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Original article

Impact of respiratory-correlated CT sorting algorithms on the choice of margin definition for free-breathing lung radiotherapy treatments

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ABSTRACT

Background and purpose: To investigate the impact of Toshiba phase- and amplitude-sorting algorithms on the margin strategies for free-breathing lung radiotherapy treatments in the presence of breathing variations.

Material and methods: 4D CT of a sphere inside a dynamic thorax phantom was acquired. The 4D CT was reconstructed according to the phase- and amplitude-sorting algorithms. The phantom was moved by reproducing amplitude, frequency, and a mix of amplitude and frequency variations. Artefact analysis was performed for Mid-Ventilation and ITV-based strategies on the images reconstructed by phase- and amplitude-sorting algorithms. The target volume deviation was assessed by comparing the target volume acquired during irregular motion to the volume acquired during regular motion.

Results: The amplitude-sorting algorithm shows reduced artefacts for only amplitude variations while the phase-sorting algorithm for only frequency variations. For amplitude and frequency variations, both algorithms perform similarly. Most of the artefacts are blurring and incomplete structures. We found larger artefacts and volume differences for the Mid-Ventilation with respect to the ITV strategy, resulting in a higher relative difference of the surface distortion value which ranges between maximum 14.6% and minimum 4.1%.

Conclusions: The amplitude- is superior to the phase-sorting algorithm in the reduction of motion artefacts for amplitude variations while phase-sorting for frequency variations. A proper choice of 4D CT sorting algorithm is important in order to reduce motion artefacts, especially if Mid-Ventilation strategy is used.

Precision in radiotherapy treatment delivery is especially challenging when the target volume moves with internal organ motion and introduces a source of uncertainty known as target "geographical miss" [1].

Motion reduction techniques such as breath-hold [2,3] and abdominal compression [4,5] are helpful in reducing target motion excursion but are often uncomfortable for patients and/or time consuming. In particular, breath-hold CT will not be susceptible to motion artefacts, but it will require an accurate reproducibility of the depth of the breath-hold during treatment.

An alternative is Free-Breathing Radiotherapy-Treatment (FBRT), which leaves the patients breathing freely making it more comfortable and needing less time consuming treatment compared to the gating techniques. However, the FBRT requires a precise knowledge of target motion to avoid possible target "geographical miss". Therefore, to estimate the trajectory of the target motion during a full cycle of breathing, a four-dimensional computed tomography (4DCT) scan is acquired in free breathing conditions [6–10]. In that way, the margins are calculated by taking into account the target motion. This is followed by a 4D CBCT scan just before the start of the irradiation to verify the target motion and the applied margins. This technique is called 4D image-guided radiation therapy (4D IGRT) [11].

The images of a 4D CT scan can be binned either according to the phase or amplitude of the breathing signal.

In the phase-sorting algorithm, an easily-identified reference-frame is selected (e.g. maximum inspiration); the other frame positions are determined by dividing the interval between two reference instances in the breathing cycle into a fixed number of bins. Though this algorithm is widely used in clinics, the sorted data are subject to misalignment, as variation in amplitude is ignored.

The amplitude-sorting algorithm identifies two average amplitudes corresponding to the reference frames, maximum inspiration and maximum expiration. The other intermediate average amplitudes are obtained by interpolation between the previously defined reference frames. Although this algorithm eliminates the

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frame misalignment errors, it increases the potential for missing data for larger or smaller breathing amplitudes than the ones encountered during the reference cycles [12].

All 4D CT sorting algorithms, by incorporating the motion induced by breathing, can decrease the image artefacts usually present in conventional 3D CT images. Nevertheless, motion artefacts may still appear whether the patient is breathing irregularly or target motion is so large that it causes improper binning because of residual motion within the bins (intra-frame motion) [13]. If breathing irregularities occur during the CT slice acquisition where the target is imaged, then artefacts will occur at that position.

The observed artefacts may introduce systematic errors, as in the target delineation, having an impact on the entire treatment course. For example, artefacts may affect the representation of the shape and the volume size of both normal organs and target volumes which may subsequently influence the treatment outcome.

In free-breathing conditions, uncertainties in the representation of the target volume have to be included in the definition of treatment margins. Typically, two margin definition strategies can be applied: Mid-Ventilation strategy (MidV) and Internal Target Volume-based strategy (ITV).

The MidV strategy is based on determining one specific frame over the respiratory cycle (MidV CT frame) where the target is closest to its time-averaged position [14]. The main advantage in using this strategy lies in the principle of minimising the systematic error caused by planning in an arbitrary breathing frame, as is the case on a conventional 3D CT scan.

The ITV-based strategy consists of determining the ITV volume, as described in the International Commission on Radiation Units & Measurements (ICRU) reports 50 [15] and 62 [16]. Practically, the ITV is obtained by contouring the Clinical Target Volume (CTV) in each bin of the 4D CT and by taking the union of each delineated CTV. Alternatively, it can be delineated on a hybrid CT data set using Maximum Intensity Projection (MIP) from the 4D dataset, which directly displays the volume of interest, i.e. the target motion envelope, with its maximum CT number [17,18]. This latter approach is the one used in this paper (further in the text “ITV-based strategy” means “ITV-based strategy with MIP approach”). The MIP derived CT will directly show the Gross Target Volume (GTV) extension including respiratory motion and therefore reduces the contouring workload to only one volume instead of ten, if ten frames are used.

Some authors have discussed whether the phase- or the amplitude-sorting algorithm is more efficient in terms of reducing motion artefacts and better representing the correlation between the internal movement and the external breathing surrogate [19–21] . However, it has not yet been investigated how the 4D CT reconstruction algorithms impact the margin requirement. In particular, breathing irregularities generate artefacts in the images that compromise the target delineation [22] and consequently the margin definition.

The aim of this study was to investigate the ability of the Toshiba phase-and amplitude-sorting algorithms in reducing motion artefacts, in the presence of breathing irregularities, thus ensuring reliable margin definition on target volume for FBRT.

Materials and methods

4D CT data acquisitions

The 4D CT images were acquired with a sixteen-slice CT scanner (Aquilion LB, TSX-201A; Toshiba, Japan) in helical mode. The 4D CT scan parameters were 120 kV, 150 mA, a detector width of 320 mm and a rotation time of 0.5 s, corresponding to the maximal temporal resolution. The pitch (couch movement [mm/rot] divided by nominal slice thickness [mm]) was less than 0.1 in order to ensure that at least one complete respiratory cycle was included in the scan acquisition [10]. The reconstructed image slices were 2 mm thick and separated by 2 mm. A 3 cm-diameter sphere with a density close to 1 g/cm^3 typical of target tissue, was embedded in a CIRS Dynamic Thorax Phantom (CIRS, USA) having a simulated lung density of 0.3 g/cm^3. The sphere inside the phantom was moved periodically along the longitudinal axis of the CT couch according to Eq. (1):

$$z(t) = A \cdot \cos^4 \cdot \left(\frac{2 \cdot \pi \cdot t}{T_b} \right) \tag{1}$$

where $z(t)$ represents the sphere centre longitudinal position as a function of time t, A is the motion amplitude of the sphere and T_b is the breathing cycle period. The cosine power was set to 4 because it describes a typical asymmetric respiratory cycle in free breathing motion [23].

In order to mimic typical patient respiratory variations [24–29] we simulated three types of irregular breathing variations, with a target displacement in the longitudinal axis only [24]: (i) amplitude variations, (ii) frequency variations, and (iii) combined amplitude and frequency variations. A total of thirty irregular breathing variations, ten for each type, were uniformly generated by randomly modifying the amplitude A and the frequency F_b (reciprocal of T_b), without correlation between them. In this study we decided to change the amplitude (A) and frequency (F) in an uncorrelated way in order to test the influence of each variable (A and F) independently with respect to the 4D CT sorting algorithm. Table 1 summarises the range of A and F values used to generate the breathing variations.

The respiratory signal was recorded with the ANZAI belt (AZ-733V; ANZAI Medical Solutions, Japan) measuring the changes of pressure on the belt generated by the breathing motion. The signal was monitored by the accompanying software. The respiratory signal triggers were set at the inspiration peak corresponding to a frame value of 0% in the respiratory cycle. These triggers, as well as the respiratory curve, were sent in real time to the CT scanner. After the acquisition was completed, the data sets were retrospectively reconstructed by interpolation between successive triggers. In this study, ten respiratory data sets were reconstructed with the phase- and amplitude-sorting algorithms. Note that only the phase-sorting algorithm is currently used in clinic. The two sorting algorithms were evaluated for the three types of simulated irregular breathing variations.

A 4D CT, with a regular breathing cycle, fixed amplitude of 9 mm, and frequency of 0.30 Hz, was chosen as the reference for the target-volume analysis, as it corresponds to the average of the typical amplitude and frequency observed in patients [3,14].

In order to ensure correct sampling of the data, the 4D CT data sufficiency condition (Eq. (2))was verified for each acquisition. The pitch was set so that a full set of projections could be acquired by the detector array for a single couch position, over one breathing cycle. In particular, the pitch for a half scan reconstruction was defined as follows [30]:

$$p \leqslant \frac{T_g}{T_b + \frac{2}{3} \cdot T_g} \tag{2}$$

Table 1
Range of breathing variations used in the respiratory cycle simulations. A is the motion amplitude of the sphere and F_b is the frequency rate.

Breathing variations	A [mm]	F_b [Hz]
Amplitude	5–20	0.25
Frequency	10	0.2–0.4
Amplitude and frequency	5–20	0.2–0.4

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