Physica Medica 31 (2015) 963–968

Contents lists available at ScienceDirect

Physica Medica

journal homepage: http://www.physicamedica.com

Original Paper

Impact of motion induced artifacts on automatic registration of lung tumors in Tomotherapy

Samuel Goossens [a], Antonin Descampe [a], Jonathan Orban de Xivry [a], John A. Lee [a], Antoine Delor [b], Guillaume Janssens [c], Xavier Geets [b,*]

[a] ICTEAM Institute, Université catholique de Louvain, Louvain-la-Neuve, Belgium
[b] MIRO Lab., Université catholique de Louvain, Saint-Luc University Hospital, Brussels, Belgium
[c] IBA s.a., Louvain-la-Neuve, Belgium

ARTICLE INFO

Article history:
Received 28 August 2014
Received in revised form 11 June 2015
Accepted 6 July 2015
Available online 16 September 2015

Keywords:
IGRT
Tumor-based positioning
MV-CT
Averaged kV-CT

ABSTRACT

Purpose: Tomotherapy MV-CT acquisitions of lung tumors lead to artifacts due to breathing-related motion. This could preclude the reliability of tumor based positioning. We investigate the effect of these artifacts on automatic registration and determine conditions under which correct positioning can be achieved.
Materials and methods: MV-CT and 4D-CT scans of a dynamic thorax phantom were acquired with various motion amplitudes, directions, and periods. For each acquisition, the average kV-CT image was reconstructed from the 4D-CT data and rigidly registered with the corresponding MV-CT scan in a region of interest. Different kV–MV registration strategies have been assessed.
Results: All tested registration methods led to acceptable registration errors (within 1.3 ± 1.2 mm) for motion periods of 3 and 6 s, regardless of the motion amplitude, direction, and phase difference. However, a motion period of 5 s, equal to half the Tomotherapy gantry period, induced asymmetric artifacts within MV-CT and significantly degraded the registration accuracy.
Conclusions: As long as the breathing period differs from 5 s, positioning based on averaged images of the tumor provides information about its daily baseline shift, and might therefore contribute to reducing margins, regardless of the registration method.

Introduction

Tomotherapy is an attractive radiation therapy (RT) technique for treating lung tumors. It combines a helical dose delivery mode with an embedded online MegaVoltage computed tomography (MV-CT) scanner that both contribute to deliver an accurate and conformal dose to the target volumes for complex treatments such as Stereotactic Ablative Radiotherapy (SABR) [1,2] and dose escalation strategies [3,4].

Achieving accurate dose distribution in lung cancer not only involves sophisticated delivery techniques, but also intrinsically requires the geometrical uncertainties of patient setup and motion to be optimally managed [5–8]. Such uncertainties, like tumor motion correlated to breathing and baseline shifts (BS), i.e. the daily variations of the mean tumor position stemming mostly from diaphragm driven processes [9], must be taken into account with safety margins. In that regard, the mid-position (MidP) strategy [10] allows a significant reduction of the tumor motion contribution in the planning target volume (PTV) margin computation, while MV-CT scans efficiently decrease the residual patient setup errors [11].

At the moment, the tumor baseline shift (BS) remains the most difficult geometric uncertainty to be corrected for when considering a high-precision Tomotherapy treatment. In that regard, setup correction protocols based on the tumor itself, instead of the bony anatomy, may significantly minimize the systematic and random components of the tumor BS [5,12–14]. However, these tumor-based setup correction protocols implicitly require images acquired during the successive IGRT sessions to be accurately registered in the tumor vicinity with the planning CT images. In this context, the slow MV-CT scan bears some similarity in terms of density distribution with the average kV-CT scan derived from respiratory-synchronized 4D-CT [13]. This resemblance could be harnessed to implement a tumor-based setup correction protocol suitable for helical treatment, which could be easily integrated in MidP strategy. However, such tumor-based registration between the average kV-CT and MV-CT scans has to deal with artifacts caused by the tumor motion, that could potentially jeopardize the registration accuracy [15].

Still, whether accurate tumor-based registration can be achieved in various realistic motion scenarios remains unclear. Indeed,

* Corresponding author. Department of Radiation Oncology, Cliniques Universitaires Saint-Luc, Avenue Hippocrate, 10, B-1200 Brussels, Belgium. Tel.: +32 2 764 4719; fax: +32 2 764 9425.
E-mail address: xavier.geets@uclouvain.be (X. Geets).

http://dx.doi.org/10.1016/j.ejmp.2015.07.140
1120-1797/

previous phantom studies mostly focused on the impact of motion artifacts on the object distortion from the actual occupancy images [15], or on the automatic registration accuracy at the global phantom level, rather than at the tumor level [16]. Only one study reported that manual registration between average planning 4D-CT and MV-CT could be achieved with about millimetric residual uncertainties for lateral motion with a 4 s period [17]. In all these studies, lateral and cranio-caudal motions were investigated separately, although tridimensional motions are expected in real patients (hysteresis). In addition, the motion artifacts were characterized for specific periods of 1 s (not clinically relevant) and 4 s. Though, a 5 s-breathing period, i.e. half of the Tomotherapy gantry period during MV-CT acquisition, may generate even more severe artifacts. In this specific aliasing case, each position of the tumor along its trajectory is imaged under the same gantry angle during the whole acquisition time, and motion information can be lost.

In the context described above, this study aimed to validate a tumor-based registration in clinically realistic conditions. We have assessed the accuracy of 4 registration algorithms between regions of interest (ROIs) of the averaged planning kV-CT and the MV-CT scans of a dynamic thorax phantom. Images of various motion patterns were acquired, with different periods, amplitudes, and directions. This allowed us to assess the impact of these parameters on MV-CT artifacts and registration accuracy, especially when gantry rotation and breathing motion synchronize.

Material and methods

Tumor-based registration workflow

A workflow has been set up to assess the tumor-based registration (Fig. 1). It is described as follows:

MV-CT and 4D kV-CT scans defined the workflow inputs. Initially, an automatic translational alignment [18] between the average kV-CT, computed by averaging all 4D kV-CT phases, and its corresponding MV-CT is performed such as in clinical practice (called hereafter as global registration). This global registration is mainly driven by bony structures, principally by vertebras [12,14], and could possibly induce a misalignment at the local target level presumed to correspond to the BS. Indeed, the lung and the tumor undergo respiratory-correlated motion and baseline shift that are not correlated with vertebras [19]. Therefore, a local registration based on a cropped image containing target vicinity might solve this issue. This latter registration is achieved within a ROI encompassing all plausible positions of the target. Such a ROI corresponds to a volume that takes into account all geometrical uncertainties (including the expected BS, the delineation error and the residual setup positioning error of the global registration) according to van Herk's formalism [19,20].

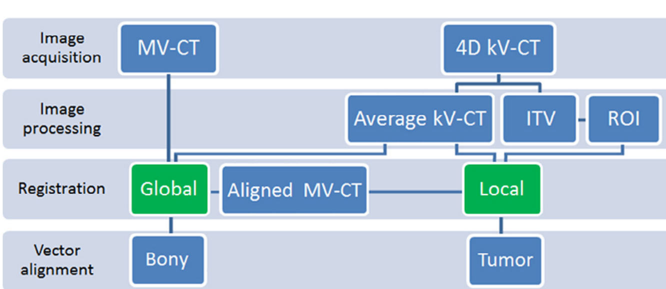

Figure 1. Schematic diagram of the tumor-based registration procedure. Green boxes illustrate the methods (global and local) while blue boxes correspond to data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

An additional margin can be used to encompass also the surrounding image artifacts due to helical MV-CT acquisition.

Image acquisition and delineation

The 4D kV-CT was acquired on a big bore CT scanner (Aquilon LB, Toshiba Medical System Corporation, Japan) using an axial FOV of 550 mm, a slice thickness of 2 mm and a reconstruction interval of 2 mm. Axial images were reconstructed using a matrix of 512×512 pixels, corresponding to a voxel size of $1.074 \times 1.074 \times 2.000$ mm^3 in the x, y, and z directions, respectively. The scanner automatically set the helical pitch according to the motion period estimated from the RPM system (Varian Medical Systems, Palo Alto, CA) [21].

The MV-CT acquisitions were performed on a Tomotherapy online CT system (Tomotherapy Inc., Madison, WI) using a 3.5 MV x-ray beam. The axial FOV of 400 mm was reconstructed using a matrix of 512×512 pixels with a voxel size of $0.780 \times 0.780 \times 4.000$ mm^3 in the x, y, and z directions, respectively. Acquisitions were performed in normal scanning mode corresponding to a slice spacing of 4 mm with a gantry rotation period of 10 s.

All 4D-CT images were reconstructed into 10 equally distributed temporal bins. The resulting 3D respiratory phase images were averaged to compute an average kV-CT. This average kV-CT was used for the registration with the MV-CT acquired with identical phantom motion features. The gross tumor volume (GTV) was automatically segmented using the threshold segmentation implemented by Otsu [22]. Then, non-rigid registration, relying on a diffeomorphic Morphon algorithm [23], was used to propagate this contour to the 10 respiratory phases derived from the 4D-CT [24]. Registration accuracy was visually checked for all phases. The union of the propagated volumes led to the definition of an ITV. In order to perform the global registration, the MV-CT voxels were re-sampled with the voxel size of the kV-CT. The average kV-CT and MV-CT scans were aligned using a registration method based on the sum of squared HU differences for all voxels, without accounting for rotations.

Dynamic thorax phantom validation

The validation step aimed at applying the workflow on phantom images to evaluate the accuracy of 4 registration methods between ROIs of the average kV-CT and its corresponding MV-CT. Since the baseline shift is assumed to be zero with the phantom, the local alignment vector should theoretically be close to zero in ideal conditions. Any deviation was thus considered to quantify the impact of motion-induced MV-CT artifacts on the efficiency of the local registration. This local alignment vector, regarded as tumor-based registration error, has been computed for different motion patterns in order to establish theoretical conditions to validate the tumor-based positioning protocol. Statistical analyses have been performed using a logarithm transformation on the registration results to obtain Gaussian-like distributions, as most statistical tests rely on this assumption.

Phantom motion characteristics

The dynamic phantom (Dynamic Thorax Phantom, Model 008A, CIRS, Norfolk, VA) represents an average human thorax. It is composed of lung equivalent rod containing a spherical target, and inserted into the lung equivalent lobe of the phantom. In this protocol, 4D kV-CT and MV-CT scans were performed using various combinations of motion parameters deemed to be clinically realistic: (1) motion peak-to-peak amplitudes of 15 and 30 mm in the longitudinal plane (superior-inferior (SI) direction), and 5 and 10 mm in the axial plane (combined motion between left-right (LR) and anterior-posterior (AP) directions), with or without a motion delay of $\pi/2$ between the axial and the longitudinal components; (2)