Brachytherapy planning

Calcifications in low-dose rate prostate seed brachytherapy treatment: Post-planning dosimetry and predictive factors

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ABSTRACT

Background and purpose: The brachytherapy dose algorithm of the American Association of Physicists in Medicine Task Group (TG) Report 43 overrides all tissue materials with water. In reality, dose discrepancies will occur around tissue calcifications. This study investigates these perturbations in low dose rate prostate brachytherapy dosimetry.

Materials and methods: 43 cancer patients with prostatic calcifications are identified. Geant4 Monte Carlo (MC) simulations are made with materials assigned based on TG186 recommendations. Five dose calculation scenarios are presented: MC in water (MCW), MCW with calcifications, (MCCA), MCCA with seeds (MCCA$_{SEED}$) and full tissue definition and seeds with dose to medium in medium (FMC) and dose to water in medium (FMC-$D_{w,m}$).

Results: The mean FMC prostate D90 (V100) difference relative to TG43 is −6.4% (range [−1.8, −14.1]) (−2.6% [−0.3, −6.7]). For MCCA we obtained −3.9% [−1.0, −8.7] (−1.5% [−0.2, −4.1]). The mean urethra D10 difference is −4.5% [−1.3, −9.9] for FMC, −2.4% [−0.7, −5.1] with MCCA. FMC-$D_{w,m}$ D90 has a −0.45% smaller dose difference than FMC on average. The calcification/prostate volume ratio is a good predictor of dose perturbation (R^2 = 0.75).

Conclusion: Based on these results, calcifications alter the dose coverage and may have severe dose perturbation that requires recalculation.

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Permanent prostate brachytherapy (PPB) is a common procedure to treat early stage prostate carcinoma. In this procedure, radioactive seeds emitting low energy photons are implanted in the entire prostate with transperineal needles. The precise position and the number of seeds are determined in a treatment planning system. The biochemical control related to the implant has been directly correlated to the quality of the dose distribution [1], quantified through the dose volume histogram (DVH) metrics calculated on the post-implant CT or MRI images. Therefore, the American Association of Physicists in Medicine (AAPM), the American Brachytherapy Society (ABS) and the European Society for Radiotherapy and Oncology (ESTRO) [2–4] recommend post-implant

dosimetry should be performed on every patient undergoing PPB. Currently, recommendation for clinical TPS at the low energy range (<40 keV) is to use the TG43-U1 dose protocol [5], a homogeneous analytical water-based algorithm to simulate the dose deposition. However, several studies have previously demonstrated that tissue heterogeneity and interseed attenuation (ISA) alter the dose distribution [6–14]. Furthermore, seed positions may alter after the implant procedure leading to dose differences compared to the treatment plan [15].

In PPB, the photoelectric effect plays an important role and is dependent upon the tissue effective atomic number (Z_{eff}) [7]. At the low-energy regime (<40 keV), calcifications (Z_{eff} = 14.92) represent important tissue heterogeneity in the prostate. The potential importance of prostate calcification was mentioned by Chibani et al. [9], Carrier et al. [6,16] and both the AAPM TG64 [1] and TG186 [10].

The spatial distribution of the calcifications within the prostate has been studied [17]. A majority of patients with calcifications have them located either within the prostate and ejaculatory system (88.6%) or in the seminal vesicles (58.1%). However, prostate

calcification composition is not known with great accuracy. Pope et al. [18] looked at the pathological calcification samples of four patients undergoing radical prostatectomy to determine the calcification composition. The techniques they used did not allow the detection of light elements such as carbon, hydrogen or oxygen, which are important when looking at diffuse calcifications at low energy. Also, they found a large variability (difference of 12% on the ^{40}Ca fractional mass) in the atomic composition of their samples. Considering lack of precise information regarding the prostate calcification composition, TG186 [10] recommends the use of breast calcification, reported by the ICRU Report 46 [19], as a surrogate. Dual-Energy CT imaging is considered as a potential avenue to improve tissue definition in LDR brachytherapy [11,20,21,22] and to better estimate the calcification composition.

Chibani et al. [9] quantified the potential dose impact of calcifications by using Monte Carlo (MC) simulations. They used randomly distributed calcifications in 1%, 2% or 5% of the voxels belonging to the prostate of case 1 (case 2) and found respective differences of 7.6% (8%), 17% (15%) and 37% (30)% on the D90 relative to the non-calcified prostatic tissue. Youssef et al. [13] studied a case of prostate calcification and found a region of underdosage on the calcifications (0–35%) relative to the water tissue. Recently, Mason et al. [14] have analyzed 40 patients with 10 of them having prostatic calcification. They compared simulations in water and in tissues, using contours and CT data to assign materials. Their D90 was reduced (relative to the reference) up to −7.4% on the group with calcification.

It is hypothesized that dose coverage will be decreased in the shadow of calcifications. Until now, no study has been performed on a large cohort of calcified PPB patients using TG186 recommendations. This study aims to investigate the effects of the calcifications by performing MC simulations for a patient cohort selected from an anonymous dosimetry database.

Methods and materials

In this retrospective study, a cohort of 43 prostate brachytherapy patients was selected from a dosimetry database numbering 1987 cases by visual detection of calcifications within the clinical target volume (CTV). Each case had post-planning CT images (Somatom Emotion; Siemens, Munich, Germany) acquired 30 days post-implant. Voxel sizes were [0.289, 0.289, 2.5] mm^3. Physician contours of the urethra and the prostate drawn on the CT images were extracted from the DICOM-RS files. Seed positions were obtained from the DICOM-RP file. The seed model was SelectSeedI125 (Nucletron; Elekta, Stockholm, Sweden). The number of seeds varied between 36 and 75 with a mean of 51 seeds. Mean seed strength was 0.7685 U (0.751–0.783 U).

Five MC simulation models were employed to isolate different effects. First, only water was simulated (1: MCW). Then, water and calcified tissues were taken into account in the simulation (2: MCCA). Next, seeds were added to the geometry (3: MCCA$_{SEED}$) with the aid of Geant4 Layered Mass Geometry (LMG) [23]. Finally the full MC simulations with complete material definitions, based on TG186 [10] recommendations, and LMG seed geometry was implemented with dose scoring to medium (4: FMC) and dose scoring to water (5: FMC $D_{w,m}$).

Patient geometry

Electron density assignation based on CT calibration curve

The Hounsfield Units (HU) of the day 30 post-planning CT images are converted first to electron densities and then to physical densities to scale the cross-sections for increased simulation accuracy. For this purpose, the clinical calibration curve between HU and electron density is used. For our Siemens CT scanner, the curve is obtained using a CIRS phantom (model 062M; Norfolk, USA). The TG186 [10] linear fit is used to convert electron density to physical density.

Composition of human tissues based on TG186

The TG186 [10] formalism is used to assign material composition (Z_{eff}) for each voxel within the geometry. Elemental composition and mass densities of tissue are taken from the ICRU Report 46 [19] and TG186 [10]. Air (40% humidity) composition is based on TG43 [5]. The recommendation of TG186 is to use breast calcification composition (ICRU Report 46 [19]) as a surrogate. In the patient cohort, the calcified area density varied between 1.2 and 2.16 g/cm^3. To account for this variability, 6 composite elements were created by linear interpolation between prostatic tissue and calcified tissue composition, at 20% interval (Table 1), with 100% calcification corresponding to the TG186 recommendation.

First, the midpoint between two material densities is chosen as the threshold (Table 2) to assign materials to voxels within each organ. Then, the voxel densities are scaled to the CT physical density while keeping Z_{eff} invariant.

Simple threshold region artifact removal algorithm

The high-density brachytherapy seeds cause artifacts in the CT images. These artifacts decrease the image quality by increasing the noise in the surrounding areas and diminishing the soft-tissue contrast [24]. Above all, high-density and high Z_{eff} material will be allocated in the region around the seeds if no correction is applied. A spherical region ($r = 2$ mm) is defined around each seed position and the medium is replaced with TG186 prostate tissue. Precise seed material and geometric definition are added back to the Geant4 geometry in the LMG parallel world [23] to account for the effects of ISA on the dose distribution.

Calcification ROIs and distance relative to the CTV

To define the calcification region of interest (ROI), the density threshold defined in Section II-A-2 with the minimal composite material (20% Ca Table 2) is used. The center of mass (COM) of the calcification is defined as the ROI center. Calcification distances are computed with the geometrical center of the CTV as origin. The ROIs allow us to quantify the calcification volume and their physical density.

TG43 formalism

The TG43 dosimetry protocol [4] and its update [5] have been a standard for almost 20 years of brachytherapy treatment planning. The dose kernel of a single seed in a spherical water region (radius 15 cm) is determined and superimposed over each seed position.

The calculation geometry has a large variability between patients due to the differences in the seed positions, in the physician contours, and the presence, position and volume of calcifications within the region of interest. Thus, the direct comparison of DVH metrics between patients is impossible. For every patient, every scenario is normalized by the TG43 dose. This choice is also motivated by the fact that TG43 is the current clinical standard.

Monte Carlo simulation code and analysis tool

MC Geant4 simulation code (v4.9.6.p02) is used because of the LMG [23] functionality that allows the superposition of a parametric construction of the seeds over the voxelized grid geometry. This functionality stops the transported particles at each boundary, either from the CT grid or the parametric parallel world. Parametric materials have priority in the simulation to CT assigned material. All simulations in our study use the Linear Track-Length Estimator