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Proton therapy

Sensitivity of intensity modulated proton therapy plans to changes in patient weight

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Abstract

***Purpose*: A retrospective study to investigate the sensitivity of intensity modulated proton therapy (IMPT) to changes in body weight occurring during the course of radiotherapy for patients treated in the sacral region.**

***Materials and methods*: During therapy, important weight gain and loss were observed for two patients treated to para-spinal tumors, which resulted in both patients being re-scanned and re-planned. Both patients were treated as part of their therapy, with a narrow-angle IMPT (NA-IMPT) plan delivering a 'dose hole' around the cauda equina (CE), which was mainly formed through modulation of Bragg peaks in depth. To investigate the impact of these weight changes on the proton range and delivered dose, the nominal fields were re-calculated on the new CT data sets. Results were analyzed by comparing these new plans with those originally delivered and by calculating changes in range and delivered doses in target volumes and normal tissues.**

***Results*: Maximum differences in proton range in the CE region of up to +8 mm and −13 mm, respectively, for the patient who gained weight and for the patient who lost weight, increased the maximum dose to the CE by only 2%. This indicates that both IMPT plans were relatively insensitive to substantial range uncertainties. Even greater differences in range (16 mm) in the planning target volume only slightly affected its dose homogeneity (differences in $V_{90\%}$ of 6% in the worst case). Nevertheless, some large undesired local dose differences were observed.**

***Conclusions*: We demonstrated, that, at least for the two analyzed cases, NA-IMPT plans are less sensitive to weight variations than one may expect. Still, we would advise to calculate new plans in case of substantial change in weight for patients treated in the sacral region, primarily due to the presence of new hot/cold area.**

Keywords: IMPT; Plan robustness

The delivery of highly conformal treatments with protons strongly depends on the accuracy of the definition of proton range in the patient. In particular, for target volumes which are positioned close to organs at risk (OARs), any error in the range evaluation may cause under-dosage of tumor volumes and/or over-dosage of critical normal structures. This is particularly important when an Intensity Modulated Proton Therapy (IMPT) plan is applied [1,2]. IMPT allows the delivery of highly conformal dose distributions to intricate target shapes which, for example, may include dose-limiting critical structures. IMPT differs from conventional proton therapy (PT) in its flexibility to deliver multiple, arbitrarily shaped proton fluence maps for each incident field direction, in which the prescribed dose is obtained by combining this set of individually in-homogeneous proton fields. As the final dose distribution is dependent on how these fields 'patch' together, this technique is potentially more sensitive to range uncertainties than conventional proton therapy.

The proton range in the patient is dependent on the proton energy and on the radiological path length along the beam direction, whose value (relative to water) is calculated from the planning CT. The conversion from Hounsfield Unit (HU) to stopping power (SP) values is obtained through a calibration curve, which, at our institute, provides a range precision of $\leqslant$3% in typical treatment situations [3,4]. However, any intra-fraction changes (e.g. breathing, organ motion, and patient movement due to discomfort) as well as inter-fraction changes (e.g. positioning uncertainties and anatomic changes during the course of radiation treatments) could affect the range of protons within the patient and consequently the delivered dose distribution. In particular, weight changes of the patient could cause significant changes in proton range, depending on the anatomical site treated.

Typically, with passive scattered proton therapy, uncertainties are dealt with through modifications of the compensator, both by systematically removing material to

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overshoot the target volume and by smearing the compensator in order to allow for possible misalignments of density heterogeneities due to daily positioning inaccuracies [5–7]. In contrast, with spot scanning, as no field compensators are required, such errors are dealt with through the use of the more familiar PTV concept. Despite these measures, little work has been done in dosimetrically assessing the potential effects of systematic range errors in proton therapy.

Inter-fraction positioning errors are limited at our institute by using patient specific immobilization tools such as individually tailored vacuum casts and bite blocks, and by the use of a daily imaging and correction protocol, based on the daily acquisition of CT topogram (scout view) images on a 'remote' (i.e. outside the treatment room) CT scanner, as described in detail elsewhere [8].

In this paper, we investigate the dosimetric consequences of significant, and uncorrected, anatomic changes (i.e. weight changes) on dose distribution for patient treated with IMPT plans in the sacral region. For treatments of lesions along the spinal axis, we generally treat patients in the prone position such that we can irradiate the lesion with beams from the posterior aspect [9]. This allows for a minimal path length through normal tissue to the target volume without the beams being perturbed by the patient table and almost complete sparing of the anterior abdomenal and thoracic organs. However, this approach has the disadvantage that there can be a vertical motion of the spinal axis, and therefore of the tumor, as a result of chest wall motion during breathing. In order to limit the effect of this motion on the spot scanning technique, a so-called 'narrow angle' configuration is used [10]. In this configuration, beam incidences are chosen as close as possible ($\leqslant 30^\circ$) to the posterior–anterior (PA) direction, which corresponds to the major axis of the motion. As motion along the beam axis has little effect on the delivered dose, by selecting these angles the effects of this motion can be significantly reduced [11]. On the other hand, as all of the fields are incident from the same aspect of the patient, such plans could be particularly sensitive to uncertainties in the range, especially if the cause of the range uncertainty is common to all beam directions. This could be the case, for instance, due to anatomical changes in the patient during the course of treatment. Therefore in this paper we studied the effect of substantial weight gain and loss in two patients treated with narrow-angle IMPT (NA-IMPT) from the point of view of changes in proton range and consequent changes in the delivered dose distributions.

Materials and methods

Patients' treatments

An 8-year-old boy (patient-A) and a 54-year-old man (patient-B), presenting with a sacral osteosarcoma and sacral chordoma, respectively, were referred to PSI in 2004 for proton therapy. For both cases a planning CT (CT_{plan}), extending from the femoral heads to the lumbar region, was acquired with a slice separation of 3 mm and a pixel size of 1.9 mm. Doses of 70 Cobalt Gray Equivalent (CGE) for the pediatric osteosarcoma and 74 CGE for the chordoma were prescribed to the planning target volume (PTV), which in both cases circumferentially encompassed the cauda equina (CE) of the patients. The dose per fraction was 2 CGE and the maximum tolerance dose allowed to the cauda equina (CE) was 64 CGE. Both patients were treated in the prone position using the 'narrow angle' beam configuration, to limit the effect of the respiratory movement on the dose deposition, and to minimize dose to the anterior organs [10].

The treatment for the pediatric patient was split into three series: the first delivered 36 CGE homogeneously to a symmetrical PTV, which included both sacral iliac joints to avoid asymmetric bone growth; the second course aimed to deliver a homogeneous dose distribution up to 48 CGE to an asymmetrical PTV which spared the contralateral sacral iliac joint. The last series delivered 22 CGE to the asymmetrical PTV, using the 3-field, 'narrow-angle' IMPT plan, creating a 'dose hole' around the CE to limit the maximum dose to this critical structure (Fig. 1a). Field incidences were all coplanar and predominantly from the posterior aspect at angles 0° and $\pm 30^\circ$. The maximum dose for the whole treatment did not exceed 64CGE to the CE.

For the adult patient, the planned treatment was split into two series: the first was delivered to 46 CGE, to the whole PTV including the CE; the second course (to 74 CGE) was a 3-field (of angles 0° and $\pm 20^\circ$ from posterior), narrow-angle IMPT plan, selectively sparing the CE, planned to the PTV (Fig. 1b). Again, the maximum planned dose in the CE for the whole treatment was 64 CGE.

Patient weight changes

During the course of treatment patient-A (pediatric patient) gained 1.5 kg in weight. At the same time, at fraction 25 of the treatment, it was observed as part of the daily imaging and positioning process that there was a clear excess of adipose tissue in comparison to the reference scout view performed during the treatment planning CT (CT_{plan}) study. This was also partly responsible for the measured mean positioning error on this day of +6.5 mm (range 5.2; 7.3 mm) in the anterior–posterior (AP–PA) direction. Mean errors (over all points close to the tumor) in positioning in the lateral and caudal-cranial directions on this day were, respectively, 0 mm (range −1.8; 0.0 mm) and −1 mm (range −0.5; −2.8 mm). Although this translational misalignment of the bony structures would be corrected directly on the treatment machine [8], due to the clearly altered anatomy resulting from the weight gain, a new planning CT was performed (CT_{new}) with the patient in the treatment position (see Fig. 2). Subsequently, CT_{new} was used to completely re-plan the patient, and the treatment was continued with the new plan on fraction 28, which was then applied until completion of the treatment.

A similar scenario was observed at fraction 18 for patient-B, but with the anatomical change being a significant (about 8 kg) weight loss, resulting in a visible loss of soft tissue all around the patient. Positioning errors on this day were 6.0, −6.5 and −2.5 mm, respectively, in the lateral, AP–PA and caudal-cranial directions. As, due to the weight loss, patient fixation was compromised, a new vacuum mould was created prior to the acquisition of a new planning