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CINE COMPUTED TOMOGRAPHY WITHOUT RESPIRATORY SURROGATE IN PLANNING STEREOTACTIC RADIOTHERAPY FOR NON–SMALL-CELL LUNG CANCER

Adam C. Riegel, B.A.,* Joe Y. Chang, M.D., Ph.D.,† Sastry S. Vedam, Ph.D.,‡
Valen Johnson, Ph.D.,*§ Pai-Chun Melinda Chi, Ph.D.,‡ and Tinsu Pan, Ph.D.*‡

Departments of *Imaging Physics, †Radiation Oncology, ‡Radiation Physics, and §Biostatistics,
University of Texas M.D. Anderson Cancer Center, Houston, TX

Purpose: To determine whether cine computed tomography (CT) can serve as an alternative to four-dimensional (4D)-CT by providing tumor motion information and producing equivalent target volumes when used to contour in radiotherapy planning without a respiratory surrogate.

Methods and Materials: Cine CT images from a commercial CT scanner were used to form maximum intensity projection and respiratory-averaged CT image sets. These image sets then were used together to define the targets for radiotherapy. Phantoms oscillating under irregular motion were used to assess the differences between contouring using cine CT and 4D-CT. We also retrospectively reviewed the image sets for 26 patients (27 lesions) at our institution who had undergone stereotactic radiotherapy for Stage I non–small-cell lung cancer. The patients were included if the tumor motion was >1 cm. The lesions were first contoured using maximum intensity projection and respiratory-averaged CT image sets processed from cine CT and then with 4D-CT maximum intensity projection and 10-phase image sets. The mean ratios of the volume magnitude were compared with intraobserver variation, the mean centroid shifts were calculated, and the volume overlap was assessed with the normalized Dice similarity coefficient index.

Results: The phantom studies demonstrated that cine CT captured a greater extent of irregular tumor motion than did 4D-CT, producing a larger tumor volume. The patient studies demonstrated that the gross tumor defined using cine CT imaging was similar to, or slightly larger than, that defined using 4D-CT.

Conclusion: The results of our study have shown that cine CT is a promising alternative to 4D-CT for stereotactic radiotherapy planning. © 2009 Elsevier Inc.

Four-dimensional computed tomography, 4D-CT, Cine computed tomography, Contouring.

INTRODUCTION

Respiratory motion remains a large source of uncertainty in planning radiotherapy for non–small-cell lung cancer (NSCLC), and standard helical computed tomography (CT) can induce artifacts when imaging thoracic lesions under the influence of respiratory motion (1). Managing respiratory motion, however, can be a complicated and expensive endeavor (2, 3). The American Association of Physicists in Medicine Task Group 76 (2) has provided several alternatives for ‘‘motion-encompassing’’ methods of CT scanning, including breath-hold CT, which often differs from the natural inspiration and expiration of normal breathing (4), and slow-CT scanning (5), which produces reconstruction artifacts (6).

Four-dimensional CT (4D-CT) overcomes these issues by collecting multiple images at a single couch position, thereby capturing different phases of the respiratory cycle (7–10). Normally, 10 three-dimensional image sets, representing 10 phases in the respiratory cycle, are formed. Several studies have shown that 4D-CT is useful in implementing 4D treatment planning (11–14). Recently, 4D-CT was demonstrated to be effective in target definition for stereotactic radiotherapy (SRT) for NSCLC (14, 15), and 4D-CT is currently used at our institution for this purpose.

Although 4D-CT is useful, its implementation could be costly for some clinics. The setup cost for General Electric 4D-CT includes a respiratory surrogate, commercial software, and a proprietary workstation, in addition to the scanner itself. The cost of this additional hardware and software can be as great as the cost of a CT scanner without 4D-CT.

In the present study, we investigated the potential of making 4D-CT–caliber imaging more accessible by offering an

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Reprint requests to: Tinsu Pan, Ph.D., Department of Imaging Physics, Unit 56, University of Texas M.D. Anderson Cancer Center, 1515 Holcombe Blvd., Houston, TX 77030. Tel: (713) 563-2714; Fax: (713) 563-2720; E-mail: tpan@mdanderson.org

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alternative approach to obtaining tumor motion information that does not use 4D-CT and yet accomplishes most of the functions of 4D-CT imaging. We propose the use of the maximum intensity projection (MIP) and respiratory-averaged CT (RA-CT) images directly obtained from cine CT data, the unsorted images from which 4D-CT phase images are selected (16, 17), together for radiotherapy planning. Our approach does not rely on any respiratory surrogate measurement device and thus would be applicable to all clinics with a GE LightSpeed multislice CT (MSCT) scanner (GE Health Care, Waukesha, WI). Because cine CT is a standard feature on all GE LightSpeed MSCT scanners and approximately several thousand of these scanners are available in clinics worldwide, our approach, if validated, could potentially be implemented on a widespread basis with dedicated additional software and no additional hardware. Previously, we qualitatively explored the use of MIP and RA-CT together for contouring small lesions (17). The purpose of the present study was to quantitatively compare contour delineation using standard 4D-CT imaging (including MIP) vs. our proposed cine CT method (contouring with cine MIP and cine RA-CT together) and to demonstrate their potential equivalence for a population of NSCLC patients who underwent SRT.

This task was undertaken in two steps. First, phantom scans were used to explore the differences between cine CT and 4D-CT imaging. Second, Stage I NSCLC lesions in patients who had received SRT were contoured on cine CT and 4D-CT image sets to determine whether the resulting target volumes were equivalent.

METHODS AND MATERIALS

Cine acquisition and image processing

The acquisition of 4D-CT images by GE scanners operating in cine mode has been previously described (7, 10). In brief, cine mode scanning uses a stationary couch while the X-ray beam is on. The gantry goes through multiple revolutions at each couch position for the duration of one breath cycle plus 1 s, continuously collecting projections of the subject. The stream of data is retrospectively reconstructed into 20–50 images at each couch position called cine CT images.

To create the 4D-CT images, the cine CT images are correlated with the patient's respiratory cycle, which is indicated by the trace of a respiratory surrogate, such as a spirometer (8), an abdominal pressure belt (18), or an external fiducial marker tracking system, such as the RPM system (Varian, Palo Alto, CA), which was used in this study. Ten images are selected to represent the 10 phases of the respiratory waveform at each couch position. This process, called ''phase binning,'' culminates in 10 three-dimensional image sets that represent 10 specific phases of the respiratory cycle, which are collectively referred to as the 4D-CT image set.

The MIP of a 4D-CT image set finds the largest CT value across the 10 phases of the respiratory cycle for every voxel and displays it in a single three-dimensional image set (7). Simply stated, if a lung tumor is present at a certain location in any of the 10 phases, it will show up in the MIP. Studies have demonstrated the similarity of volumes contoured on 4D-CT MIP and 4D-CT phase images (19, 20).

The same process can be used to form a MIP from cine CT except that all the cine images at each slice location are used, not only the images that have been sorted into the 10 phases. Thus, cine MIP is produced from many more images (between 20 and 50) than 4D-CT MIP (10 images, 1 per phase). As in 4D-CT, if the tumor is present in any of these images, it will appear on the MIP.

Gross tumor contouring on the MIP essentially includes delineation of the tumor's physiologic motion during respiration. This new gross tumor volume, which we have called the internal gross tumor volume (IGTV), includes patient-specific motion information derived from CT imaging. In this report, the source of an image set or target volume is denoted in a subscript after the volume or image set name, such as $\text{MIP}_{\text{4D-CT}}$ to denote MIP processed from 4D-CT, or $\text{IGTV}_{\text{cine}}$ to denote IGTV contoured on cine CT image sets.

One drawback of contouring on the MIP is that the surrounding structures can ''overwrite'' the CT value recorded by a moving tumor. For example, the motion paths of the liver and a tumor in the lower lobe of the lung could overlap, and, because the tumor and liver are of similar density, a loss of contrast between them occurs in the resulting images. This problem has been noted by several investigators, who have recommended caution when using MIP in these circumstances (19–21).

Respiratory-averaged CT was originally intended for attenuation correction of positron emission tomography (PET) in thoracic PET-CT imaging (4, 16, 22). In 4D-CT, RA-CT is a temporal arithmetic average of the 10 phase image sets at each slice location, which results in a blurred appearance. In the case of a solitary lung lesion, the CT numbers are roughly proportional to the interval the voxel is occupied by tumor (23). Again, the same process can be applied to cine CT, except using all the cine images at a slice location. This technique has been successfully applied to attenuation correction CT for cardiac PET-CT (16). A diagram comparing $\text{RA-CT}_{\text{4D-CT}}$ and $\text{RA-CT}_{\text{cine}}$ generation is shown in Fig. 1.

Cover *et al.* (23) used $\text{RA-CT}_{\text{4D-CT}}$ to assess tumor motion. We investigated the use of $\text{RA-CT}_{\text{cine}}$ to provide contrast in situations in which the motion extent on the MIP is obscured by surrounding tissue and had promising qualitative results (17). In the present study, we show quantitatively that using MIP_{cine} and $\text{RA-CT}_{\text{cine}}$ together provides sufficient data for radiotherapy target definition even in cases in which the lesion is adjacent to tissue of equal or greater density.

Phantom study

The objective of the phantom study was to show that MIP_{cine} captured the full extent of irregular motion more precisely than $\text{MIP}_{\text{4D-CT}}$ (*i.e.,* show that the volumes segmented on $\text{MIP}_{\text{4D-CT}}$ are smaller than those from MIP_{cine}).

We scanned a NEMA IEC 2001 phantom (Data Spectrum, Chapel Hill, NC) that contained six water-filled spheres using a GE Discovery ST PET-CT scanner, the CT portion of which is a LightSpeed eight-slice scanner. The phantom was placed on a platform driven by a single-axis stepper motor (Velmex, Bloomfield, NY) for one-dimensional motion. The irregular motion (previously described by Starkschall *et al.* [24]) was nearly sinusoidal, with the amplitude and frequency, respectively, varying from 0.7 to 1.10 cm and 15 to 20 cycles/min. Ten cine scans were acquired with the following cine scan protocol: 120 kV, 50 mA, 2.5-mm slice thickness, gantry rotation of 0.5 s, cine interval of 0.2 s, and cine duration of 7.5 s (twice the average breathing cycle of the irregular pattern plus one gantry rotation). MIP_{cine} and $\text{MIP}_{\text{4D-CT}}$ were reconstructed.

A threshold of −700 Hounsfield units was used to segment the IGTV on both MIP_{cine} and $\text{MIP}_{\text{4D-CT}}$. Volume measurements