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Scientific Article

Model evaluation of rapid 4-dimensional lung tomosynthesis

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Abstract

Purpose: This is an investigation of a lung motion digital tomosynthesis (DTS) model using combined stationary detector and stationary cold cathode x-ray sources at projection acquisition rates that exceed the present norms. The intent is to reduce anatomical uncertainties from artifacts inherent in thoracic 4-dimensional computed tomography (CT).

Methods and materials: Parameters necessary to perform rapid lung 4-dimensional DTS were studied using a conventional radiographic system with linear motion of the x-ray source and a simple hypothetical hardware performance model. Hypothetical rapid imaging parameters of sweep duration, projections per second, pulse duration, and tube current (mA) were derived on the basis of 0.5 mm and 1 mm motion captures per phase, 10 and 15 breaths per minute (bpm), 10 to 40 mm breathing amplitude, and 2 signal-to-noise ratio (SNR) levels. Anterior-posterior and lateral projection images of a normal size anthropomorphic thorax phantom with iodine contrast inserts were collected and reconstructed with an algebraic algorithm to study the effects of reduced x-ray output associated with field emission cold cathodes composed of carbon nanotubes or metal Spindt-type. Radiographic projections were collected at 3 SNR levels that were set at standard clinical DTS milliampere-seconds (mAs) and reduced corresponding to 50% and 25% standard DTS mAs to simulate a reduced x-ray output.

Results: The DTS SNR of the inserts was superior in all reconstructions at clinical mAs versus automatic exposure-control radiographs and superior in 3 of 4 at the 50% and 25% mAs levels. The most demanding performance parameters corresponding to 40 mm amplitude, 15 bpm, 0.5 mm motion capture limit, and 61 projections were sweep duration (10.4 msec), projection rate (5862 projections per second), pulse duration (0.161 msec), current 189 mA anterior-posterior, and 653 mA lateral.

Conclusions: Feasibility depends on the output performance of stationary cold cathode hardware being developed for DTS. Present image receptor technology can accommodate frame acquisition rates.

Introduction

Stereotactic body radiation therapy (SBRT) requires accurate delineation of the internal target volume. Lung SBRT simulation involves 4-dimensional computed tomography

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(CT), often with iodine contrast administered. The advantage of 4-dimensional CT is the target localization during respiration, assuming the simulation breathing pattern is repeated during treatment. There are several approaches for performing 4-dimensional CT to this end: helical or cine, prospectively or retrospectively, with amplitude-based or phase-based reconstruction.[1] Four-dimensional CT is often accompanied by artifacts that can be grouped into 4 types: blurring, duplicate structure, overlapping structure, and incomplete structure.[2] Intrinsic causes are organ motion exceeding the temporal resolution of the scanner and changes in respiration rate or amplitude over the course of a complete scan wherein the body is imaged in sections over several breathing cycles that encompass irregular respiration.

Lung digital tomosynthesis (DTS) has been investigated as a modality for pulmonary nodule detection and management.[3] However, nodules are not necessarily indicative of cancer and play no role in SBRT target delineation.[4-6] The application of DTS to nodule detection lends support to inclusion in treatment planning. Investigations into stationary x-ray sources for gated chest DTS were conducted at the University of North Carolina at Chapel Hill.[7-9] Shan et al focused on prospective gated chest DTS using stationary carbon nanotube x-ray sources.[9] Their study captured 10 breaths per minute (bpm), end of exhalation images at 30 projections per second (pps), 80 kVp, 5 mA anode current, 25 and 50 milliseconds per projection pulse, and 5 projections per respiration cycle with the whole sequence requiring 36 seconds across 6 respiration cycles.

Studies have been published on radiation therapy guidance DTS. Maurer et al proposed linac on-board 4-dimensional DTS using respiratory-correlated cone beam CT projections and found greater craniocaudal motion artifact suppression relative to 4-dimensional CT.[10] Hsieh and Ng proposed linac gantry-mounted DTS to provide real-time guidance at up to 30 frames per second.[11] Zhang et al proposed lung localization during linac radiation therapy via DTS reconstructions from 4-dimensional CT simulation, phase-matched, digitally reconstructed radiographs and DTS images from cone beam CT collected at treatment.[12] Zhang et al later published a phase-matched, orthogonal-view, retrospective study that showed a tumor localization average error of 1.8 ± 0.7 mm and a phantom study error within 1 mm.[13] Santoro et al compared linac on-board imaging respiration-correlated DTS from cone beam CT projections with respiration-correlated cone beam CT to determine tumor position, motion extent, and displacement between treatment sessions and found agreement, in most cases within 2 to 3 mm.[14] Maltz et al published a fixed-gantry DTS guidance system using a multisource x-ray tube with carbon nanotube cathodes.[15]

Rapid 4-dimensional DTS in SBRT planning requires capture of multiple phases over a single breathing cycle. This paper explores the performance requirements using multiphase or multiamplitude capture with constraints on allowable lung tissue displacement per phase. Rapid 4-dimensional DTS offers the advantages of capturing full craniocaudal and lateral extent in the coronal projections, plus the full anterior-posterior (AP) extent in sagittal projections, with a user-selected maximum range of craniocaudal motion within each phase, which was selected here as 0.5 and 1 mm. Capturing all phases and anatomy in a single breathing cycle preserves the spatiotemporal integrity of tissue, which can be compromised in multicycle, slow 4-dimensional DTS and provides a direct link between lung and diaphragm motion.

In 4-dimensional CT, amplitude and rate variations coupled with scan volume limitations leads to artifacts. For example, inhalation rate or amplitude may vary between different sections of the lung in the craniocaudal direction as the z-limited beam passes over. Lung hysteresis is affected by differences in breathing amplitudes and rates, all of which are patient specific and variable, making tumor motion prediction difficult.[16] The working premise in rapid 4-dimensional DTS is that spatiotemporal uncertainties in 4-dimensional CT can be reduced or eliminated by single-cycle imaging of the entire lung, provided the patient can perform a single good breathing cycle.

Rapid 4-dimensional DTS will limit motion artifacts and provide high resolution in the coronal and sagittal reconstruction planes. Spatial resolution in the reconstruction plane will depend on geometric blur and flat-panel detector dexel pitch. In-plane resolution in the coronal and sagittal planes can facilitate precise target segmentation. The approximate 1 cm slice thickness inherent in DTS can be compensated by orthogonal projections, with Boolean merger of segmentations from orthogonal image sets compensating for lower resolution in the orthogonal depth direction.[13] Four-dimensional CT will continue to provide curvilinear contour accuracy in the axial plane, complemented by rapid 4-dimensional DTS. Target conspicuity may be enhanced through intravenous iodine contrast as administered for 4-dimensional CT.[17]

Operation of this model would entail 61 projections through a linear sweep angle ≥40°. The sources configuration and sweep orientation can be 2-dimensional and the number of projections negotiable.[11,15] Sweep refers to the sequential firing of all focal spots during the collection of a complete set of tomographic projections at a given single breathing phase. A larger number of projections minimizes the ripple artifact, and a greater sweep angle improves depth resolution.[18] Tube current milliampere-seconds (mAs) per projection over a single arc are a fraction of the mAs required for a conventional radiograph.[19] Projections per second per phase is set to limit the captured motion during any phase to a predefined limit. Heart motion artifacts may be reduced by simultaneous cardiac gating with imaging that is performed during the quiescence, although this would extend imaging beyond a single breathing cycle. Digital Imaging and Communications in Medicine coordinate