Physics and Imaging in Radiation Oncology 6 (2018) 25–30

Contents lists available at ScienceDirect

Physics and Imaging in Radiation Oncology

journal homepage: www.elsevier.com/locate/phro

Original Research Article

Inter-centre variability of CT-based stopping-power prediction in particle therapy: Survey-based evaluation

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ARTICLE INFO

Keywords:
Particle treatment planning
Hounsfield look-up-table
CT scan protocol
Stopping-power ratio prediction
Inter-centre comparison
Dual-energy CT

ABSTRACT

Background and purpose: Stopping-power ratios (SPRs) are used in particle therapy to calculate particle range in patients. The heuristic CT-to-SPR conversion (Hounsfield Look-Up-Table, HLUT), needed for treatment planning, depends on CT-scan and reconstruction parameters as well as the specific HLUT definition. To assess inter-centre differences in these parameters, we performed a survey-based qualitative evaluation, as a first step towards better standardisation of CT-based SPR derivation.
Materials and methods: A questionnaire was sent to twelve particle therapy centres (ten from Europe and two from USA). It asked for details on CT scanners, image acquisition and reconstruction, definition of the HLUT, body-region specific HLUT selection, investigations of beam-hardening and experimental validations of the HLUT. Technological improvements were rated regarding their potential to improve SPR accuracy.
Results: Scan parameters and HLUT definition varied widely. Either the stoichiometric method (eight centres) or a tissue-substitute-only HLUT definition (three centres) was used. One centre combined both methods. The number of HLUT line segments varied widely between two and eleven. Nine centres had investigated influence of beam-hardening, often including patient-size dependence. Ten centres had validated their HLUT experimentally, with very different validation schemes. Most centres deemed dual-energy CT promising for improving SPR accuracy.
Conclusions: Large inter-centre variability was found in implementation of CT scans, image reconstruction and especially in specification of the CT-to-SPR conversion. A future standardisation would reduce time-intensive institution-specific efforts and variations in treatment quality. Due to the interdependency of multiple parameters, no conclusion can be drawn on the derived SPR accuracy and its inter-centre variability.

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[1] On behalf of the European Particle Therapy Network (EPTN), an ESTRO task group.
[2] Dr. Ludvig Muren, a co-author of this paper, is Editor-in-Chief of Physics & Imaging in Radiation Oncology. A member of the Editorial Board managed the editorial process for this manuscript independently from Dr. Muren and the manuscript was subject to the Journal's usual peer-review process.

https://doi.org/10.1016/j.phro.2018.04.006
Received 13 March 2018; Received in revised form 20 April 2018; Accepted 23 April 2018

1. Introduction

The heuristic conversion from CT number to particle stopping-power ratio (SPR) is one of the main contributions to uncertainties in treatment planning of particle therapy [1,2]. The conversion between CT number and SPR is usually performed by applying a piecewise linear function, referred to as a Hounsfield Look-Up-Table (HLUT).

In general, two different approaches exist for HLUT generation, "tissue-substitute-only" [3] and "stoichiometric" HLUT definition [4]. In the first case, only measured CT numbers and SPR from tissue-mimicking materials are used, whereas in stoichiometric approach the CT number and SPRs are predicted for different (biological) tissues of known tissue composition. The CT number prediction is specific for the used scan settings and requires a calibration, again with tissue substitutes.

As photon attenuation is dependent on photon energy, the CT number for a specific tissue will depend on the X-ray energy spectrum and detector response of the CT scanner, as well as the reconstruction parameters. Furthermore, beam-hardening will lead to CT number variations, especially for high-density materials, depending on the surrounding material and the size of the entire scanned object [5]. An improved CT number constancy can be obtained by applying reconstruction algorithms with sophisticated beam-hardening correction (BHC) that distinguishes between bone- and water-like contents.

Hence, a multitude of parameters influence the CT-to-SPR conversion: (a) CT scan parameters (e.g. energy spectrum, energy filters, type of detector); (b) reconstruction parameters (reconstruction kernel, including BHC, and image smoothing); (c) HLUT definition details. This leads to a cumbersome, work intense and error-prone process, which each particle centre currently must perform individually for their specific hardware (CT scanner) and software settings. This process consists of the following steps: [1] Definition of CT scan and reconstruction protocol, ideally after its optimisation regarding image noise and contrast as well as CT number constancy for different body regions (minimising remaining beam-hardening effects); [2] HLUT definition for this CT protocol; [3] Validation of the HLUT in a realistic scenario.

Currently, 68 new particle facilities are in planning or construction phase [6]. Hence, missing standardisation in CT-to-SPR conversion and resulting inter-centre differences as well as limited accuracy in range prediction, already today a problem for centres in operation [7], are becoming even more of an issue in the near future.

To assess the inter-centre variability of CT image acquisition and reconstruction as well as calibration and validation of HLUT-based CT-to-SPR conversion, a survey-based qualitative evaluation was carried out in the framework of the European Particle Therapy Network (EPTN). Aiming to access the current status of inter-centre differences, this investigation was intended as a first step towards better standardisation of CT-based SPR derivation.

2. Material and methods

A questionnaire was sent to ten currently operational particle therapy centres connected to the EPTN, an ESTRO task group, and two operational centres in the US in the period from 1st of December 2016 to 1st of February 2017. The questionnaire concerned the conversion of CT numbers in treatment planning CT datasets to SPRs used for dose and range calculations in particle therapy. It mainly focused on (a) details on CT scanners, acquisition and reconstruction parameters, (b) HLUT definition, (c) HLUT validation, (d) body-region specific HLUT selection, (e) artifact handling and, (f) quality assurance (see Supplementary data).

As the HLUT depends on the specific scan and reconstruction parameters, a direct comparison of the different HLUTs and their respective SPR accuracy was not possible per definition. The questionnaire therefore focused on how the HLUT had been designed and how beam-hardening was handled.

The centres were also asked if they intended to change their current calibration method in the near future and their views on how the accuracy of treatment planning could be improved. Further, five upcoming innovations and technological improvements, currently under strong investigation were rated from 1 (most important) to 6 (least important) regarding their potential to improve range prediction accuracy. These five suggestions were dual-energy CT (DECT), proton CT, photon-counting-detector CT (PCD-CT), better calibration methods, and Monte Carlo based dose calculation.

3. Results

3.1. Facility specifications

Most of the centres participating in this survey had recently started clinical operation. The median operational time was three years. The most experienced centre had been treating patients since 1991. This centre implemented their current HLUT in 2001. Only one other centre had been in operation for more than ten years. One centre was not yet in operation at the time of answering the questionnaire, but has in the meantime started treating patients.

All centres had the ability to treat with pencil beam scanning (PBS); however, five centres also used passive double-scattering (DS). The following treatment planning systems (TPSs) were used: Eclipse (Varian Medical Systems, Palo Alto, CA, USA; six centres), RayStation (RaySearch Laboratories, Stockholm, Sweden; four centres) and Syngo RT Planning (Siemens Healthineers, Forchheim, Germany; two centres). Two centres using RayStation also used XiO (Elekta, Stockholm, Sweden).

All centres treated tumours situated in the brain, the head-and-neck region, and the pelvis area (Fig. 1). Other common treatment sites were abdomen (nine centres), thorax (eight), and extremities (seven). Less common treatment sites were ocular tumours (five), and breast tumours (three).

A relative range uncertainty margin (RUM) of 3.5% of the total particle range was applied by seven institutions. An additional absolute RUM of 2 mm or 1 mm was used by two and one centre, respectively. One centre chose the additional margin based on the delivery technique, 1 mm for PBS plans and 3 mm for DS plans. Another centre, also using a relative RUM of 3.5%, increased their RUM in some cases, e.g. for cranio-spinal irradiations. A relative RUM of 3% was used by a

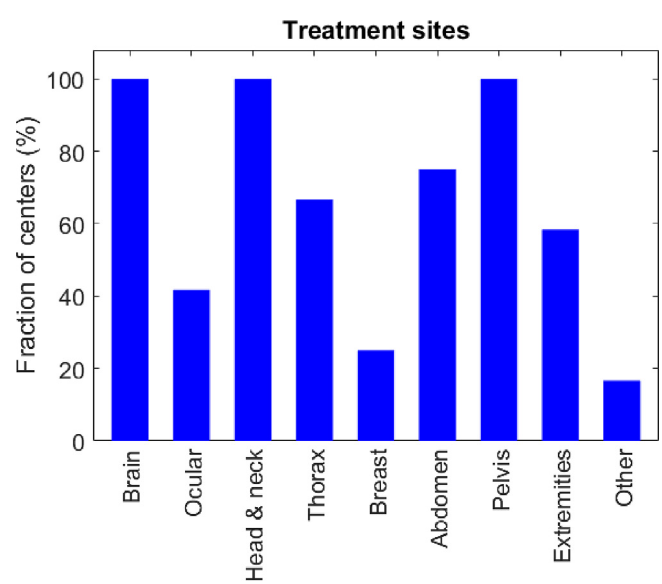

Fig. 1. Anatomical sites treated at the different particle therapy centres. The category "Other" includes cranio-spinal treatments and irradiations close to the spine.