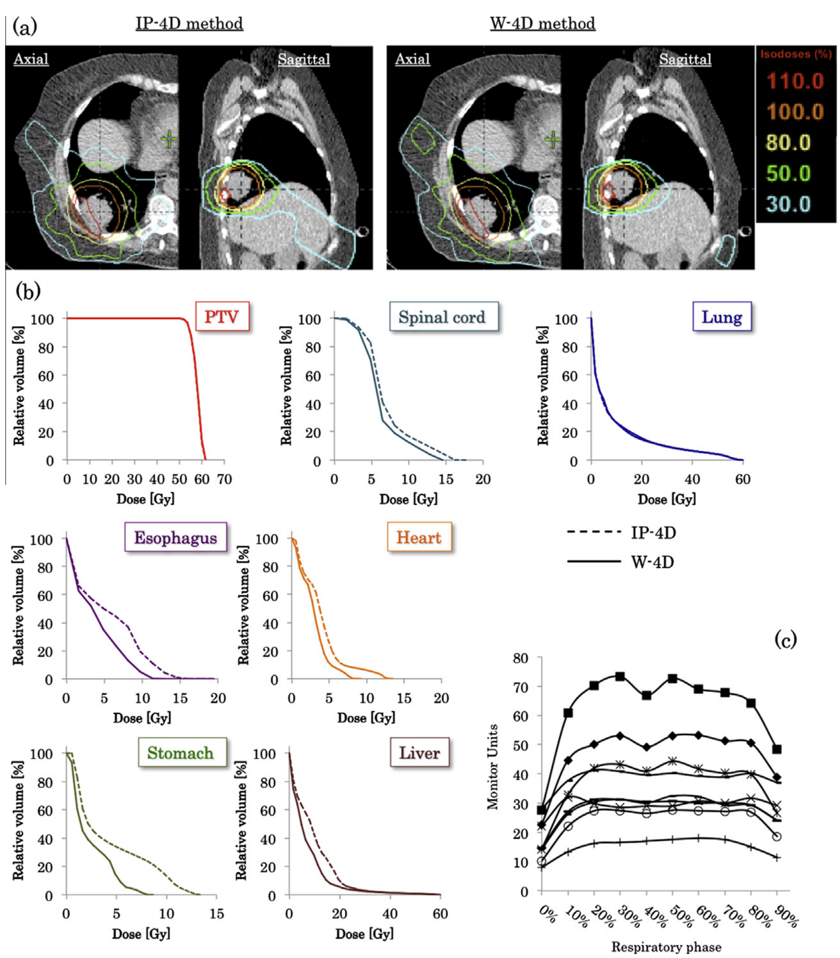


**Fig. 1.** (a) Dose distributions and (b) dose-volume histograms for nine-field individual-phase 4D (IP-4D) and weighted-4D (W-4D) plans for Patient 3. (c) Number of monitor units (MUs) as a function of phase is shown for each beam for the W-4D plan. The modulation of MUs for the W-4D plan is a result of the optimization process (Eq. (3)), which enables the use of respiratory motion as an additional degree of freedom.

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