Int. J. Radiation Oncology Biol. Phys., Vol. 76, No. 1, pp. 303–312, 2010

0360-3016/10/$–see front matter

doi:10.1016/j.ijrobp.2009.05.026

PHYSICS CONTRIBUTION

COMPARISON OF RESPIRATORY-GATED AND RESPIRATORY-UNGATED PLANNING IN SCATTERED CARBON ION BEAM TREATMENT OF THE PANCREAS USING FOUR-DIMENSIONAL COMPUTED TOMOGRAPHY

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Purpose: We compared respiratory-gated and respiratory-ungated treatment strategies using four-dimensional (4D) scattered carbon ion beam distribution in pancreatic 4D computed tomography (CT) datasets.
Methods and Materials: Seven inpatients with pancreatic tumors underwent 4DCT scanning under free-breathing conditions using a rapidly rotating cone-beam CT, which was integrated with a 256-slice detector, in cine mode. Two types of bolus for gated and ungated treatment were designed to cover the planning target volume (PTV) using 4DCT datasets in a 30% duty cycle around exhalation and a single respiratory cycle, respectively. Carbon ion beam distribution for each strategy was calculated as a function of respiratory phase by applying the compensating bolus to 4DCT at the respective phases. Smearing was not applied to the bolus, but consideration was given to drill diameter. The accumulated dose distributions were calculated by applying deformable registration and calculating the dose–volume histogram.
Results: Doses to normal tissues in gated treatment were minimized mainly on the inferior aspect, which thereby minimized excessive doses to normal tissues. Over 95% of the dose, however, was delivered to the clinical target volume at all phases for both treatment strategies. Maximum doses to the duodenum and pancreas averaged across all patients were 43.1/43.1 GyE (ungated/gated) and 43.2/43.2 GyE (ungated/gated), respectively.
Conclusions: Although gated treatment minimized excessive dosing to normal tissue, the difference between treatment strategies was small. Respiratory gating may not always be required in pancreatic treatment as long as dose distribution is assessed. Any application of our results to clinical use should be undertaken only after discussion with oncologists, particularly with regard to radiotherapy combined with chemotherapy. © 2010 Elsevier Inc.

Carbon beam, Computed tomography, Four-dimensional, Pancreas, Treatment planning.

INTRODUCTION

Organ positional and geometric variations resulting from intrafractional respiratory motion degrade treatment accuracy in two ways, first by moving the tumor out of the beam field, and second by altering the radiologic pathlength (WEL = water-equivalent length) from the patient surface to the tumor (1–9). These effects degrade dose conformation in scattered and scanned charged particle beams, and also in photon beam treatments such as intensity-modulated radiotherapy and Cyberknife.

Several techniques to mitigate dose variation due to intrafractional respiratory motion have been recently introduced (10–16). Among these, respiratory-gated irradiation delivers the treatment beam at the most reproducible respiratory phase, which generally occurs around exhalation (17), and findings from several treatment centers have now been implemented (18, 19). Our previous study using four-dimensional computed tomography (4DCT) datasets in lung cases reported that WEL variation was caused by intrafractional respiratory motion (2) and that this variation could be minimized by respiratory-gated treatment (2). Although a single case was presented at the 2008 meeting of the American Society for Therapeutic Radiology and Oncology (20), we are unaware of any comprehensive comparison of respiratory-gated and respiratory-ungated treatment strategies in abdominal regions using charged particle beam.

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Received Sept 18, 2008, and in revised form May 23, 2009. Accepted for publication May 26, 2009.

Table 1. Patient characteristics

Pt. no	T-stage		Location	COM movement (cm) (PE-PI)	GTV volume ratio (Tn/T50)	
					Ungated treatement	Gated treatement
1	T4NOMO	3	pancreas body	1.0	0.92-1.04	0.95-1.04
2	T4N2MO	3	pancreas tail	0.6	0.94-1.27	1.00-1.05
3	T4NOMO	3	pancreas body-tail	0.4	0.88-1.00	0.90-1.00
4	T4NOMO	3	pancreas head	1.7	0.94-1.03	0.94-1.00
5	T4NOMO	3	pancreas head	1.2	0.93-1.00	0.94-1.00
6	T4NOMO	3	pancreas head	0.8	0.89-1.04	1.00-1.04
7	T4NOMO	3	pancreas head	0.7	0.85-1.00	0.89-1.00
Average				0.9	0.9-1.1	0.9-1.0

Abbreviations: ADC = adenocarcinoma; COM = center of mass; PE = peak exhalation; PI = peak inhalation; GTV = gross tumor volume; T50 = peak exhalation; Tn = respiratory phase.

When gas is not present in the bowel, the abdominal region is filled with tissue of almost uniform density. Here, WEL variation due to respiratory motion may be less problematic than in the lung region, where lung tumors are surrounded by low-density tissue. Against this, however, tumors in the abdominal region occur more closely to organs at risk (OARs) than do those in the thoracic region. Dosimetric comparison of the two treatment strategies is therefore clinically relevant in both charged particle and photon beam therapy.

Current treatment planning systems remain three-dimension based but optimize treatment parameters for a single respiratory phase only. Because thoracic and abdominal treatments are performed under free-breathing conditions, however, comparison of strategies throughout the treatment course should include information on respiratory phase, in other words the fully complete 4D dose calculation, including deformable registration (21–26). This is particularly important because radiation oncologists and medical physicists more easily understand the results of single-dose assessment (accumulated dose), including time information, than results for several dose assessments conducted at discrete respiratory phases.

Here, to compare respiratory-gated and respiratory-ungated treatment strategies using 4DCT datasets, we evaluated 4D scattered carbon ion beam distribution in the pancreatic region.

METHODS AND MATERIALS

Patients

The participants in this study were 7 patients with pancreatic tumors randomly selected from inpatient pancreatic cancer patients (adenocarcinoma; mean age $\pm$ SD, 60.9 $\pm$ 5.8 y) at our hospital who were receiving carbon ion beam treatment with chemotherapy (Table 1). All gave informed consent to participate in the study, which was approved by the Institutional Review Board of the National Institute of Radiological Sciences.

Treatment planning

To evaluate the two treatment strategies in the pancreatic region, we performed 4D treatment planning using carbon ion beam. The 4D treatment planning with photon beam involves assessing geometric motion to cover the internal target volume (ITV) and defining a monitor unit value at the reference point (27). Given the finite range of carbon ion beam and other charged particle beams, 4D treatment planning with these beams should also consider induced WEL variations due to respiratory motion. In this section, we describe the 4D treatment planning process (imaging, target definition, bolus design, and dose calculation), including respiratory motion.

Four-dimensional CT imaging. To acquire volumetric CT data as a function of time, 4DCT scanning was done under free-breathing conditions using a rapidly rotating cone-beam CT (CBCT). To minimize anxiety that would perturb the stable breathing pattern (*e.g.,* respiratory cycle, baseline drifts), 4DCT scanning was done after a 10-minute rest in the supine position on the CT bed. The CBCT was an integrated two-dimensional wide cylindrical detector (256 slices) with high spatiotemporal resolution (28, 29). Inasmuch as the scan range of this equipment in the superior–inferior direction is about 12 cm in a single rotation, the patient bed was not moved during 4DCT scanning. Because the CT volume obtained in this study was not a composite of several breathing cycles, 4DCT resorting errors did not occur, and 4DCT image quality was not affected by irregular breathing. Patients were fixed on the patient bed with immobilization (body cast in supine position) in accordance with routine practice in our center. The respiratory signal was acquired using a respiratory sensing system consisting of a position-sensitive detector sensor and infrared-emitting light marker (Toyonaka Kenkyujo, Osaka, Japan) (18) affixed to the patient's abdomen. Scan conditions were slice collimation of 128 $\times$ 1.0 mm, 0.5 sec in a single rotation, and scan time of less than 6 sec to obtain one respiratory cycle.

Volumes from the 4DCT datasets were classified into 10 phases (T0: peak inhalation, T50: peak exhalation) based on the amplitude of the respiratory signal. We chose an amplitude-based phase assignment method because of the greater accuracy of amplitude-based gated treatment over phase-based gating in clinical situations (30, 31).

Contouring. The gross tumor volume (GTV) and clinical target volume (CTV), which included the GTV plus a 5-mm margin and tumor encasement of the celiac trunk and/or superior mesenteric artery, pancreas, kidneys (right and left), and duodenum, were manually contoured on the CT data at peak exhalation (T50) by a certified oncologist (R.H. or T.Y.) with more than 10 years' clinical experience. All contours at other respiratory phases were then automatically calculated by B-Spline-based deformable registration (32). This registration calculates transformation maps based on the 4DCT data, which are then applied to the contours to transform