Physica Medica 34 (2017) 28–37

Contents lists available at ScienceDirect

Physica Medica

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

Original paper

Evaluation of residual abdominal tumour motion in carbon ion gated treatments through respiratory motion modelling

Giorgia Meschini [a,*], Matteo Seregni [a], Andrea Pella [b], Mario Ciocca [b], Piero Fossati [b,c], Francesca Valvo [b], Marco Riboldi [a], Guido Baroni [a,b]

[a] Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, Pizza Leonardo da Vinci 32, I-20133 Milano, Italy
[b] Centro Nazionale di Adroterapia Oncologica, Strada privata Campeggi 53, I-27100 Pavia, Italy
[c] Istituto Europeo di Oncologia, via Ripamonti 435, I-20100 Milano, Italy

ARTICLE INFO

Article history:
Received 12 October 2016
Received in Revised form 22 December 2016
Accepted 11 January 2017
Available online 18 January 2017

Keywords:
Motion modelling
4DCT
Deformable image registration
Gating
Particle therapy

ABSTRACT

At the Italian National Centre for Oncologic Hadrontherapy (CNAO) patients with upper-abdominal tumours are being treated with carbon ion therapy, adopting the respiratory gating technique in combination with layered rescanning and abdominal compression to mitigate organ motion. Since online imaging of the irradiated volume is not feasible, this study proposes a modelling approach for the estimation of residual motion of the target within the gating window. The model extracts a priori respiratory motion information from the planning 4DCT using deformable image registration (DIR), then combines such information with the external surrogate signal recorded during dose delivery. This provides estimation of a CT volume corresponding to any given respiratory phase measured during treatment. The method was applied for the retrospective estimation of tumour residual motion during irradiation, considering 16 patients treated at CNAO with the respiratory gating protocol. The estimated tumour displacement, calculated with respect to the reference end-exhale position, was always limited (average displacement is 0.32 ± 0.65 mm over all patients) and below the maximum motion defined in the treatment plan. This supports the hypothesis of target position reproducibility, which is the crucial assumption in the gating approach. We also demonstrated the use of the model as a simulation tool to establish a patient-specific relationship between residual motion and the width of the gating window. In conclusion, the implemented method yields an estimation of the repeatability of the internal anatomy configuration during gated treatments, which can be used for further studies concerning the dosimetric impact of the estimated residual organ motion.

1. Introduction

The inverted depth-dose profile of charged particles, characterized by the Bragg peak, enables an optimal conformation of the dose distribution within the treated volume: the dose distribution can be accurately shaped around the target volume while surrounding structures receive a limited amount of dose, thus reducing the probability of side effects [1–3]. However, the increased geometric selectivity with respect to photon radiation therapy results in higher sensitivity to organ motion, both among different treatment sessions (inter-fractional motion) or within a single session (intra-fractional motion) [4–6]. Such phenomena, in addition to the risk of geographical misses, also affect the penetration range of charged particles, resulting in severe alterations of the delivered dose distribution. Moreover, when active beam scanning is considered, the interference between tumour and beam motion leads to the so-called interplay effect [4].

The dominant cause of intra-fractional organ motion is patient respiration, involving both the thorax and abdomen site. Different solutions are available for respiratory motion mitigation (e.g. immobilizing devices, abdominal pressure, breath hold and active breath control, [4]) and also for motion compensation during treatment, since margin-based approaches are generally not sufficient [7]. Different 4D-optimization techniques have been investigated, which entail the integration of organ motion information in the treatment plan [8–10]. In principle, the most efficient solution is real-time tumour targeting, which consists in repositioning the radiation beam dynamically so as to follow the changing tumour position. However, its implementation in particle therapy is

* Corresponding author.
E-mail address: giorgia.meschini@polimi.it (G. Meschini).

http://dx.doi.org/10.1016/j.ejmp.2017.01.009

challenging, mainly due to the need of compensating for motion induced range variations [11], and therefore it is not currently applied in any clinical protocol, although being implemented in prototypes [12–15]. Another solution is the gating technique, which involves the irradiation within a particular phase of the patient's breathing cycle, commonly referred to as the gating window [16]. Typically, the gating window corresponds to end-exhale, when the tumour position is more stable and repeatable.

At the National Centre for Oncologic Hadrontherapy (CNAO, Pavia, Italy) the gating protocol is applied since September 2014 to treat patients with abdominal tumours using scanned carbon ion beams [17,18]. To our knowledge, gated carbon ion therapy for abdominal lesions was implemented in two other particle therapy centres. Habermehl et al. reported a case of respiratory gating implementation for a liver patient at the Heidelberg Ion-Beam Therapy Centre (HIT, Heidelberg, Germany) where the detection of the irradiation window relied on a pressure sensor attached to a waist belt [19]. At the National Institute of Radiological Sciences (NIRS, Chiba, Japan), liver [20] and pancreatic [21] cancer patients were selected for carbon ion treatments guided by stereoscopic X-ray fluoroscopic imaging, which allows detecting the tumour position in real-time. Ultrasound technologies have been investigated as a non-invasive and dose-free alternative to fluoroscopy for internal gating [22], but further investigation is needed before its clinical implementation [9].

At CNAO, an external gating approach is implemented, as a system for real-time X-ray imaging in treatment position is not available. External gating allows sparing additional non-therapeutic dose to the patient and the implantation of radiopaque markers, which would be recommended in case of tumours in low contrast sites such as the abdomen. In addition to the gating technique, abdominal compression by means of an individualized thermoplastic mask and layered multiple rescanning of the treated volume are applied in order to reduce organ motion and mitigate residual interplay effects, respectively [17,23].

To study the impact of organ motion on dose delivery, it is necessary to know the position of the tumour and of every structure along (and in proximity of) the beam path. When a direct measurement of patient's intra-fractional motion is not feasible, a modelling approach can be applied to estimate the lacking piece of information [24]. In this case, the correspondence between breathing motion information obtained from planning time-resolved imaging and a respiratory surrogate signal can be used to estimate anatomical variations caused by respiration during treatment [24].

Surrogate-driven motion models previously proposed in the literature are mainly developed and applied for lung cancer studies [24,25]. Nonetheless, their application to abdominal sites (e.g. liver) have already been reported [26–28]. In this work, a motion model previously tested for lung cancer cases [25] has been applied to abdominal CT images. Clearly, such sites exhibit specific challenges related to low contrast structures in CT, therefore, a dedicated optimization of the modelling pipeline was carried in a previous study [29].

The aim of the present work is to propose a model-based method for residual motion estimation during external gated treatments, which we propose as a solution to the lack of direct feedback of the irradiated volume. Then, we aimed at a preliminary evaluation of the gating strategy adopted at CNAO. Specifically, we focused on the retrospective geometrical quantification of residual tumour motion within the gating window for 16 patients treated at CNAO. Finally, we demonstrated the use of the motion model as a simulation tool, to establish a patient-specific relationship between the maximal allowed residual motion and the corresponding width of the gating window.

2. Materials and methods

2.1. Respiratory gating protocol at CNAO

Before the planning 4DCT is acquired, the patient is positioned on the CT couch. A custom rigid cushion (CIVCO AccuForm, USA) is moulded below the patient and a semi-rigid mask of thermoplastic material is tightly shaped on the body surface. This guarantees patient immobilization and abdominal compression during imaging and irradiation, while leaving a limited displacement for volume variations caused by breathing. Optical markers (5 to 7) are placed on the mask surface for stereotactic patient positioning. The 4DCT is acquired by means of a Siemens SOMATOM Sensation Open CT scanner and retrospectively sorted using a pressure sensor (ANZAI AZ-733V), which is placed between the thorax and the mask. Four volumes are usually reconstructed:

- the end-exhale (labelled as 0EX, Fig. 1) used for treatment planning;
- two volumes to test the plan against residual motion in the gating window [30]; such volumes represent symmetrical respiratory phases with respect to end-exhale during breathe out and breathe in, corresponding to a given percentage Δ of the maximum signal amplitude. $\Delta = 30$ both for exhalation and inhalation is the standard choice in the protocol, suited for regular breathing curves as in Fig. 1a. However, it can be varied in case of asymmetrical curves, as shown in Fig. 1b;
- the end-inhale volume (100IN), needed for the assessment of the total range of motion.

Before each fraction, patient positioning is performed using a robotic system that applies the corrections computed through the in-room optical tracking device and the X-ray imaging system [31,32].

The same pressure sensor used for 4DCT reconstruction provides guidance for beam gating during treatment delivery. Specifically, through the ANZAI System interface the medical physicist sets the parameters characterizing the gating window, adjusting its width as specified in the treatment plan. The Gate ON signal, which is high only when the beam is on, is represented by the green line in Fig. 1a and b: its maximum theoretical width, extending from ΔEX to ΔIN respiratory phases, is depicted. The ANZAI System acquires the respiratory signal at 40 Hz, computes the respiratory phase in real time, recognizes the desired phase window and controls the beam accordingly.

2.2. Data

We collected 4DCT datasets in 16 patients (resolution $0.98 \times 0.98 \times 2\ mm^3$), each one consisting of the four volumes described in the previous paragraph (i.e. 0EX, ΔEX, ΔIN, 100IN). Moreover, the pressure surrogate signals recorded during each treatment fraction, with the associated "Gate ON" binary signal, were also collected. Table 1 lists, for each patient, the treatment site and the GTV (Gross Target Volume) volume as contoured by a clinician on 0EX.

2.3. Respiratory motion model

For respiratory motion modelling, we used the method already employed and tested by Fassi et al. [25]. In Fig. 2 there is a schematic representation of the current implementation. In the building stage, deformable image registration (DIR) between the reference CT (0EX) and all the other 4DCT volumes is used to calculate a set of time-resolved DVFs (Deformation Vector Fields),