Possibilities and challenges when using synthetic computed tomography in an adaptive carbon-ion treatment workflow

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Objective

Anatomical surveillance during ion-beam therapy is the basis for an effective tumor treatment and optimal organ at risk sparing. For photon therapy synthetic CT (sCT) based on MRI can replace X-ray based planning CT (X-rayCT), and reduce the workload and imaging dose for the patients, but for ion-beam therapy this technique is scarcely explored. The challenges that arise for carbon-ion therapy are manifold:

- complex patient positioning due to limited beam angles,
- unique anatomical situations,
- and limited training data to train neural networks.

Aim: This study provides an outlook on the possibilities and challenges for sCTs in carbon-ion treatment workflows.

Patients and Methods

11 patients with head and neck tumors treated with carbon-ion therapy at the MedAustron Ion Beam Therapy Center in Wiener Neustadt were included in this study. All patients were immobilized with thermoplastic masks of 2 or 3.2 mm thickness.

Imaging for all included patients:

- CT and a T1 MRI sequences prior treatment on the same day
- All image acquisitions in treatment position including all immobilization devices

The sCT generation was performed with a pre-trained model (for proton therapy patients) based on a 3D U-Net architecture[1]. Carbon-ion treatment plans were created on the X-rayCT with the TPS RayStation and re-calculated on the sCT.

Evaluation:

- Image conversion quality: mean absolute error (MAE)
- Plan quality comparing sCT and X-rayCT: DVH parameters, spot displacement.

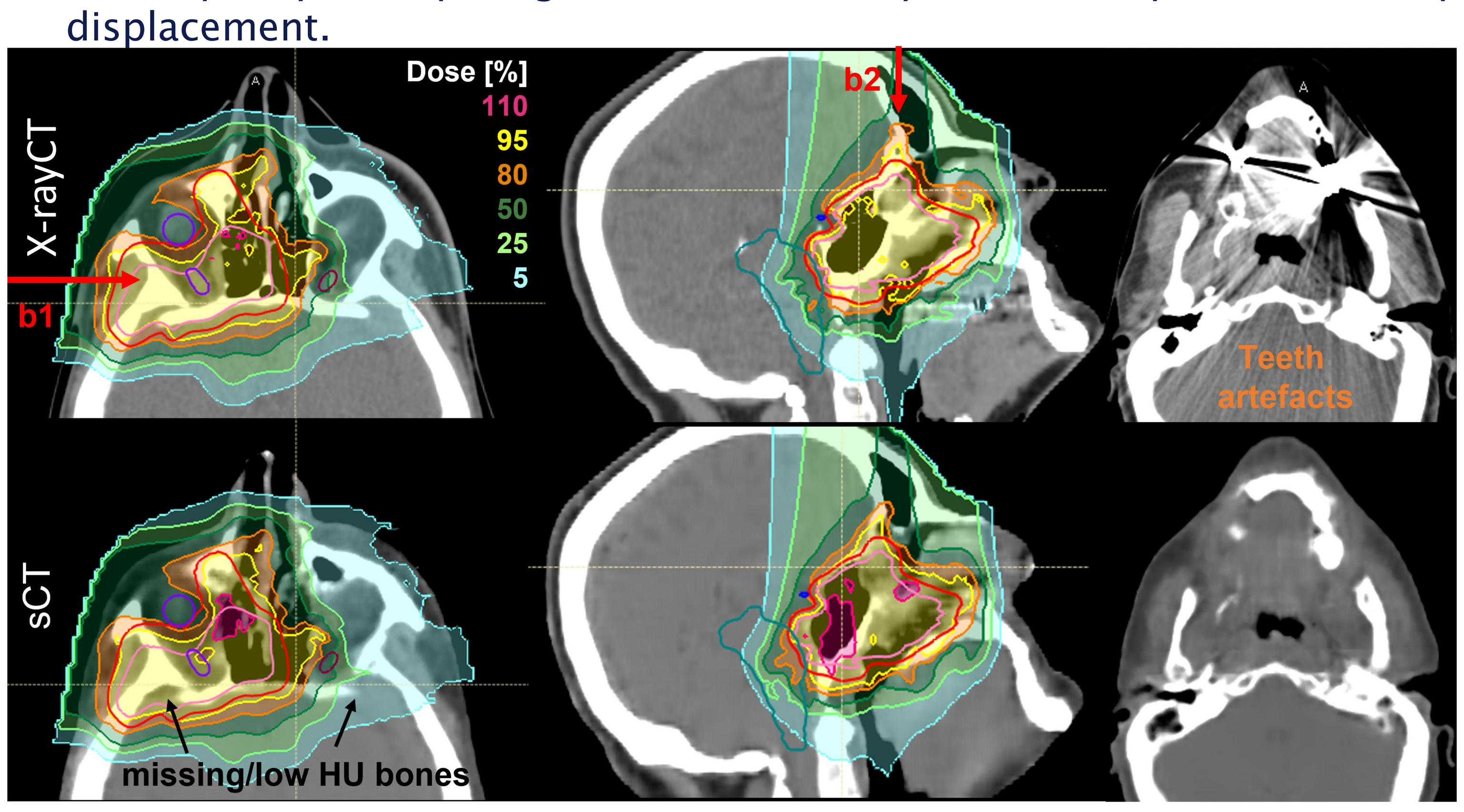

Figure 2: Representative patient for a hyperextended head position with a tumor located close to the surface. The patient was treated with a horizontal beam (b1) and a vertex beam (b2) Top row shows the dose distribution on the X-rayCT and the bottom row on the sCT. The very right column shows teeth artefacts on the X-rayCT that are non-existing on the sCT.

Results

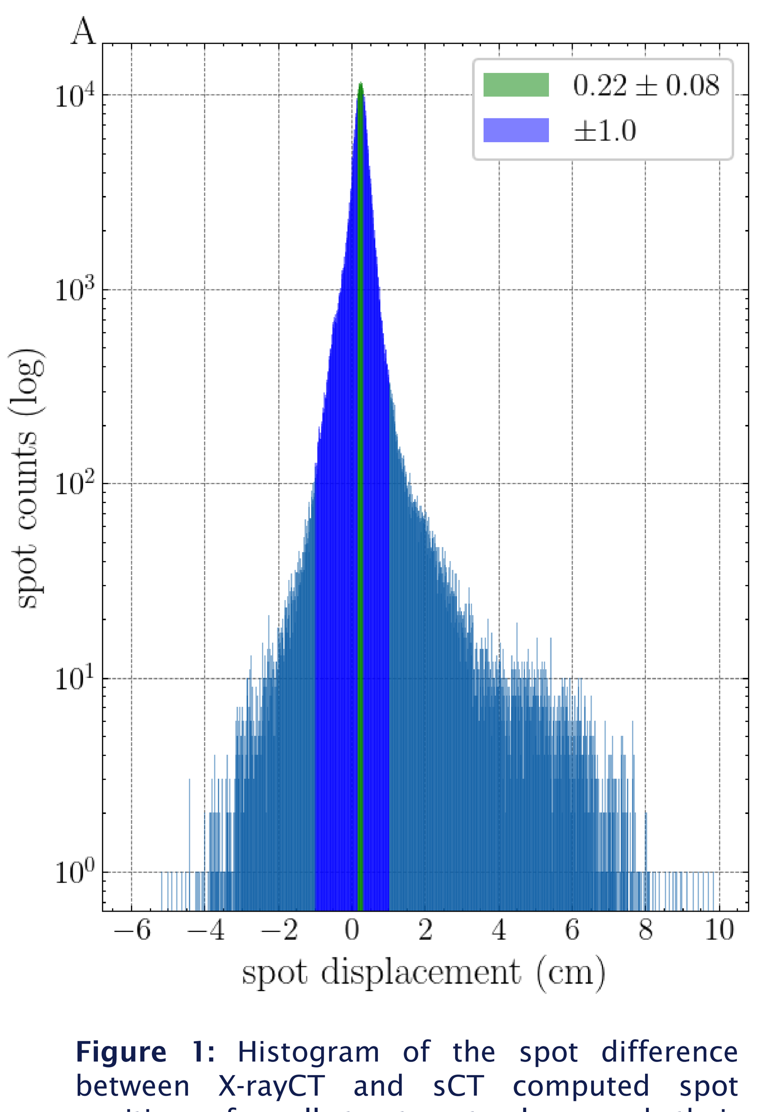

Figure 1: Histogram of the spot difference between X-rayCT and sCT computed spot positions for all treatment plans and their related spots in logarithmic scales (A).

- Spot displacement: 30.3% of the spots were shifted by the mask material (which is not visible on MRI) as shown in Figure 1. This peak was detected at 0.22±0.08 cm for every patient. Maximum displacement ranged from -5.2 cm to 10.5 cm.
- Target structures: For both target structures (i.e. PTV and CTV) the main dose differences was observed for the $D_{0.1cc}$ with a median overdosage of 4.2% for the CTV and 3.8% for the PTV. For the CTV $D_{50\%}$ and $D_{2\%}$ differed by -0.2% and 1.7% as summarized in Figure 3. The median conformity index for the PTV changed by 6% [1%-26%], but only by 2% [-5%-20%] for the CTV.
- Organs at risk: The dose to optical system (chiasm or optical nerves) was deteriorated in 7 out of 11 patients. A representative DVH is shown in Figure 4.
- sCT quality: The MAE between X-rayCT and sCT was 89.2±20.2 HU for the whole body covering the range from -1000 to 3000 HU.
- sCT benefit: The sCT generation technique was able to reduce teeth artefacts, as illustrated in Figure 2.

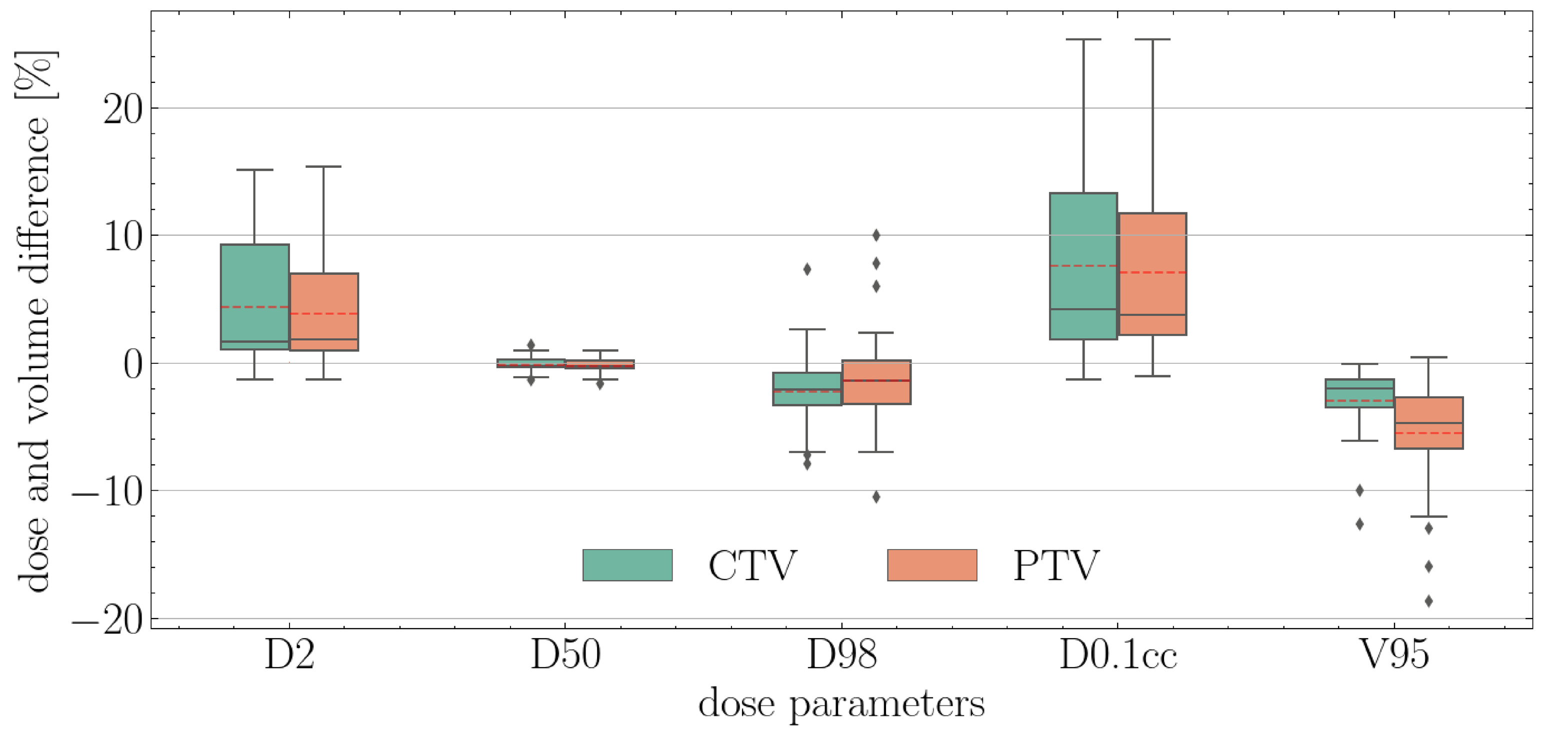

Figure 3: Differences between X-rayCT and sCT computed DVH parameters for the target structures. Dose values recomputed on the sCT were subtracted from the original dose values on the X-rayCT.

Discussion and Conclusion

While every radiotherapy workflow benefits from the use of sCTs in terms of workload, resources and imaging dose, this study focused on the challenges and characteristics that come along when applying carbon-ion therapy. There is no commercially available sCT generator validated for carbon-ion therapy, so the neural network-based generator presented in Zimmermann et al[1] was applied. This generator provided results for proton therapy patients that agree with other literature on proton therapy.

sCT conversion performance for carbon-ion therapy patients:

- Worse performance compared to previous study caused by challenging immobilization and sometimes unique anatomical situations.
- Training data sets collection is difficult due to limited number of carbon-ion therapy patients.
- Requirement of collecting training data in a multi-center approach, which requires an MRI sequence independent sCT generator.

One uncertainty identified in this study was the thermoplastic mask, which caused a shift between X-rayCT and sCT based dose distribution of 0.22±0.08 cm. As the mask material is stretchable the thickness varies and a compensation without the X-rayCT information is challenging.

Even it seems to be a long way towards a full MRI-only workflow in carbon-ion therapy, the use of sCTs in certain steps of the workflow has high potential. sCTs show reduced teeth artefacts and could be used in an adaptive therapy workflow concept instead of replacing the initial planning CT completely.

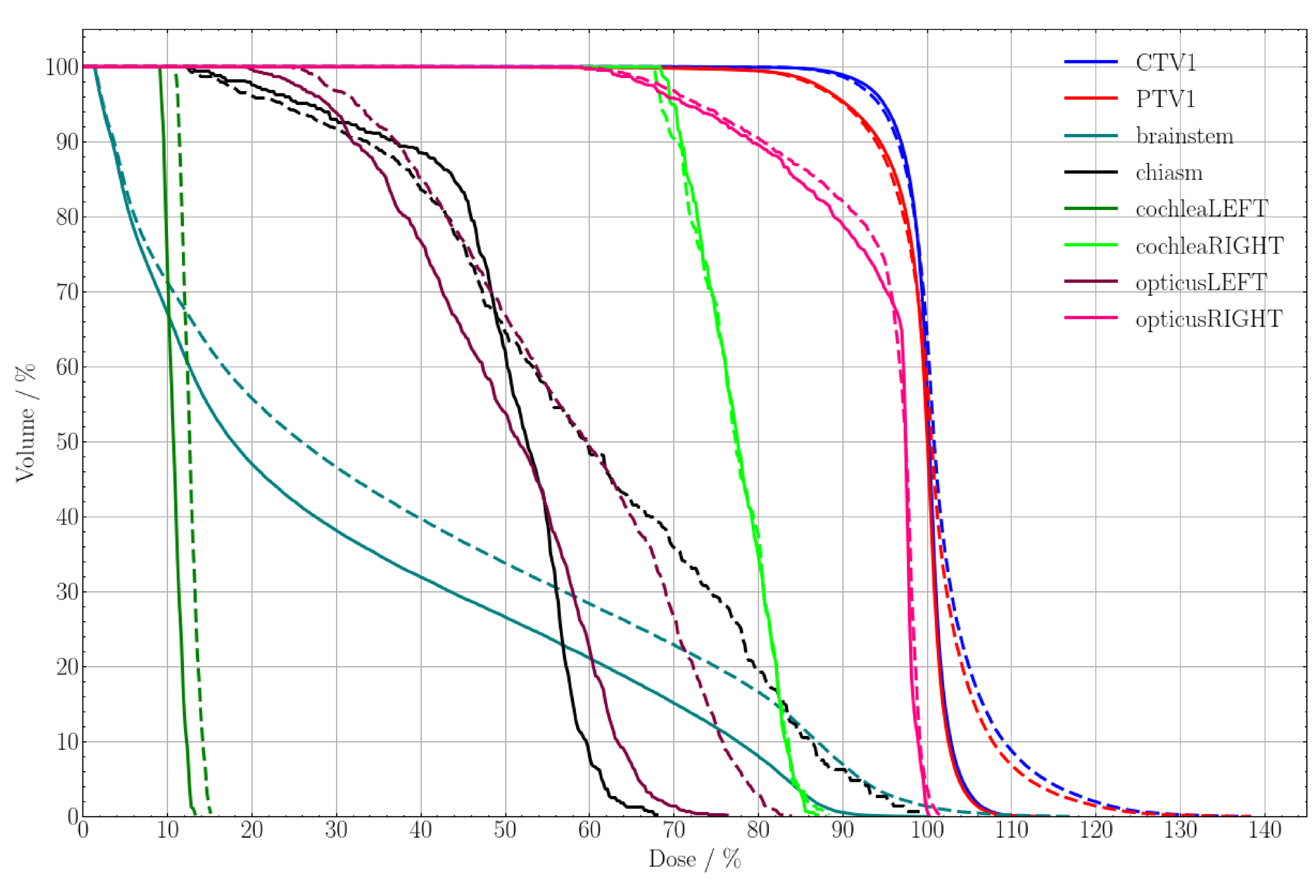

Figure 4: Representative DVH for CTV, PTV, as well as organs at risk. The solid lines represent the original dose computed on the X-rayCT and the dashed line show the dose re-computed on the sCT. This patient was irradiated in hyperextended position and the MAE of 77 HU was one of the lowest observed in this study.

References

[1]Zimmermann et al: Z Med Phys:. 2021 Dec 14;S0939-3889(21)00089-1. doi: 10.1016/j.zemedi.2021.10.003.