Int. J. Radiation Oncology Biol. Phys., Vol. 63, No. 1, pp. 253–260, 2005

0360-3016/05/$–see front matter

ELSEVIER

doi:10.1016/j.ijrobp.2005.05.045

PHYSICS CONTRIBUTION

USE OF MAXIMUM INTENSITY PROJECTIONS (MIP) FOR TARGET VOLUME GENERATION IN 4DCT SCANS FOR LUNG CANCER

René W. M. Underberg, M.D., Frank J. Lagerwaard, M.D., Ph.D., Ben J. Slotman, M.D., Ph.D., Johan P. Cuijpers, Ph.D., and Suresh Senan, M.R.C.P., F.R.C.R., Ph.D.

Department of Radiation Oncology, VU University Medical Center, Amsterdam, The Netherlands

Purpose: Single four-dimensional CT (4DCT) scans reliably capture intrafractional tumor mobility for radiotherapy planning, but generating internal target volumes (ITVs) requires the contouring of gross tumor volumes (GTVs) in up to 10 phases of a 4DCT scan, as is routinely performed in our department. We investigated the use of maximum intensity projection (MIP) protocols for rapid generation of ITVs.

Methods and Materials: 4DCT data from a mobile phantom and from 12 patients with Stage I lung cancer were analyzed. A single clinician contoured GTVs in all respiratory phases of a 4DCT, as well as in three consecutive phases selected for respiratory gating. MIP images were generated from both phantom and patient data, and ITVs were derived from encompassing volumes of the respective GTVs.

Results: In the phantom study, the ratio between ITVs generated from all 10 phases and those from MIP scans was 1.04. The corresponding center of mass of both ITVs differed by less than 1 mm. In scans from patients, good agreement was observed between ITVs derived from 10 and 3 (gating) phases and corresponding MIPs, with ratios of 1.07 ± 0.05 and 0.98 ± 0.05, respectively. In addition, the center of mass of the respective ITVs differed by only 0.4 and 0.5 mm.

Conclusion: MIPs are a reliable clinical tool for generating ITVs from 4DCT data sets, thereby permitting rapid assessment of mobility for both gated and nongated 4D radiotherapy in lung cancer. © **2005 Elsevier Inc.**

4DCT scans, Internal target volume, Lung cancer, Maximum intensity projection.

INTRODUCTION

Recent studies have shown that individualized planning margins are required to account for the variability and unpredictability of lung tumor motion (1–4). Four-dimensional (4D) radiotherapy has been defined as the explicit inclusion of temporal changes in anatomy during the imaging process, dose planning, and delivery of radiotherapy (5). Such spatial and temporal information on tumor mobility can be derived with single CT scan procedures such as "slow" CT scans (6–8) or respiration-correlated 4DCT scans (9–11). Both techniques allow for the generation of individualized internal target volumes (ITVs) for treatment planning (12), but 4D scans have the added advantage of permitting the retrospective selection of phases for gated radiotherapy (10, 13).

The need to contour tumors and/or normal organs in up to 10 phases of respiration is a major drawback to the routine clinical use of 4DCT scans. Our recent analysis revealed that significant changes in tumor volume can occur during fractionated stereotactic radiotherapy for Stage I non–small-cell lung cancer (14), which implies that repeat CT planning may be appropriate during 4D radiotherapy, thereby adding to the workload. Reliable autosegmentation tools are not yet available and remain the subject of active ongoing research (15, 16). We currently manually contour gross tumor volumes (GTVs) in all 10 phases of a 4D scan for planning stereotactic radiotherapy for Stage I lung cancer and derive ITVs from the volume encompassing these GTVs (11).

To reduce the workload of contouring multiple target volumes, we evaluated the postprocessing tools of maximum intensity projection (MIP) and minimum intensity projection (MinIP) for use with 4DCT data sets. Briefly, MIP projections reflect the highest data value encountered along the viewing ray for each pixel of volumetric data, giving rise to a full intensity display of the brightest object along each ray on the projection image. Conversely, MinIP projections reflect the lowest data value encountered along the viewing ray for each pixel of volumetric data. Both MIP

Reprint requests to: Frank J. Lagerwaard, M.D., Ph.D., Department of Radiation Oncology, VU University Medical Center, De Boelelaan 1117, 1007 MB Amsterdam, The Netherlands. Tel: (+31) 20-4440414; Fax: (+31) 20-4440410; E-mail: fj.lagerwaard@vumc.nl

Acknowledgments—The lung phantom was kindly provided by Mr. F. Gum of BrainLAB AG, Ammerthalstr. 8, 85551 Heimstetten, Germany.

Received Nov 10, 2004, and in revised form May 19, 2005. Accepted for publication May 20, 2005.

and MinIP are standard volume-rendering techniques used in diagnostic radiology (17–22), e.g., to extract high- or low-intensity structures such as blood vessels (18) from volumetric CT or MRI data. We compared ITVs derived from contouring GTVs in all respiratory phases (Fig. 1a) with MIPs generated from 4DCT data sets (Fig. 1b), for both a mobile phantom and patients.

METHODS AND MATERIALS

4DCT procedure

We routinely perform 4DCT scans for radiotherapy planning of lung tumors on a LightSpeed 16-slice CT scan (General Electric Co., Waukesha, WI) during quiet, uncoached respiration with an index and slice thickness of 2.5 mm. During the scanning procedure, respiratory signals are recorded using the Varian Real-Time Position Management respiratory gating hardware (Varian Medical Systems, Palo Alto, CA). The Real-Time Position Management system uses infrared-reflecting markers on the upper abdomen, which are illuminated by infrared-emitting diodes surrounding a camera. The camera captures the marker motion, and a respiratory signal is recorded in synchronization with the X-ray "on" signal from the CT scanner. The scanner is operated in axial cine mode, with multiple scans performed at each couch position for a duration that is at least equal to the length of the patient's respiratory cycle. Each image from the acquired data set is sorted into one of 10 phase bins using the Advantage 4DCT application running on an Advantage Workstation 4.1 (General Electric Co., Waukesha, WI). The phase bins are, to a good approximation, evenly spaced in time over the respiratory cycle.

Motion phantom

As the initial step, MIP and MinIP images were generated from the raw (i.e., nonphase-sorted) data of 4DCT scans performed on a motion phantom, which consisted of a human body–like torso with lungs and a bone-equivalent spine model. The phantom was filled with water to have human body equivalent properties for CT scanning and dose measurements. A 3-cm-large silicon tumor substitute attached rigidly to a metal cylinder was positioned in the left side of the phantom, which could move longitudinally by approximately 1.5 cm. For detecting an external breathing signal, a vertically movable board holding infrared reflective markers was mounted above the phantom chest. Both the board and the tumor were moved under computer control by independent servo drives, and the software permitted the simulation of a simple sinusoidal breathing curve. The silicon tumor substitute was contoured on both the MIP and MinIP data sets, and these results were compared with manual contouring of all 10 phases from the 4DCT scan. These target volumes were compared also to those generated using a "slow" CT scan performed with a CT revolution time of 4 s.

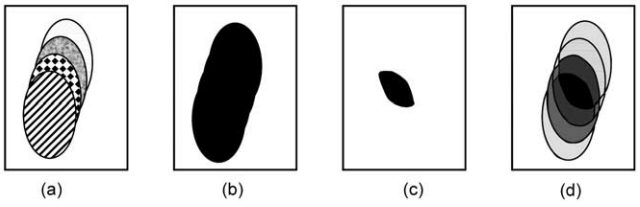

Fig. 1. Pixel-based intensity projection protocols from four-dimensional computed tomography (CT) data sets of a mobile tumor, illustrating (a) separate phases of the four-dimensional CT, (b) maximum intensity projection, (c) minimum intensity projection, and (d) mean intensity projection.

Table 1. Tumor characteristics

Tumor	T stage	Mean gross tumor volume (cc)	Location	3D mobility vector (mm)
A	T1	3.9	Left lower lobe	23.6
B	T1	1.5	Right upper lobe	11.3
C	T2	8.1	Left upper lobe	4.3
D	T1	4.9	Left lower lobe	11.6
E	T1	3.3	Right upper lobe, adjacent to hilus	5.3
F	T1	2.1	Right upper lobe	10.9
G	T1	2.0	Left lower lobe, adjacent to hilus	12.0
H	T1	2.9	Left lower lobe	29.5
I	T2	37.2	Right lower lobe, adjacent to chest wall	24.2
J	T1	0.7	Left upper lobe	2.9
K	T1	2.3	Right upper lobe, adjacent to chest wall	2.5
L	T1	1.5	Left lower lobe	16.0

Patient study

A retrospective analysis was performed on 4DCT scans from 11 patients with 12 relatively mobile peripheral Stage I lung tumors that were treated with stereotactic radiotherapy (Table 1). The 3D mobility vectors of tumors were determined by manual contouring of GTVs in all phases of the 4DCT scans, and these ranged from 2.5 to 29.5 mm. To evaluate the performance of the MIP software, we included tumors at different anatomic locations in the lung, including the hilus and lesions adjacent to the chest wall. GTVs were manually contoured on all 10 phases of the 4DCT scan using standard window/level settings. A window consisting of three consecutive phases at end-expiration was selected for respiratory

Table 2. Summary of different internal target volumes used

Volume	Definition
$ITV_{10\ phases}$	ITV derived from contouring of all 10 phases of the 4DCT
$ITV_{3\ phases}$	ITV derived from contouring of 3 consecutive phases at end-expiration
$ITV_{MIP\ 10\ phases}$	ITV derived from maximum intensity projection of all 10 phases of the 4DCT
$ITV_{MIP\ 3\ phases}$	ITV derived from maximum intensity projection of 3 consecutive phases at end-expiration
ITV_{MinIP}	ITV derived from minimum intensity projection of all 10 phases of the 4DCT
$ITV_{slow\ CT}$	ITV derived from single "slow" CT scan
$ITV_{overlap\ 10\ phases}$	ITV derived from contouring the volume that was common to all 10 4D phases

Abbreviations: ITV = internal target volume; 4DCT = four-dimensional CT.