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Original paper

# The impact of respiratory gating on lung dosimetry in stereotactic body radiotherapy for lung cancer

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ABSTRACT

The purpose of this study was to evaluate the impacts of respiratory gating and different gating windows (GWs) on lung dosimetry in stereotactic body radiotherapy (SBRT) for lung cancer.

Gated SBRT plans were developed using the four-dimensional computed tomography data from 17 lung cancer patients treated with SBRT. Using amplitude-based end-exhalation gating, we established 2 fixed GWs with approximate duty cycles of 50% (50% GW) and 25% (25% GW), respectively, for this study.

For highly mobile tumors (3D mobility > 10 mm), additional benefits in lung-dose reductions were achieved with the 25% GW, as a result of inadequate mobility and planning target volume reductions obtained with the 50% GW. In these tumors, the absolute differences compared to the non-gated and 50% gated plans, were 0.5 Gy and 0.33 Gy for the mean lung dose and 1.11% and 0.71% for the V20, respectively. Dosimetric benefits were achieved with the 50% GW, compared with the non-gated plan, for tumors with both low mobility and small volume (gross tumor volume $\leq$ 10 cc). Among the identified predictive factors of dosimetric benefits, the lateral distance from midspinal canal and the motion range in anterior–posterior direction might be stronger factors because of their correlations with many of the lung-dose parameters and greater predictive capacity.

The results of the present study might facilitate the selection of appropriate patients and the optimal GW according to the tumor characteristics for gated lung SBRT.



## Introduction

Stereotactic body radiotherapy (SBRT) for early-stage non-small cell lung cancer (NSCLC) and metastatic lung cancer has been reported to yield high local control rates in most studies [1]. This approach involves the delivery of an ablative dose to the tumor using highly conformal and hypofractionated radiation over a short time course, while limiting the doses to the surrounding normal tissues. In radiotherapy for lung cancer, large uncertainties exist regarding target delineation and localization because of respiration-induced tumor motion. These uncertainties are particularly influential in the SBRT technique, which administers high doses (biological effective doses >100 Gy) in small fractions (≤5 fractions) to small target volumes [2]. The magnitude of respiration-induced tumor motion in the lung can exceed 2–3 cm, depending on the tumor sites and the individual patient, if this motion is not actively controlled. In fact, this motion features a patient-specific aspect, as it is difficult to estimate the range of motion before the actual measurements [3–5]. Report 62 from the International Commission on Radiation Units and Measurements (ICRU) introduced the concept of an internal target volume (ITV), which consists of the clinical target volume (CTV) plus an additional internal margin to account for tumor motion [6]. Recently, an adaptation of the four-dimensional computed tomography (4D CT) technique allowed the acquisition of 3D CT images during multiple phases of the respiratory cycle. Using this tumor and organ motion information, 4D CT can be employed for individualized ITV delineation and respiratory gated radiotherapy (RGRT) of moving lung tumors [5,7]. Together with this 4D imaging technique, various methods have been used to reduce the impact of respiratory motion during radiotherapy. These methods have included motion-encompassing, respiratory gating, breath-holding, forced shallow

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breathing with abdominal compression, and beam tracking techniques [5,8,9]. Of these methods, respiratory gating involves the delivery of radiation only during a predetermined portion (gating window) of the breathing cycle. Therefore, RGRT could potentially reduce the CTV-planning target volume (PTV) margin, and thereby reduce the doses to the surrounding normal tissues and/or escalations of the tumor dose.

In recent studies [10–16] of 4D CT datasets from patients with stages I–III lung cancer, the use of a patient-specific margin (individualized ITV) or respiratory gating (gated ITV) yielded improved target coverage and significant reductions in the PTV and lung-doses, compared with population-based (conventional) margins. However, the additional dosimetric benefits from respiratory gating were modest or very limited compared with the non-gated ITV approach and, interestingly, some studies have reported variations in these additional benefits according to some tumor parameters, such as location and mobility [10,12,13]. The use of 4D CT scanning data, which constitute the gold standard for ITV delineation, is strongly recommended for SBRT planning in cases of lung cancer [17]. However, there are currently no established criteria regarding the additional use of motion-reducing methods, such as respiratory gating, in SBRT for lung cancer. Despite the highly conformal dose distributions in small target volumes exhibited by this technique, high fractional doses can result in significant toxicity to the surrounding normal tissues [18]. The long treatment time of gated SBRT results in patient discomfort and might thereby induce setup errors due to the movement of uncomfortable patients. Therefore, the use of larger gating windows (GWs) might be more patient friendly, and some patients might be indicated for large GWs or non-gating without significant increases in the lung dose. To date, reports describing the dosimetric effects of respiratory gating in lung SBRT have been limited [15,16], and the optimal portion of respiratory cycle for gating remains unknown and controversial. Controversy also remains with regard to the threshold of tumor motion or other parameters for which RGRT should be considered. The American Association of Physicists in Medicine (AAPM) has produced a report about the methods for reducing the impact of respiratory motion, and it recommends that respiratory management techniques be considered when the range of tumor motion exceeds 5 mm in any direction [8]. Normally, motion-reducing techniques, such respiratory gating, should be considered in cases with considerable tumor motion (e.g., >1 cm). The dosimetric benefits achieved with gating and a threshold of tumor motion or other parameters that could facilitate appropriate patient selection should be defined to allow for additional recommendations for respiratory gating in SBRT for lung cancer. In addition, the determination of an optimal GW according to the tumor characteristics might facilitate more efficient treatment delivery during gated SBRT.

The present study was undertaken to evaluate the impacts of respiratory gating and different GWs on target volume and lung dosimetry and to identify the tumor parameters predictive of the dosimetric benefits achieved with gating in lung cancer patients treated with SBRT.

## Materials and methods

### *Patient characteristics*

Following the approval of our institutional review board (IRB approval number: DIRB-00109_1-003), 17 patients who had been treated at our institution with SBRT via 4D CT scans for early-stage NSCLC (15 tumors) or for pulmonary metastases (2 tumors) were included in this retrospective study. The median patient age was 68 years old (range, 55–86 years), and the sample included 15 men and 2 women. The tumors were located in the upper ($n = 9$), middle ($n = 1$), and lower lobes ($n = 7$). Of the 17 tumors, 16 were peripherally located, and 1 was centrally located.

### *4D CT data acquisition and tumor motion analysis*

A 4D CT technique using a multi-slice CT scanner (SOMATOM Sensation 64; Siemens Medical Solutions, Erlangen, Germany) was performed for SBRT planning in all of the patients. The patients were immobilized with a Wing board and Vac-Lok body cushion (CIVCO Medical Solutions, Orange City, IA, USA) with the arms placed above the head. The patients were advised to breathe freely and regularly, and abdominal compression to reduce breathing motion was not applied to any patient. A single helical 4D CT scan that included the whole lung was acquired under fixed acquisition parameters (pitch of 0.1, rotation time of 0.5 s, 120 kV, and 400 mA), with a commercially available motion-monitoring system (AZ-733V; Anzai Medical, Tokyo, Japan). A pressure sensor (AZ-733V), fixed to the upper abdominal region with an elastic belt, generated the external respiratory signal. A lower signal amplitude (low pressure) corresponded to the exhalation (Ex) phase of the breathing cycle, and a higher amplitude (high pressure) corresponded to the inhalation (In) phase [19]. Using the Syngo software package (Siemens Medical Solutions), the projections were sorted retrospectively according to the corresponding breathing phases (Ex and In) and the relative amplitudes at 25% intervals from 0% to 100%, and the images were reconstructed into 8 respiratory phase bins (100%, Ex 75%, Ex 50%, Ex 25%, 0%, In 25%, In 50%, and In 75%), which were equally distributed throughout the breathing cycle with slice thicknesses of 3.0 mm. Immediately following the 4D CT scan, a modified slow CT scan with the same scanning range and slice thickness was obtained with the same scanner while using the longest possible gantry rotation time (1.0 s) and a reduced pitch factor (0.5) [20]. The tumor motion amplitude was determined by measuring the tumor movement in the 8-phase 4D CT datasets with the InSpace 4D software package (Siemens Medical Solutions). The motion ranges at the tumor centroid in the superior–inferior (SI), anterior–posterior (AP), and left–right (LR) directions were measured on the transverse, sagittal, and coronal planes with grid spacing of 1 mm for all 8 phase bins registered by this software. In our amplitude-based gating around the end of exhalation (EOE, 0% bin), we established 2 fixed GWs with approximate duty cycles of 50% and 25%, respectively, for this study. The 50% GW and 25% GW were defined as 5 phases (Ex 50%, Ex 25%, 0%, In 25%, and In 50%) and 3 phases (Ex 25%, 0%, and In 25%) around the EOE, respectively. The tumor residual motions within each GW were also determined, together with the full motion range for all 8 phases.

### *Target volume definitions and volumetric analysis*

All of the CT datasets were transferred to a commercial treatment-planning system (Pinnacle3 version 8.0m; Philips Medical Systems, Fitchburg, WI, USA), and thereafter, the 4D CT and modified slow CT images were superimposed using an automated algorithm from the Syntegra® software package (Philips Medical Systems). The matched results were visually verified by reviewing the alignment of the spinal vertebrae. The gross tumor volumes (GTVs) in each of the 8 phases of the 4D CT images were delineated with the lung window setting by the same radiation oncologist and were projected onto the modified slow CT image of the same slice. The GTV size on the EOE (GTVeoe), the lateral distance from the midspinal canal to the GTVeoe centroid, and the craniocaudal distance from the carina to the GTVeoe centroid were additionally measured on the EOE images for use as tumor parameters. The craniocaudal position was expressed as a positive or negative