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Liver proton therapy

# An evaluation of rescanning technique for liver tumour treatments using a commercial PBS proton therapy system

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ABSTRACT

*Background and purpose:* The treatment quality of pencil beam scanned (PBS) proton therapy to mobile tumour treatments can be compromised due to interplay effects. The aim of this work is to systematically evaluate the effectiveness of rescanning for liver tumour treatments for a commercial PBS delivery system.

*Materials and methods:* Plans were calculated to patient specific ITV's ($2Gy_{RBE}$), using spot spacings of 4 and 8 mm for 1- and 3-field plans. 4D dose calculations were performed using regular and irregular motion extracted from nine 4DCT(MRI) liver datasets with 4 different starting phases. Up to 19 times adaptive-scaled layered and volumetric rescanning were simulated using beam profiles and delivery dynamics of a commercial proton therapy system.

*Results:* For small (~10 mm) motions, 3-field plans achieved CTV HI's (D5–D95) to within 8.5% (80th percentile) of the static case without rescanning. For larger motions, volumetric rescanning resulted in 4.5% improved HI in comparison to layered, but requires 5 times longer treatment times and is more sensitive to detailed plan characteristics and delivery dynamics. Increased spot spacings were found to reduce sensitivity to interplay and reduce delivery times by 60%, whilst reduced energy switching times decreased treatment time by up to 75% for volumetric rescanning without however improving plan quality.

*Conclusion:* For the investigated proton therapy system, rescanning can help recover dose homogeneity under conditions of motion but, particularly for motions over 10 mm, should be combined with additional motion mitigation techniques.



Pencil Beam Scanned proton therapy (PBS) is becoming one of the most attractive radiotherapy techniques, with promising clinical outcomes being demonstrated for various indications [1–3]. However, its efficacy for the treatment of moving tumours (e.g. lung, liver and other tumour sites in the upper abdomen or pelvic region) is still a matter of concern, mainly due to the interplay effects [4]. In addition to motion induced dose blurring effects at the edge of the target volume, which can be efficiently addressed using an internal target volume (ITV) [5], additional over- and under-dosage *within* the target volume, due to the interplay of delivery dynamics and anatomical motion, cannot be compensated by margins only. Therefore, selecting and implementing additional motion mitigation approaches for PBS are essential for assuring the advantages of this technique in terms of delivery quality.

Various strategies have been proposed to mitigate motion effects for PBS based treatments [6,7]. For instance, interplay can be reduced if motion amplitude is controlled, such as by breath-hold [8] or beam gating [9–12] strategies or, at the other end of the spectrum of complexity, by tumour tracking [13–15]. Alternatively, rescanning [16,17] can be regarded as a relatively straightforward way to deal with the interplay effect, since it is only dependent on statistical averaging and is independent of any extra equipment, implementation or active cooperation from the patient.

Although the effectiveness of rescanning for mobile tumours has been demonstrated in a number of simulations and experiments [18–23], its performance is highly machine-specific, simply due to its sensitivity to small variations in the relative timelines of beam delivery and respiratory tumour motion [18]. In addition, beam size, as well as machine specific scanning parameters, spot distance, dose rate, lateral position switching time, energy layer switching time etc., all have a significant impact on the timeline of each delivered spot and can therefore result in substantial differences in the final dose distribution and motion mitigation efficacy. Consequently, it is important to study such effects using as accurate a simulation of the actual delivery conditions as possible, so

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as to be able to obtain a meaningful quantification of the interplay effects, as well as to investigate the optimal parameters for applying a robust plan.

In this study, we have systematically evaluated the effectiveness of different liver tumour treatments using the delivery characteristics of the Varian ProBeam PBS system, through the use of dedicated 4D dose calculations (4DDC) which consider the specific parameters of this system (raster scanning with variable dose rate), together with a comprehensive motion database which not only takes into account realistic patient geometries and deformable motion, but also includes inter-cycle breathing variability. In particular, we have compared the efficacy of different rescanning approaches and treatment plan scenarios, as well as the dosimetric effects of motion irregularity.

## Materials and methods

### *Patient and motion data*

Nine 4DCT(MRI) datasets [24] have been used in this study, generated from three 4DCT data sets of three liver patients (denoted as I, II and III respectively), each additionally modulated by three different motion scenarios (denoted as A, B and C) extracted from a 4DMRI motion library of liver motion using dynamic image fusion [24]. In order to produce these datasets, the mechanical correspondence of liver meshes in MRI and CT were firstly determined by defining landmarks which move similarly across different livers. Then, the simulated 4DCT(MRI) are created by warping these deformation fields, extracted from 4DMRI, to a static 3DCT data set. The tumour locations and characteristics of each patient are shown in Fig. 1. CTV volumes at End-of-Exhalation (EE, the reference phase) were 403, 264 and 122 cc for Patients I, II and III respectively. The extracted liver motions (with respect to the reference EE phase of the first breathing cycle) have also been shown in Fig. 1, as acquired from 4DMRI with a temporal resolution of 2–3 Hz. The mean, inter-cycle averaged motion magnitudes for motion A, B and C were of the order of 10, 15 and 20 mm with mean/range periods, calculated using Fourier analysis of the breathing signals, of 3.3(2.9–4.0), 6.3(5.2–7.2), 5.3(4.7–6.3) seconds respectively.

### 4D dose calculation

The beam profiles and scanning parameters used for all 4DDC's are those of the Varian ProBeam PBS system. As such, proton pencil beams have been modelled using an energy dependent parameterisation of integral depth dose curves in water and a two-dimensional Gaussian representation of lateral profiles with beams sizes (sigma) in air of 4–5.5 mm at isocentre (depending on the energy). For each field, pencil beam separations orthogonal to the beam direction of either 4 or 8 mm have been used, together with energy switching times (for 3.5 MeV, corresponding to range steps of 3.9–8.6 mm (75–245 MeV) in water)) of 700, 500, 200 and 100 ms. The faster energy switching times have been included in this analysis in order to analyse the potential impact of energy switching time on interplay effects, rescanning efficiency and treatment duration. For lateral motion of pencil beams, raster scanning has been modelled by including the magnetic scanning time in the delivery timeline calculation. Raster scanning speeds are 20 mm/ms and 5 mm/ms for the two directions respectively, with maximum dose rates being set to be around $2 \times 10^{10}$ protons/s (energy dependent). For consecutive pencil beams spaced by more than 10 mm, the beam is switched-off in between. In addition, the duration of each spot irradiation depends on the fluence (number of protons per spot resulting from the field specific optimisation process) and the dose rate (protons/s) of the proton beam at the given energy, as the ProBeam system varies dose rate on an energy layer-by-layer basis, such that the pencil beam with the smallest weight in the layer can be delivered with a duration of at least 3 ms.

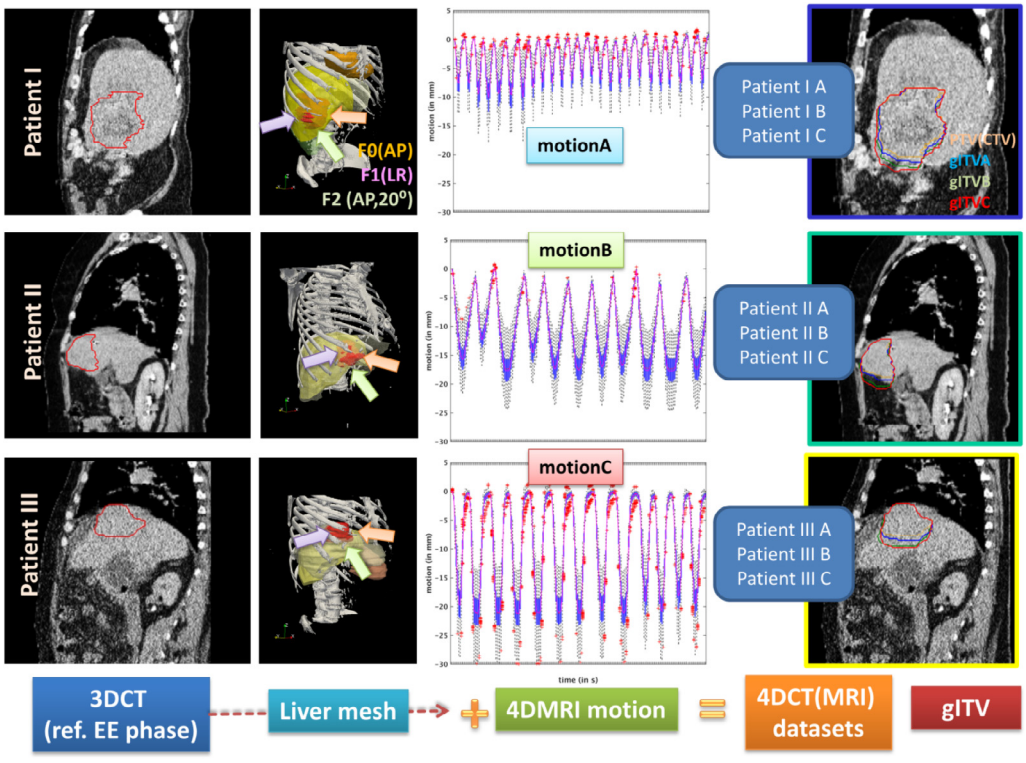


**Fig. 1.** Components used for generating 4DCT(MRI) datasets for 4D dose calculations.