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Motion management

Respiratory motion-management in stereotactic body radiation therapy for lung cancer – A dosimetric comparison in an anthropomorphic lung phantom (LuCa)

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A B S T R A C T

Background and purpose: The objective of this study was to compare the latest respiratory motion-management strategies, namely the internal-target-volume (ITV) concept, the mid-ventilation (MidV) principle, respiratory gating and dynamic couch tracking.
Materials and methods: An anthropomorphic, deformable and dynamic lung phantom was used for the dosimetric validation of these techniques. Stereotactic treatments were adapted to match the techniques and five distinct respiration patterns, and delivered to the phantom while radiographic film measurements were taken inside the tumor. To report on tumor coverage, these dose distributions were used to calculate mean doses (D_{mean}), changes in homogeneity indices ($\Delta H_{2\text{-}98}$), gamma agreement, and areas covered by the planned minimum dose ($A_{>Dmin}$).
Results: All techniques achieved good tumor coverage ($A_{>Dmin} > 99.0\%$) and minor changes in D_{mean} (±3.2%). Gating and tracking strategies showed superior results in gamma agreement and $\Delta H_{2\text{-}98}$ compared to ITV and MidV concepts, which seem to be more influenced by the interplay and the gradient effect. For lung, heart and spinal cord, significant dose differences between the four techniques were found ($p < 0.05$), with lowest doses for gating and tracking strategies.
Conclusion: Active motion-management techniques, such as gating or tracking, showed superior tumor dose coverage and better organ dose sparing than the passive techniques based on tumor margins.
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The intra-fractional motion of lung tumors during radiotherapy treatment is strongly affected by respiration. Internal tumor motion larger than 30 mm in cranial-caudal direction has been reported [1]. This internal motion is a relevant uncertainty in radiotherapy, conventionally mitigated by extension of the target volume to cover the full motion envelope. As a consequence, this approach leads to higher radiation doses delivered to organs at risks (OARs). The management of respiratory motion, using breath-hold, beam gating or tracking techniques could lead to a desirable reduction in irradiation of OARs. In stereotactic body radiotherapy (SBRT), where high radiation doses are applied in a few fractions, this reduction might be beneficial to avoid increased toxicity to late-responding tissues associated with large fraction sizes.

The four main motion-management strategies under free breathing are the internal-target-volume (ITV) concept, the mid-ventilation (MidV) principle, respiratory gating, and dynamic target tracking. For the ITV concept [2], the whole extent of tumor motion is taken into the safety margin. This increases the target volume but ensures tumor coverage. In the MidV principle [3], the tumor motion is assumed to be a random position error of the tumor. The safety margins are based on probability calculations and added to the tumor volume in the MidV position, resulting in smaller treatment volumes than the ITV concept. Using a gating approach [4,5], the tumor is only irradiated in a predefined respiratory window with a smaller range of motion. This technique leads to a reduction of irradiated volumes but increases overall treatment time. Lastly, dynamic target tracking is the continuous compensation of tumor motion by either following the motion with the treatment beam, or shifting the patient position according to their internal tumor motion, keeping the tumor at the treatment

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isocenter. Former is commercially realized in the robotic CyberKnife system [6] and the Vero gimbaled linac system [7,8]. Alternatively to these specialized treatment systems, tracking can also be integrated at conventional linear accelerators, which are widely used in clinics. This can be accomplished by either adapting the multi-leaf collimator, which is shaping the treatment field, to the changing target position (MLC tracking) [9–11], or by counter-steering the target motion with the treatment couch (couch tracking) [12,13]. Tracking allows for a reduction of the treatment volume with continuous irradiation. Both gating and tracking require real-time information on the tumor position, whereas the ITV concept and the MidV principle are both passive motion-management techniques based on the a priori extent of tumor motion.

Interplay and gradient effects also influence the dose delivered to moving targets. The moving tumor accumulates dose irregularly since, firstly, the tumor moves through the inhomogeneously planned SBRT dose (gradient effect) and secondly, the motion of the MLC leaves coupled with the continuous gantry rotation interferes with the target motion (interplay effect). These effects additionally could be reduced by gating the treatment to a steady tumor position or tracking the moving tumor.

Planning studies [8,14–16] and phantom studies [17,18] for comparisons between motion-management techniques have been performed previously. Planning studies are generally based on four-dimensional computed tomography data sets (4DCT), which provide patient-specific data for the dose calculation, but neglect actual capabilities of the delivery systems and are prone to motion artifacts [19]. The delivery capability of the techniques has only been reported in phantom studies with rigid, geometric phantoms. To date no study has compared all four techniques, nor has tumor coverage been considered as endpoint.

In the present study, SBRT treatments adapted to all the above-mentioned respiratory motion-management techniques were delivered to an anthropomorphic, dynamic thorax phantom [20,21]. The four techniques were compared in respect to tumor coverage and OAR dose sparing.

Materials and methods

The phantom

An anthropomorphic thorax phantom (LuCa) [20,21] was employed to simulate the anatomy and respiratory motion of a lung cancer patient (Fig. 1). LuCa consists of an inflatable lung including a spherical wooden tumor (60 mm in diameter) with two coronal planes for film inserts at 20 and 40 mm depth, fitted to the size of the rigid tumor. Around the lung are a tissue-equivalent ribcage and a skin layer. A heart model, containing a film insert, is placed within the lung. The inflation of the lung is controlled externally with a ventilator, which follows any desired respiration pattern and directly influences the cranial-caudal tumor motion. This study was focused on known regular motion patterns. The following five respiration patterns were chosen for this study: The ventilator was operated with four regular curves following a *sin* or sin^4, with a respiratory cycle period of 4 s and internal peak-to-peak motion amplitudes of 10 or 20 mm (10 * Sin, 20 * Sin, 10 * Sin^4 and 20 * Sin^4), and additionally with one curve following an irregular, patient-specific respiration pattern (Patient) with mean cycle period of 6.5 s and mean internal motion amplitude of 14 mm. The shape of the internal motion trajectory differed slightly from the actual pressure input waveform due to hysteresis effects in the phantom [20].

Treatment planning

The phantom was operated with the five respiration patterns while phase-sorted four-dimensional computed-tomography (4D-CT) scans were taken with a SOMATOM Definition AS Open (Siemens AG, Germany) CT scanner. An average CT and ten breathing phases (phase CTs) were reconstructed using the RPM system (Varian Medical System, Palo Alto, CA). The gross tumor volumes (GTV) were delineated in all phase CTs. They were used to adapt the planning target volume (PTV) to match the five respiration patterns and the four investigated motion-management techniques:

- *ITV concept:* The entire tumor excursion, retrieved from the 4DCT, was contoured as internal target volume (ITV). A safety margin of 5 mm was added for the PTV_{ITV}.
- *MidV principle:* The mid-position of the tumors from the 4DCT phases was estimated. The phase with the tumor closest to this mid-position was estimated and taken as GTV_{MIDV}. The extent of tumor motion was retrieved from the 4DCT. Probabilistic margins based on the van–Herk formula [3] were added to the GTV_{MIDV} to get the PTV_{MIDV}. The margin recipe guaranteed that 90% of patients in the population receive a minimum cumulative GTV dose of at least 80% of the prescribed dose.
- *Gating:* The gating window with a 30% duty cycle was set at end of inhale to maximize the tumor-heart separation and increased lung volume during irradiation. The residual motion within this gating window was retrieved from the 4DCT data set and later used as gating threshold. The tumor volumes of the corresponding three phases were added to the GTV_{GATE}. A fixed 5-mm margin was added for the PTV_{GATE}.
- *Tracking:* GTV_{TRACK} was also chosen to be the tumor volume closest to the mid-position, but a fixed 5-mm margin was added for the PTV_{TRACK}.

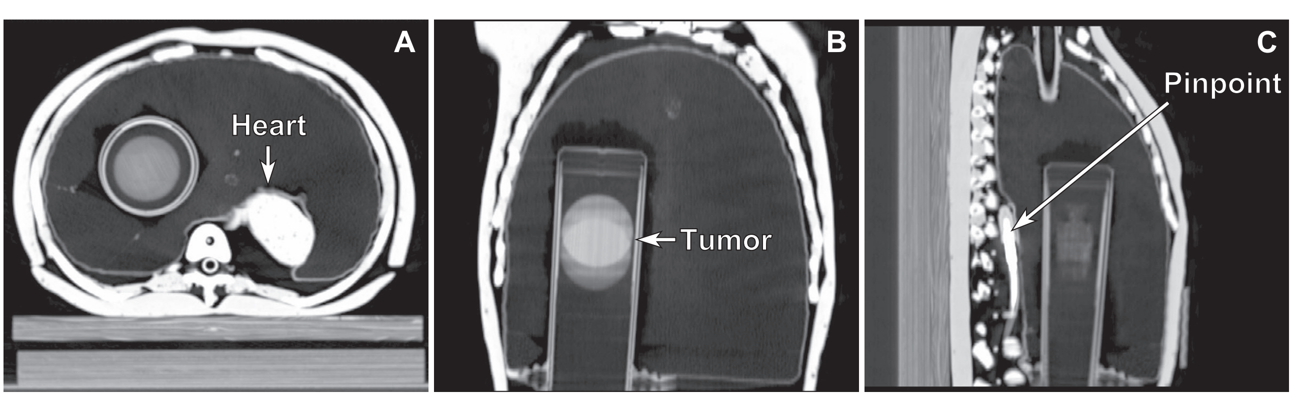

Fig. 1. Average CT of LuCa with tumor, heart and Pinpoint: Transverse (A), coronal (B) and sagittal (C) plane.