Override of High-density Implants and Validation of their Dose Perturbation in Pencil-beam-scanning Proton Therapy

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JULY 12–16 2020 VIRTUAL
JOINT AAPM | COMP MEETING
EASTERN TIME [GMT-4]

INTRODUCTION

Significant uncertainty of the proton dose calculation could happen beyond the high-density implants if sufficient material information (mass density, mass fraction of atomic elements and mean excitation energy) is not provided to the dose calculation engine.

AIM

To propose a clinical workflow for material override of high density implants in treatment planning system and validate their dose perturbation in pencil beam scanning proton therapy.

METHOD

Implants:

- A ceramic femoral head (Zirconia toughened Alumina ceramic (ZTA)), a titanium alloy stem (Ti-6Al-4V) in a hip replacement system (DePuy Synthes)
- A PEEK spine spacer (DePuy Synthes)
- A Vitallium rod (Stryker)
- A bone cement sample (Kyphon® HV-R™, Medtronic)

CT Imaging

- Implants were scanned using a clinical head protocol on top of a 4cm-high egg crate foam to effectively eliminate the imaging artifacts and eliminate the scatters from the couch.

Material override in TPS

- Stopping power ratio (SPR) of implant was calculated using SRIM.
- Water equivalent mass density was found by searching in the mass density-SPR table in TPS, then assigned to the override material.
- Override material is based on a reference material which has the same elemental composition and mean excitation energy, if possible, otherwise similar excitation energy. This step has nothing to do with the effective mass density.

Dose perturbation verification

- The implant was placed on top of the solid water as in Figure 1 with the EBT3 film sandwiched inside the solid water in the transverse or sagittal plane.
- A square ($10x10x6cm^3$) verification plan was delivered to measure the dose perturbation in the presence of implant.
- Dose perturbation plane was exported to RIT and registered with film dose to verify the range pull-back due to the implant.

RESULTS

- PEEK: mass density 1.32g/cm^3; SPR=1.24, effective mass density=1.31. Using CT number to interpret the mass density resulted in no significant dose difference from using material override.
- Bone cement: mass density 1.29g/cm^3; SPR=1.18, effective mass density=1.225, Overrride material is based on bone 1 in TPS.
- Titanium alloy: mass density 4.42 g/cm^3; SPR=3.12 (3.08-3.15), effective mass density=4.22. Overrride material is based on Ti in TPS.
- Ceramic: mass density 4.37 g/cm^3; SPR=3.43 (3.40-3.45), effective mass density=4.63. Overrride material is based on Aluminum 2 in TPS.
- Vitallium: mass density 8.46; SPR=5.71 (5.63-5.78), effective mass density=8.12. Overrride material is based on steel in TPS.
- CT number can't be used for TPS to interpret the mass density for those materials except PEEK.
- Figures 2 and 3 show that the correct way to override is using the effective mass density and is based on a reference material with similar excitation energy.
- In Figure 4, the profiles demonstrate that the range difference of three high density implants was less than 1mm, and the override materials were acceptable for clinical use.

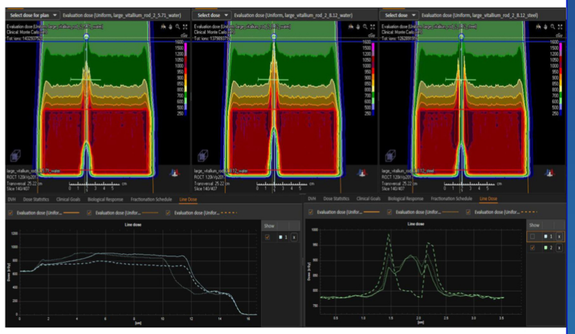

Figure 2. Vertical dose profile of Vatillum rod shows the calculated dose difference between override based on steel (large dashed SPR=5.71, correct) and water (solid SPR=5.71,dashed SPR=8.12) when the rod is in air and right on top of the solid water. Lateral dose profile explains the discrepancy is caused by different nuclear scattering cross section of the override materials.

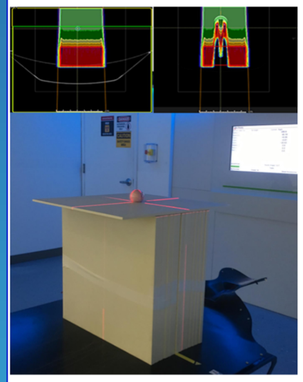

Figure 1. Implant and solid water setup for film measurement.

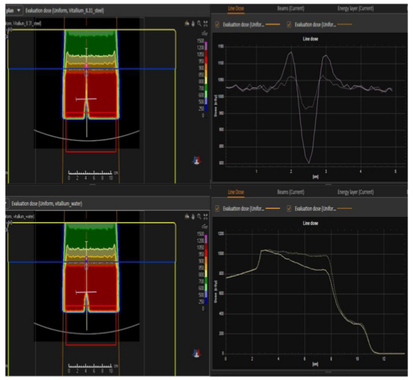

Figure 3. Vertical dose profile of Vatillum rod shows the calculated dose difference up to 18% between override based on steel (solid, correct) and water (dashed) when the rod is right on top of the target volume. Lateral dose profile explains the discrepancy is caused by different nuclear scattering cross section of the override materials.

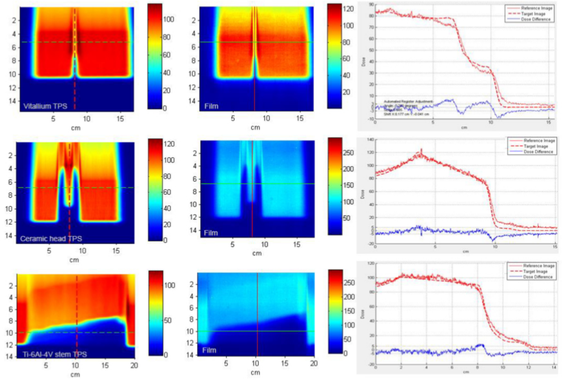

Figure 4. Range discrepancy of film dose (Right) with calculated dose in TPS (Left) was less than 1mm. When the excitation energy of the override materials was similar with the experimental materials, not only the stopping power ratio is closely mimicked, but also the nuclear scatting cross-section. Top: Vitallum rod, Middle: Ceramic, Bottom: Ti-6Al-4V.

CONCLUSIONS

The proposed clinical workflow is feasible and easy to implement when the SPR of a high density implant needs to be validated before clinical use.

Range uncertainty of the implant can be effectively improved to be less than 1 mm with the accurate SPR of the material and choosing a proper override material with the closest possible excitation energy.

This is especially important when the high density implant lies inside the target volume or adjacent to it, and therefore accurately predicting dose perturbation could result in improved target volume coverage, reduced plan complexity, and higher robustness.

ACKNOWLEDGEMENTS

The authors would like to thank the following collaborators for generously sharing or providing the samples to this work: Ben Thomas, Jerold Simpson, Brian Thompson, and Mike Alonzi.

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