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EFFECTIVE DOSES IN FOUR-DIMENSIONAL COMPUTED TOMOGRAPHY FOR LUNG RADIOTHERAPY PLANNING

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Abstract—The recent broad adoption of 4-D computed tomography (4DCT) scanning in radiotherapy has allowed the accurate determination of the target volume of tumors by minimizing image degradation caused by respiratory motion. Although the radiation exposure of the treatment beam is significantly greater than that of CT scans used for treatment planning, it is important to recognize and optimize the radiation exposure in 4DCT from the radiological protection point of view. Here, radiation exposure in 4DCT was measured with a 16 multidetector CT. Organ doses were measured using thermoluminescence radiation dosimeter chips inserted at respective anatomical sites of an anthropomorphic phantom. Results were compared with those with the helical CT scan mode. The effective dose measured for 4DCT was 24.7 mSv, approximately four times higher than that for helical CT. However, the increase in treatment accuracy afforded by 4DCT means its use in radiotherapy is inevitable. The patient exposure in the 4DCT could be of value by clarifying the advantage of the treatment planning using 4DCT. © 2009 American Association of Medical Dosimetrists.

Key Words: **Computed tomography, Four-dimensional, Respiratory, Radiotherapy, Radiation dose.**

INTRODUCTION

Improvement of treatment accuracy requires an accurate definition of the target in treatment planning computed tomography (CT) images. Although the helical scan method can obtain 3-D data beyond the coverage of a single scan rotation, respiratory phase–based data acquisition is limited because of time-based variations in images at each couch position.[1,2] In consequence, the shapes of objects shown on helical CT images are distorted because of inconsistencies in time-dependent data, hampering accurate recognition of the target's geometrical shape.[3] To solve this, respiratory-correlated CT scan methods have been developed, such as 4-D CT (4DCT), which minimizes image quality degradation caused by respiratory motion and provides 3-D CT images for each respiratory phase.[4] The use of 4DCT data also allows the internal target volume (ITV) to be determined. In addition to observing intrafractional motion, repeated 4DCT is useful for the observation of interfractional changes in the thorax and abdomen regions over the course of treatment.[5]

Although the radiation exposure of the treatment beam is significantly greater than that of CT scans used for treatment planning, it is beneficial for the patients. Similarly, the radiation exposure of the 4DCT is also greater than that of 3DCT used for treatment planning. However, 4DCT plays an important role in radiotherapy treatment planning for the thorax and abdomen regions. The number of hospitals using 4DCT will increase. However, radiation oncologist, physicist, and dosimetrist should recognize the radiation exposure in 4DCT and optimize 4DCT scan protocols from the radiological protection point of view for patients who are expected to have a long survival or those at especially high risk of pneumonitis.

Because the photon energy and dose (order of MV) are greater for the treatment beam compared with the kV photon energy and dose from the CT scanner, skin surface dose from CT could be increased rather than organ dose.

The clinically relevant question is what dose from 4DCT is of value in radiotherapy. To solve this, we used an anthropomorphic phantom, not computed tomography dose index (CTDI) phantom, to assess the radiation dose exposure of organs during 4DCT imaging with a 16 multidetector CT (16MDCT) and compared the results with those from helical CT scan mode.

METHODS AND MATERIALS

Scan mode

Two scan modes were used for radiation dose measurements: helical CT[6] and 4DCT.[4,7]

The helical CT mode uses continuous scanning with simultaneous table movement, allowing the successful collection of imaged volume data. This method is now routinely used by most hospitals for diagnosis. However, because the images obtained differ over time at each

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Table 1. Scan conditions for 4DCT and helical CT scan modes

Items	Scan Mode 4D	 Helical
Tube voltage (kV)	120	120
Tube current (mA)	120	165
Scan time (s)	4	0.8
Rotation time (s)	0.8	0.8
Total scan time (s)	75	9.6
Beam width (mm)	20	20
Pitch	N/A	1.375
Slice collimation (mm)	16 × 1.25	16 × 1.25
Scan region (mm)	300	300

couch position, the acquisition of time-based information is restricted.

In contrast, 4DCT mode takes respiration-induced organ motion directly into account in the treatment plan. This method is used by several hospitals for radiotherapy planning in the thorax and abdominal regions. 4DCT performed in cine mode, in which the scanner operates without couch movement, acquires one respiration cycle of CT data at each couch position before moving to the next position. CT images for each couch position are then sorted for the same respiration phase using respiratory signals from a monitoring system such as a real-time position management (RPM) Respiratory Gating System (Varian Medical Systems, Palo Alto, CA, USA).[8–10]

CT scans for both modes were performed on a 16MDCT (LightSpeed 16-slice QX/i, General Electric Company, Waukesha, WI, USA). To obtain the same image quality in both scan modes, we selected the X-ray tube voltage of 120 kV and the identical effective mA value of 96 mAs, calculated as the tube current (mA) × rotation time (s)/helical pitch. Scan conditions in the two scan modes were identical, except for scan time and helical pitch. Auto-exposure control systems (AECs), which aim to prevent over and underdosing, as well as improve image quality by modulating tube current in either or both craniocaudal and angular modulation, were not adopted.

In clinical cases, information on the respiratory cycle of patients is obtained by clinical respiratory monitoring to allow scanning in a single respiratory cycle. However, because the anthropomorphic phantom does not breathe, a scan time of 4 sec per couch position in 4DCT was selected, based on the average human respiration cycle of approximately 4 sec. Scan conditions are detailed in Table 1.

Dosimetry

The anthropomorphic phantom used for organ and tissue dose measurement consisted of 34 sections of 2.5-cm thickness, each designed to simulate a human body measuring 164 cm and weighing 54 kg (Kyoto Kagaku Co., Japan). The phantom components, equivalent in density to humans, were composed of soft tissue (1.01 g/cm^3, 3.25 × 10^{23} e$^-$/g), lung (0.3 g/cm^3, 3.31 × 10^{23} e$^-$/g), and bone (1.24 g/cm^3, 3.21 × 10^{23} e$^-$/g). Organ and tissue doses were measured using two models of glass-encapsulated TLD, a Panasonic UD-170A (BeO), and UD-110S ($CaSO4{:}T_m$). TLD dose measurements were evaluated within 48 h after CT scanning, using a commercial analyzer (UD-5160P, Matsushita, Japan).

We measured a half value layer using the same 16MDCT at the center of rotation axis and peripheral position. The effective energy is 52–76 keV from this measurement. Calibrations, therefore, were done in and on a Tough-water phantom (Kyoto-kagaku, Kyoto, Japan) using X-ray energy from 52–76 keV, which can cover the energy of the 4DCT scan at 120 kV, as we measured (unpublished data).

The doses at each TLD position were determined using an ionization chamber calibrated by the National Institute of Advanced Industrial Science and Technology in Japan. Dose measurements were performed in respective organs and tissues, with tissue weighting factors described in the Recommendation of the International Commission on Radiological Protection (ICRP60), and the absorbed dose is expressed in mGy and the effective dose was calculated in mSv, in accordance with ICRP60.[11] Dose measurement was performed one time.

RESULTS

Organ, tissue, and effective doses for helical and 4DCT scans are summarized in Table 2. Because the large number of TLDs inserted into each organ resulted in large variations in organs, such as in the upper and lower lung, standard deviations for the location statistics were calculated rather than measurement reproducibility.

Critical organ doses in the esophagus, thyroid, and other organs in 4DCT were significantly higher than in the helical CT mode. The average organ dose in 4DCT was approximately 3.9 times higher than in helical CT. Scattered radiation from the CT scan in the lung region reached the eye lens, with doses of 1.2 mGy and 0.3 mGy for the 4-D and helical modes, respectively. The effective doses in the 4-D and helical CT were 24.7 mSv and 6.1 mSv, respectively.

Because the 4DCT continuously irradiates with low-energy X-rays of 40~60 keV at the same position, skin doses were also assessed. Average skin doses were 59.8 mGy and 12.2 mGy for the 4-D and helical CTs, respectively.

DISCUSSION

In this study, we evaluated organ doses in 4DCT and compared the results with those for helical CT using an anthropomorphic phantom. Results showed that, with an estimated average respiration cycle of 4 sec, effective organ doses in 4DCT were approximately four times higher than in helical CT. The effective dose measured in 4DCT (24.7 mSv) was closely similar to that in electrocardiogram-gated coronary artery CT imaging (22.7