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Commissioning Monte Carlo algorithm for robotic radiosurgery using cylindrical 3D-array with variable density inserts

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ABSTRACT

Introduction: To commission the Monte Carlo (MC) algorithm based model of CyberKnife robotic stereotactic system (CK) and evaluate the feasibility of patient specific QA using the ArcCHECK cylindrical 3D-array (AC) with Multiplug inserts (MP).

Results: Four configurations were used for simple beam setup and two for patient QA, replacing water equivalent inserts by lung. For twelve collimators (5–60 mm) in simple setup, mean (SD) differences between MC and RayTracing algorithm (RT) of the number of points failing the 3%/1 mm gamma criteria were 1(1), 1(3), 1(2) and 1(2) for the four MP configurations. Tracking fiducials were placed within AC for patient QA. Single lung insert setup resulted in mean gamma-index 2%/2 mm of 90.5% (range [74.3–95.9]) and 82.3% ([66.8–94.5]) for MC and RT respectively, while 93.5% ([86.8–98.2]) and 86.2% ([68.7–95.4]) in presence of largest inhomogeneities, showing significant differences ($p < 0.05$).

Discussion: After evaluating the potential effects, 1.12 g/cc PMMA and 0.09 g/cc lung material assignment showed the best results. Overall, MC-based model showed superior results compared to RT for simple and patient specific testing, using a 2%/2 mm criteria. Results are comparable with other reported commissionings for flattening filter free (FFF) delivery. Further improvement of MC calculation might be challenging as Multiplan has limited material library.

Conclusions: The AC with Multiplug allowed for comprehensive commissioning of CyberKnife MC algorithm and is useful for patient specific QA for stereotactic body radiation therapy. MC calculation accuracy might be limited due to Multiplan's insufficient material library; still results are comparable with other reported commissioning measurements using FFF beams.

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1. Introductions

The process of radiotherapy is complex and involves lot of individual and computerized tools. Each of these elements and interactions are cumulatively responsible for an accurate treatment delivery to the patients. One of the key element in this entire chain is the proper commissioning of a treatment planning software (TPS).

Precise calculation of the TPS (Multiplan V5.1.3, Accuray Inc.) is depending heavily of the dose calculation engine [1] as well as the inhomogeneity representation of the different materials. For the Multiplan two possible dose calculations are available, namely the RayTracing (RT, [2]) and the X-ray voxel-based Monte-Carlo (MC, [3]). The latter proved to be most accurate [4,5] especially for Stereotactic radiosurgery (SRS) and stereotactic body radiotherapy (SBRT)[6].

The process of commissioning a linac is a major undertaking that can take up a considerable amount of time and effort with various configuration such as point based, 2D or 3D measurements with their limitations [7–10].

For CyberKnife system (CK, Accuray Inc., Sunnyvale, CA), this challenge is even further pronounced (small flattening filter free (FFF) fields [11]) especially since no task group, national guideline or code of practice is addressing this topic. Finding a good balance between precision and prompt readouts while maximizing volumetric information of the delivered dose is a cornerstone of general commissioning as well as patient specific QA measurements.

In our current paper we present a novel method for commissioning the Monte Carlo dose calculation algorithm of Multiplan using a commercially available 3D cylindrical diode array ArcCHECK™ (AC, SunNuclear Corp., Melbourne, FL) phantom in various inhomogeneity situations using the supplied MultiPlug inserts (solid water, lung). Furthermore we are assessing the feasibility of patient specific pre-treatment QA measurements similar to an already published investigation [12] with an extension of multiple inhomogeneity configurations.

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2. Materials and methods

2.1. The CyberKnife robotic linac

This machine is an image-guided frameless stereotactic radiotherapy system consisting a lightweight 6-MV linear accelerator mounted on a robotic arm. For the beam collimation, 12 different cones (ranging from 5 to 60 mm in diameter defined at 800 mm source-axis distance (SAD)) can be used. These cone beams are inferior in dose flatness compared to classical linear accelerator-based SRS cone beams due to the absence of a flattening filter in the CyberKnife treatment head.

2.2. Measurements for the Monte Carlo model

The set of measurements requested by Multiplan were performed and imported into the TPS for modeling. Monte Carlo algorithm is represented by a single photon source located at the target location of the CyberKnife treatment head and assumed to be cylindrically symmetrical. The source distribution is determined based on the measured in-air cone output factors, while the proper energy spectrum is derived from the measured central axis percentage depth dose (PDD) in water for the largest (60 mm at 800 mm SAD) cone at 800 mm source-surface-distance (SSD). The fluence distribution of the photon source is deconvolved from the measured profile at the depth of maximum dose (to avoid effect of electron contamination) without any secondary collimators. Knowing the energy spectrum, the fluence and the source distribution, the beam phase space is reconstructed and used as source input for the Monte Carlo dose calculations in the patient geometry.

In order to correct for commissioning measurements uncertainties on output factors, correction factors were applied to the three smallest collimator size according to the work of Francescon et al. [13] and Huet et al. [14] prior to Monte Carlo modeling.

The Monte Carlo model was created according to the manufacturer specifications in an iterative process [15].

2.3. Management of heterogeneities

In Multiplan the delivered dose is calculated by assuming the effective depth as determined by the density variation along the beam's path by "tracing" the beam as it travels through the tissue for RT, while the MC associates the physical density of each voxel to a material type. This material type is used to define the photon mean free path type at a reference density as a function of photon energy. Local voxel mass density is used to scale each steps of the energy deposition from each particle track. Three materials types are represented in the system and associated to specific mass-density range (cf. Table 1).

2.4. The ArcCHECK with Multiplug inserts

The ArcCHECK consists of 1386 10 mm spaced N-type diodes in a helical arrangement inside a 26.59 cm cylindrical phantom. The diode size is $0.8 \times 0.8 \times 0.03$ mm^3 (width $\times$ length $\times$ height) [16].

Table 1
CyberKnife's Monte Carlo conversion table of mass density to material type.

Mass density range (g/cc)	Material type	Material type mass density (g/cc)
<0.1	Air	0.0012
0.1–1.125	Soft-tissue	1.0
>1.125	Bone	1.85

The ArcCHECK reads out the accumulated diode charge, acquiring frames with 50 ms updates. After each measurement, the individual frames are corrected for diode leakage current and angular dependence. In our study, the angular dependence was not used because of the small field size used in CyberKnife stereotactic treatment.

The Multiplug ArcCHECK central insert is composed of 25 locations of rods with different Gammex (Middleton, WI) tissue-mimicking materials such as PMMA (physical density 1.183 g/cc, referred as water equivalent or water), muscle (1.049 g/cc), bone (1.820 g/cc), and lung (0.290 g/cc). Water equivalent rods can also be substituted with ionization chambers, diodes or film detectors holders.

In a TPS, the virtual patient model is built using 3D volume from the input CT axial images. CT numbers are converted to the applicable densities using lookup table specific to the CT scanner. To avoid the artefact contamination arising from high density diode material, density override was performed over the whole AC and separately for each Multiplug insert's rod.

The ArcCHECK with homogeneous full inserts was used to perform the two-stage calibration following the User Guide. Firstly the diodes signals were calibrated in a twelve-step procedure using Elekta Agility linear accelerator flat fields. Secondly a dedicated CyberKnife specific absolute calibration was executed.

2.5. Measurements

Taking the advantage of the cylindrical shape of the ArcCHECK and the Multiplug inserts, various experimental setups were used. For easy references to the different setups we introduced Fig. 1.

For all twelve fixed CyberKnife collimators (5 to 60 mm diameter), baseline measurements were performed under reference conditions (vertical beam, SAD 800 mm at reference point assigned as the central insert in position D4 of the ArcCHECK).

After the water equivalent setup a), inhomogeneity conditions were introduced by maximizing lung inserts along the beam's central axis. Three different scenarios were constructed replacing the water with lung insert: b) B3-5; c) 4-ABC; d) A4 + B3-5 with D4 remaining as reference point. Lung inserts were placed closer to the beam entrance for the following reasons: 1) higher entrance dose is more sensible to changes 2) the backscattering is altered with changing densities and their volumes.

To synergize with the 3D cylindrical readouts with point-based measurements, we used the CC13 ionization chamber (IBA Dosimetry GmbH, Schwarzenbruck, Germany) inside the ArcCHECK. As a last step, the ability of the ArcCHECK system for CyberKnife pre-treatment QA was evaluated with nine clinical treatment cases that were planned and delivered for lung patients in our department. D4 was used as reference point for the stereotactic plan QA and A4 as lung inserts for both cases with two different Multiplug configurations: e) with and f) without A4+C3−4 +E4−5 lung inserts.

As required by the CyberKnife target-locating system (pair of orthogonal kilovoltage X-ray images), a tracking method must be defined either based on bony anatomy, fiducial makers, or soft tissue contrast. For phantom measurements, the fiducials tracking appears like the only reasonable choice. Consequently, eight fiducial markers were placed in a non-coplanar way in the C5 and E3 holes of the ArcCHECK Multiplug insert. Patient plan information are further describe in the Table 1.

In the last situation, the ArcCHECK test includes multiple beams with multiple incidence angles on a curved surface. The phantom contains multiple surface interfaces, including air–water (outer skin and C5+E3 holes), water-lung (surrounding of A4+C3−4 +E4−5 lung), and air-lung (C4–C5 and E3–E4). It is considered as

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