

# To study tumor motion and planning target volume margins using four dimensional computed tomography for cancer of the thorax and abdomen regions

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## ABSTRACT

In this study, four dimensional computed tomography (4DCT) scanning was performed during free breathing on a 16-slice Positron emission tomography PET /computed tomography (CT) for abdomen and thoracic patients. Images were sorted into 10 phases based on the temporal correlation between surface motion and data acquisition with an Advantage Workstation. Gross tumor volume gross tumor volume (GTV) s were manually contoured on all 10 phases of the 4DCT scan. GTVs in the multiple CT phases were called GTV4D. GTV4D plus an isotropic margin of 1.0 cm was called CTV4D. Two sets of planning target volume (PTV) 4D (PTV4D) were derived from the CTV4D, i.e.  $PTV4D_{2cm} = CTV4D$  plus 1 cm setup margin (SM) and 1 cm internal margin (IM) and  $PTV4D_{1.5cm} = CTV4D$  plus 1 cm SM and 0.5cm IM. PTV3D was derived from a CTV3D of the helical CT scan plus conventional margins of 2 cm.  $PTV_{gated}$  was generated only selecting three CT phases, with a total margin of 1.5 cm. All four volumes were compared. To quantify the extent of the motion, we selected the two phases where the tumor exhibited the greatest range of motion. We also studied the effect of different PTV volumes on dose to the surrounding critical structures. Volume of CTV4D was greater than that of CTV3D. We found, on an average, a reduction of 14% volume of  $PTV4D_{1.5cm}$  as compared with PTV3D and reduction of 10% volume of  $PTV_{gated}$  as compared with  $PTV4D_{1.5cm}$ . We found that 2 cm of margin was inadequate if true motion of tumor was not known. We observed greater sparing of critical structures for PTVs drawn taking into account the tumor motion.

**Key words:** four dimensional computed tomography, tumor motion and PTV margin reduction for thoracic and abdomen tumor

## Introduction

3D conformal radiotherapy is the present standard treatment modality for radiotherapy treatment of thoracic and abdominal–pelvic malignancies. Respiratory motion leads to inaccuracy in target volume definition on the planning computed tomography (CT) scan.<sup>[1,2]</sup>

To ensure sufficient dose coverage throughout the

treatment course, internal margin (IM) and setup margin (SM) are added to the clinical target volume (CTV) to make up the planning target volume (PTV).<sup>[3]</sup> Simple linear addition of the two margins generally leads to an excessively large PTV that would go beyond the patient's tolerance, and does not reflect the actual clinical consequences. Thus, the risk of missing part of the CTV must be balanced against the risk of complications due to large PTV. Geometric margins to account the respiratory motion are usually derived from fluoroscopy, clinical experience or values reported in the literature. Such literature-reviewed margins are neither accurate nor patient-specific. Patient-nonspecific margins either lead to the possibility of geometric miss or treat excess normal tissue. A geometric miss is still possible if tumor motion is greater than the assumed average motion. In addition, there can be unnecessary irradiation of normal tissue if tumor motion is smaller than expected. It is very difficult to decide margins unless we know the exact motion of tumor. Patient-specific margins for CTV have been evaluated using fluoroscopy motion study,<sup>[4,5]</sup> repeated volumetric CT scan,<sup>[6,7]</sup> breath hold CT scan,<sup>[8]</sup> slow CT scan<sup>[9,10]</sup> and time-resolved CT scan (4DCT scan).<sup>[11]</sup>

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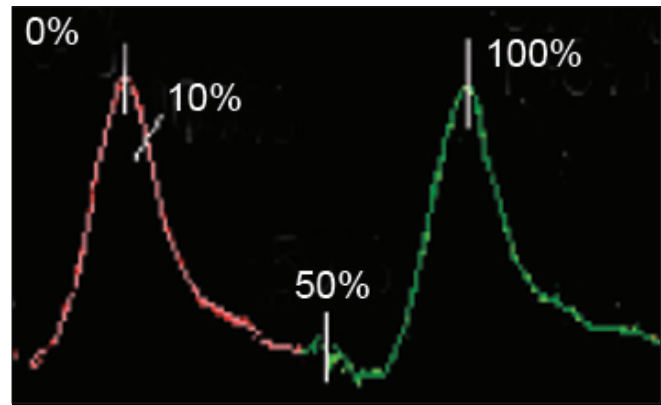
According to the guideline of AAPM TG 76, if the target motion is  $>5$  mm, a method of respiratory motion management is available and if the patient can tolerate the procedure, respiratory motion management technology is appropriate. Respiratory motion management is also appropriate when the procedure will increase normal tissue sparing.<sup>[12]</sup> A study shows that respiratory gating permits a reduction in field sizes because irradiation can be limited to phases in which the mobile target volume is in a predetermined position.<sup>[13]</sup>

In this article, we describe the clinical implementation of patient-specific PTV design using 4DCT scanning. We report the initial results on 4D target volume designs and comparison with conventional PTV volume and we also studied dose to surrounding critical structure for different PTVs.

## Materials and Methods

Ten patients were immobilized with a vacuum bag in the supine position, with arms raised during simulation. The 4DCT scanning was performed during free breathing on a 16-slice PET/CT (GEMedical Systems, Waukesha, WI, USA). A plastic box with a pair of reflective markers was placed on the patient's anterior abdominal surface, approximately midway between the xiphoid and the umbilicus. Markers' motion was captured by an infrared camera and the respiratory signal was recorded in synchronization with the X-ray "ON" signal from the CT scanner. Real-time positioning management (RPM, Varian; Palo Alto, CA, USA) was used for recording the breathing curve. The scanner was operated in an axial cine mode and continuous scans were performed at each couch position, with an interval equal to the patient's average respiratory period so that complete data were acquired over an average respiratory cycle. Data acquisition was repeated at each couch position until full longitudinal coverage of the region of interest was obtained. Parameters for CT acquisition were 120 kV, 300–400 mA and slice thickness of 2.5 mm. The whole scanning time was 90–120 s. Typically, a total of 1200–1500 slices were acquired for each patient. After 4DCT scanning, the 4D software (Advantage 4D, GEMedical Systems, Waukesha, WI, USA) used all reconstructed images along with the respiratory phases that were calculated by the RPM system. Images were sorted into 10 phases based on the temporal correlation between surface motion and data acquisition with an Advantage Workstation. The 10 respiratory phases were evenly distributed over a breathing cycle labeled as CT0%, CT10%, CT20% . . . CT90%. CT0% corresponds to end-inhalation, CT20% to mid-exhalation and CT50% to end-exhalation, as shown in Figure 1.

GTVs were manually contoured on all 10 phases of the 4DCT scan. Target volumes were defined as GTV, which represented the primary lesion visualized on the



**Figure 1: Respiratory cycle**  
If the respiratory cycle is viewed as a waveform, then a phase is a position within the breathing cycle where 0% = peak inspiration, 50% = peak expiration and 100% = peak inspiration

**Table 1: Comparison of CTV3D and CTV4D volume**

|     | CTV3D    | CTV4D    | Ratio, CTV3D/CTV4D |
|-----|----------|----------|--------------------|
| #1  | 186.3 cc | 210.1 cc | 0.88               |
| #2  | 122.2 cc | 166.3 cc | 0.73               |
| #3  | 137.5 cc | 194.4 cc | 0.70               |
| #4  | 145.3 cc | 187.4 cc | 0.77               |
| #5  | 91.4 cc  | 120.4 cc | 0.75               |
| #6  | 68.6 cc  | 98.02 cc | 0.7                |
| #7  | 65.5 cc  | 103.7 cc | 0.63               |
| #8  | 46.9 cc  | 78.1 cc  | 0.60               |
| #9  | 55.2 cc  | 73.5 cc  | 0.75               |
| #10 | 60.3 cc  | 82.3 cc  | 0.73               |

CT images. The combined volume of the GTVs in the multiple CT phases was called as GTV4D. GTV4D plus an isotropic margin of 1.0 cm was called as CTV4D. Two sets of PTV4D were derived from the CTV4D, i.e. PTV4D<sub>2cm</sub> with a conventional margin of 2 cm (CTV4D plus 1 cm SM and 1 cm IM) and PTV4D<sub>1.5cm</sub> (CTV4D plus 1 cm SM and 0.5 cm IM), with reduction in the IM margin. For PTV<sub>gated</sub> only three respiratory phases were selected in which organs at risk are at maximum distance from the tumor. PTV<sub>gated</sub> was generated with a total margin of 1.5 cm. PTV3D was derived from a CTV3D of the helical fast CT scan with conventional margins of 2 cm. All volumes of PTV, i.e. PTV4D<sub>2cm</sub>, PTV4D<sub>1.5cm</sub>, PTV<sub>gated</sub> and PTV3D were compared. To quantify the extent of the motion, we selected the two phases where the tumor exhibited the greatest range of motion, i.e. full inspiration (0%) and full expiration (50%) phases. We studied overlapping of PTV3D and PTV4D<sub>1.5cm</sub> using the Boolean operator OR.

To study the effect of PTV volumes on dose to critical structure, a set of three plans were generated for every patient with three different PTV volumes, i.e. PTV3D, PTV4D<sub>1.5cm</sub> and PTV<sub>gated</sub>. For each set of plans, an identical number of beams, gantry angle and dose prescription were

used. For Ca lung patients, lung mean dose and V20 dose were calculated and for abdominal tumors, mean dose of the kidney and liver were calculated.

**Results and Discussion**

**Analysis of CTVs and PTVs**

Evaluation of target volumes reveals that 4DCTV is larger than 3DCTV in all patients. This indicates that tumors are mobile. To estimate the extent of tumor mobility, the ratio of CTV3D and CTV4D was calculated for each patient. The average of ratio of CTV3D volume and CTV4D volume of all patients was found to be 0.72, with an SD of 0.07 [Table 1]. This ratio for completely immobile tumor is assumed to be 1.00. Table 2 represents volume PTV3D, PTV<sub>gated</sub> and PTV4D with different margin. The PTV4D<sub>1.5cm</sub> was smaller than PTV3D. PTV4D<sub>1.5cm</sub> shows reduction by an average value of 14%. Similarly, PTV<sub>gating</sub> shows reduction by an average value of 21% of PTV3D.

**Tumor motion and PTV overlapping**

Table 3 shows the observed tumor motion. The motion of tumor in peak to peak amplitude was found with a variation of 0.2 cm (min) and 1.2 cm (max). In Ca lung patients, the tumor motion during breathing was found to be varying

widely in all directions (first five patients in Table 3), but for abdominal cancer patients, tumor motion was dominant in the superior to inferior (SI) direction only (last five patients in Table 3). To determine the impact of motion on position of PTVs, overlapping of PTV4D<sub>1.5cm</sub> and PTV3D was studied. It was noticed that in only one patient, PTV4D<sub>1.5cm</sub> was completely overlapped by PTV3D, as shown in Table 2. Because a 2 cm margin was used for CTV3D to get PTV3D and a 1.5 cm margin was used for CTV4D to get PTV4D<sub>1.5cm</sub>, PTV4D<sub>1.5cm</sub> should be completely overlapped by PTV3D.

We observed that the nonoverlapping region had a direct relationship with motion of tumor. As shown in Figure 2, abdomen tumor PTVs were not completely overlapped in the SI direction because tumor motion was in the same direction, i.e. in the SI direction. As tumor motion was very complex in lung patients, nonoverlapping of PTVs was also in a different direction. Nonoverlapping of PTVs was patient specific. This clearly indicates that the nonpatient’s specific margin of 2 cm to CTV is also not sufficient if we do not know the tumor motion.

**PTV volumes and dose to critical structures**

Table 4 shows dose to critical structures. Among the three PTVs plan (PTV3D, PTV4D, PTV<sub>gated</sub>), the PTV<sub>gated</sub> plan

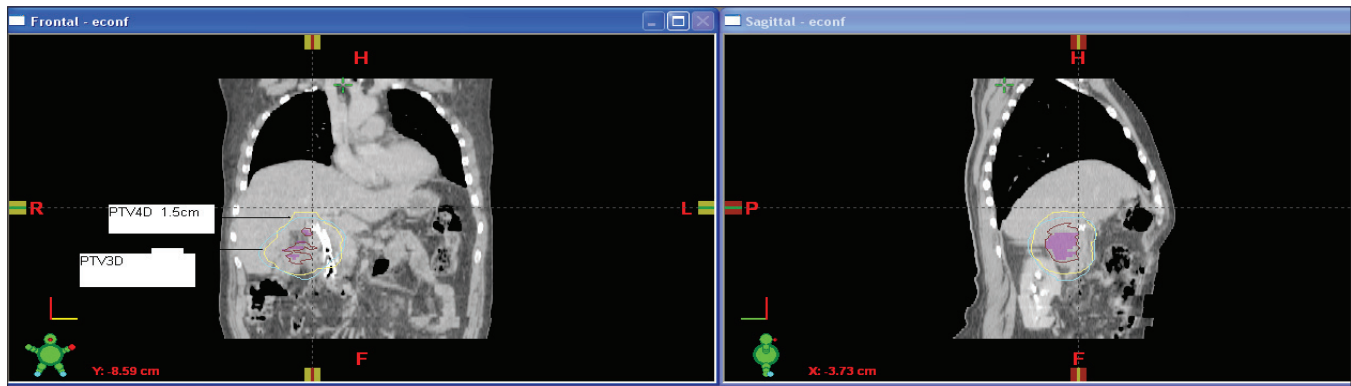
**Table 2: Comparison of PTV3D, PTV<sub>gated</sub> and PTV4D with different CTV expansion**

|     | <i>PTV3D<sub>2cm</sub></i> | <i>PTV4D<sub>2cm</sub></i> | <i>PTV4D<sub>1.5cm</sub></i> | <i>PTV<sub>gated</sub></i> | <i>PTV4D<sub>2cm</sub>/PTV3D<sub>2cm</sub></i> | <i>PTV4D<sub>1.5cm</sub>/PTV3D<sub>2cm</sub></i> | <i>PTVgated/PTV3D<sub>2cm</sub></i> |
|-----|----------------------------|----------------------------|------------------------------|----------------------------|--|--|-------------------------------------|
| #1  | 969.7 cc                   | 1023.8 cc                  | 770.9 cc                     | 757.7 cc                   | 1.05   | 0.79   | 0.78                                |
| #2  | 733.9 cc                   | 858.8 cc                   | 657.7 cc                     | 591.1 cc                   | 1.17   | 0.88   | 0.80                                |
| #3  | 737.3 cc                   | 837.2 cc                   | 590.7 cc                     | 573.8 cc                   | 1.13   | 0.80   | 0.76                                |
| #4  | 789.1 cc                   | 887.4 cc                   | 687.7 cc                     | 603.4 cc                   | 1.12   | 0.87   | 0.76                                |
| #5  | 703.9 cc                   | 808.2 cc                   | 621.7 cc                     | 567.1 cc                   | 1.16   | 0.87   | 0.79                                |
| #6  | 636.4 cc                   | 702.8cc                    | 536.2 cc                     | 490.4 cc                   | 1.10   | 0.84   | 0.77                                |
| #7  | 611.9 cc                   | 695.6 cc                   | 519.9 cc                     | 465.7 cc                   | 1.13   | 0.84   | 0.76                                |
| #8  | 388 cc                     | 488.8 cc                   | 361.3 cc                     | 314.3 cc                   | 1.25   | 0.93   | 0.81                                |
| #9  | 430.2 cc                   | 515.3 cc                   | 382.3 cc                     | 354.8 cc                   | 1.19   | 0.88   | 0.82                                |
| #10 | 519.7 cc                   | 612.5 cc                   | 489.4 cc                     | 442.9 cc                   | 1.17   | 0.94   | 0.85                                |

**Table 3: Tumor motion and PTV overlapping**

|     | <i>L-R direction (cm)</i> | <i>AP direction (cm)</i> | <i>SI direction (cm)</i> | <i>Overlapping PTV4D1.5cm and PTV3D volume (%)</i> |
|-----|---------------------------|--------------------------|--------------------------|--|
| #1  | 0.2                       | 0.2                      | 0.2                      | 100  |
| #2  | 0.2                       | 0.3                      | 0.5                      | 97.5   |
| #3  | 0.4                       | 0.8                      | 0.6                      | 97.8   |
| #4  | 0.6                       | 0.4                      | 0.5                      | 96.7   |
| #5  | 0.3                       | 0.3                      | 0.4                      | 96.4   |
| #6  | 0.2                       | 0.3                      | 0.6                      | 97.3   |
| #7  | 0.2                       | 0.2                      | 1.1                      | 94.2   |
| #8  | 0.3                       | 0.3                      | 0.8                      | 96.2   |
| #9  | 0.4                       | 0.3                      | 1.2                      | 95.2   |
| #10 | 0.2                       | 0.4                      | 0.9                      | 96.2   |

L-R, left to right; A-P, anterior to posterior; S-I, superior to inferior



**Figure 2: Overlapping of PTV volumes**  
Overlapping of PTV3D and PTV4D1.5cm in the abdomen region. Nonoverlapping region is in the superior to inferior direction

**Table 4: The averages doses in terms of percentages of prescribed dose for normal tissues for three different PTVs**

| <i>Thoracic region</i> |                  |                                  |                                |
|------------------------|------------------|----------------------------------|--------------------------------|
| <i>Normal tissue</i>   | <i>PTV3D (%)</i> | <i>PTV4D<sub>1.5cm</sub> (%)</i> | <i>PTV<sub>gated</sub> (%)</i> |
| Lung (V20)             | 18.32            | 16.5                             | 13.9                           |
| Lung (mean)            | 14.2             | 12.3                             | 10.7                           |
|                        | <i>PTV3D (%)</i> | <i>PTV4D<sub>1.5cm</sub> (%)</i> | <i>PTV<sub>gated</sub> (%)</i> |
| Kidney                 | 36.1             | 32.3                             | 30.4                           |
| Liver                  | 26.2             | 23.2                             | 20.9                           |

has the least lung mean dose and lung V20dose. For the PTV<sub>gated</sub> plan, V20 lung dose and lung mean dose was lesser than PTV3D by 24% and 25%, respectively. Similarly, for the PTV4D<sub>1.5cm</sub> plan, the lung V20 dose and lung mean dose were smaller than the PTV3D plan by 9.87% and 13.2%.

The same pattern of dose reduction was also observed for abdominal tumors. Mean dose for kidney and liver were listed for the PTV<sub>gated</sub> plan. Mean kidney dose reduction of 12% for the PTV<sub>gated</sub> plan and 16% for PTV4D<sub>1.5cm</sub> as compared with the PTV3D plan were observed.

Dose reduction is mainly due to the overlapping of PTVs and organ at risk. PTV<sub>gated</sub> has the smallest volume among the three PTVs and it has less overlapping with organ at risk. This has resulted in reduction in dose to the critical structures.

A review of the respiratory motion literature leads to the following conclusion. There are no general patterns of respiratory behavior that can be assumed for a particular patient prior to observation and treatment. The individual characteristics of breathing, like quiet versus deep, chest versus abdominal, healthy versus compromised, etc., and many motion variations associated with tumor location and pathology lead to distinct individual patterns in displacement, direction and phase of tumor motion.

Therefore, it is important to know the exact tumor motion to account for IM. Generalized IM increases the probability of not missing target and treating extra normal tissue. The PTV must account for all interfractional as well as intrafractional variations throughout a treatment course. It is not advisable to reduce the margins significantly. A careful approach to planning should be taken. Several sources of errors potentially remain, including (1) residual imaging artifacts, (2) setup variations, (3) delineation variations, (4) interfractional means tumor position variations and (5) treatment-induced changes in target size and motion patterns. The 4D target design eliminates systematic errors in CT imaging introduced by imaging a nonrepresentative target position during a standard helical scan.

Patient dose from 4DCT is a major concern because the total radiation dose for a 4DCT scan is eight-times the dose from a single conventional scan.<sup>[14]</sup>

## Conclusion

We have characterized tumor motion using 4DCT and found various tumor motion trajectories. This variability suggests that the use of 4DCT can improve the definition of the treatment target. Assuming an accurate internal motion on 4DCT images, IMs could be reduced from 1.0 cm to 0.5 cm. This will result in reduction of PTV volume and reduced chance of missing target and dose to critical structures.

With proper knowledge of trajectory of tumor motion, respiratory-gated treatment can reduce the irradiated volume and can spare more normal structures.

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