Final Assignment

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1 Introduction

1.1 Carbon ion for tumor treatment

Carbon ion hadrontherapy is an advanced form of radiation therapy based on the use carbon ions for cancer treatment, instead of traditional X rays, electrons or protons.
Compared to conventional radiation therapy, carbon ions (and hadrontherapy in general) offer several advantages. Due to their higher LET, they can damage tumor cells more effectively because they can deposit a large amount of energy in a small area, increasing the probability of damage (DSB). In addition, the use of carbon ion allows higher ballistic precision in delivering the dose to the tumor, while sparing the surrounding healthy tissue, thanks to the Bragg peak effect. The Bragg peak dose distribution is characteristic of charged hadrons, but carbon ions, due to their high mass, exhibit particularly straight trajectories at proximal depths, and a lower fractionation probability at distal depth than Neon ions. In fact, carbon ions offer high radiobiological efficiency (RBE), and a low oxygen enhancement ratio (OER), making them ideal for low or ipo fractionation treatments and for the treatment of hypoxia tumors. The high ballistic precision of carbon makes radiation delivery successful only when accompanied by high-precision imaging, to reduce the overall irradiated volume, and spare healthy tissue. For this reason, the choice of the right instrument for imaging is of great importance.

1.2 MRI imaging

The purpose of this work is to investigate whether MRI-guided planning of carbon ion treatment is feasible for clinical application.
So far, CT scans were primarily used for treatment planning. Their spatial resolution is better than that of MRI because the latter uses magnetic fields and radio waves rather than X-rays. However, the use of MRI images offers several advantages. MRI provides excellent soft tissue contrast, and therefore allows a better delineation of the structures of interest, reducing the risk of errors in dose administration. In addition, by eliminating the need for additional CT scans, the overall radiation exposure to the patient can be reduced.
In the MRI-only approach, MRI is used as the sole imaging modality. Synthetic CT images are generated from MRI data using advanced algorithms that convert MRI data into a CT-like representation. Although an MRI-only workflow offers numerous advantages, it may not be suitable for all radiation therapy scenarios.

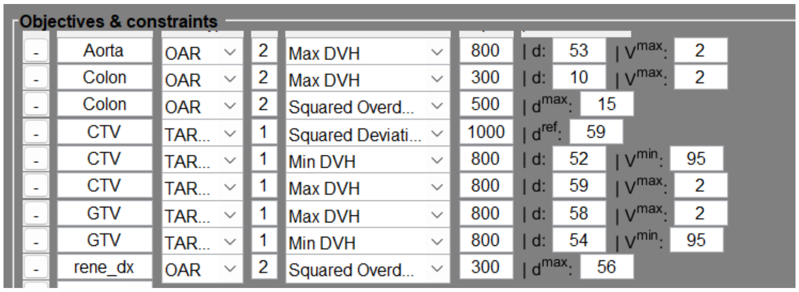
1.3 Aim of the project

In this project the aim was to replicate a reference treatment plan on the planning CT and to recalculate it on the synthetic CT, obtained from MRI. The feasibility of this approach for clinical application was assessed by performing a Gamma Analysis.

2 Treatment planning

2.1 Plan setup and optimization

The reference treatment plan consisted of treating a pancreatic tumor by administering the prescribed dose over 12 fractions of carbon ions. To replicate the reference plan on the planning site CT, the gantry angles were set at 0° and 270°. In order to obtain a sufficiently accurate plan, the targets and structures in Figure 1 were selected in the optimization process: GTV, CTV, aorta, colon, right kidney, spinal chord and stomach.



Objectives & constraints

-	Aorta	OAR	2	Max DVH	800	d: 53	V^{max}: 2
-	Colon	OAR	2	Max DVH	300	d: 10	V^{max}: 2
-	Colon	OAR	2	Squared Overd...	500	d^{max}: 15	
-	CTV	TAR...	1	Squared Deviati...	1000	d^{ref}: 59	
-	CTV	TAR...	1	Min DVH	800	d: 52	V^{min}: 95
-	CTV	TAR...	1	Max DVH	800	d: 59	V^{max}: 2
-	GTV	TAR...	1	Max DVH	800	d: 58	V^{max}: 2
-	GTV	TAR...	1	Min DVH	800	d: 54	V^{min}: 95
-	rene_dx	OAR	2	Squared Overd...	300	d^{max}: 56	

Figure 1: Objectives for the replicated treatment plan.

With this beam arrangement, the dose distribution shown in Figure 2 were obtained.

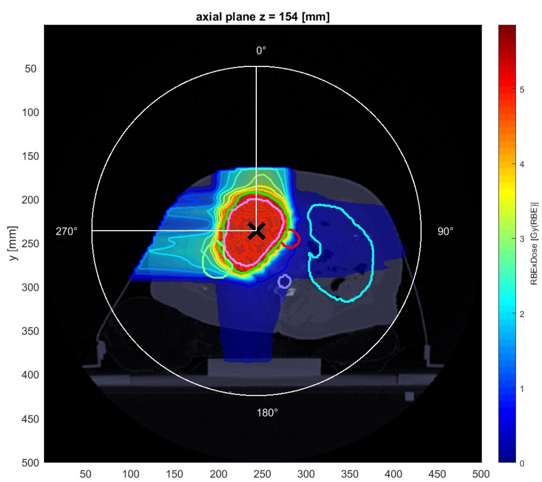


Figure 2: Replicated treatment plan on reference CT

2.2 Results

Before proceeding with the synthetic CT, a comparison was made with the reference treatment plan, at first qualitatively in the form of dose maps and DVH curves, then quantitatively with respect to dose measurements. As shown in Table 1 the clinical requirement of $57.6\,Gy$ to 95% of CTV volume was met, while complying with the dose constraints on the organs at risk.

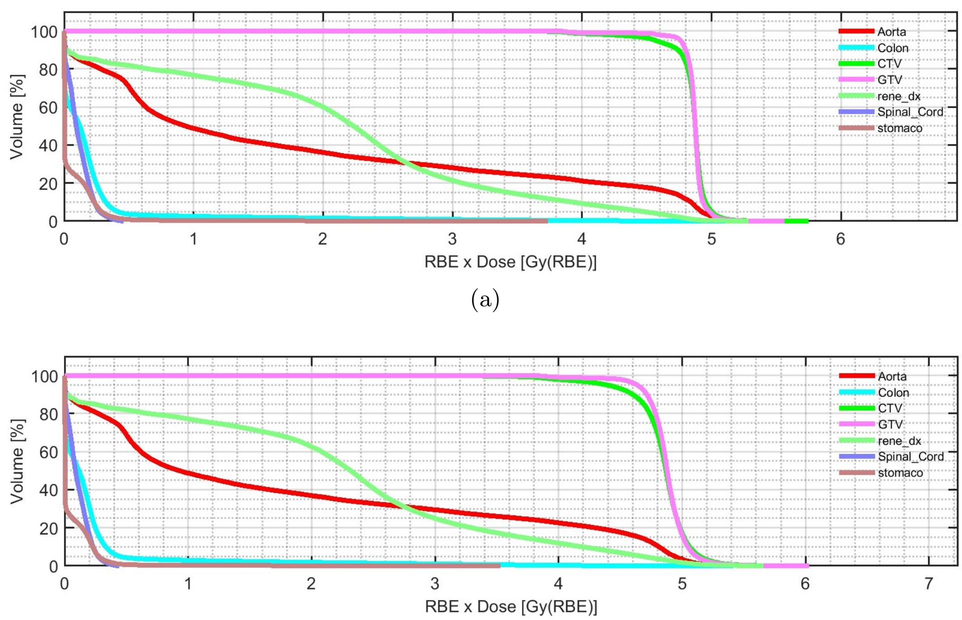
2.3 Recalculation on synthetic CT

The developed treatment plan was then recalculated, with the same setup and constraints, on the synthetic CT, obtained from MRI by Deep Learning methods.

The aim was to compare the treatment plan calculated on the conventional CT with the treatment plan computed on the synthetic CT in order to, if the results were comparable, take advantage of the MRI-only approach. Indeed, the synthetic image better highlights the soft tissues at the expense of the hard tissues and provided anatomical images without irradiating the patient.

2.4 Comparison between synthetic and reference CT

The two treatment plans were compared in terms of dose maps, DVH curves and dose profiles, as shown in Figure 3 and in Table 1. The dose constraints on aorta, colon and right kidney were not met in the replication of the plan on the synthetic CT. This could be due to uncertainties given by errors in the replication of anatomical structures in the synthetic plan or to the presence of air bubbles.



(a)

(b)

Figure 3: Dose-volume histograms for the CT-based plan (a) and the sCT-based plan (b).

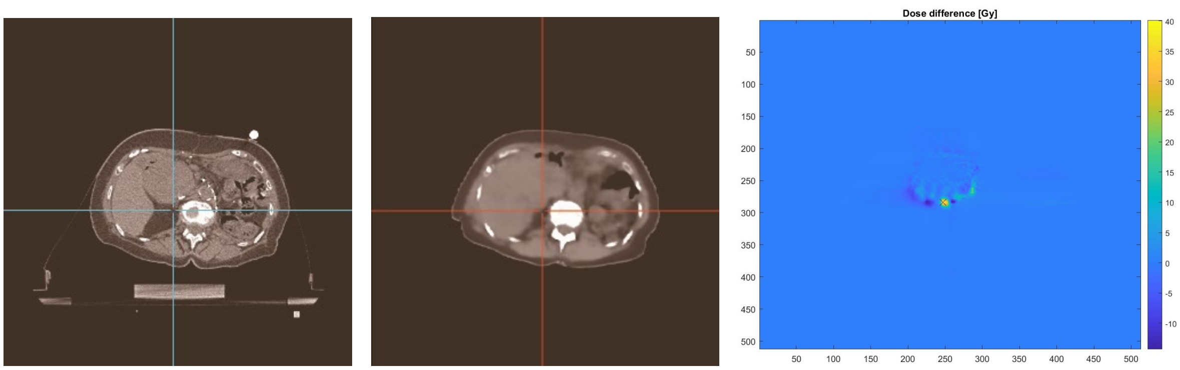
Volume	**D2 synth**	**D2 ref**	**D95 synth**	**D95 ref**
CTV	63,16	60,77	52,71	54,78
GTV	62,73	60,46	55,61	57,10
Aorta	60,90	60,27	0,007	0,007
Colon	21,52	18,06	0	0
Kidney dx	59,63	57,05	0	0
Spinal chord	3,93	4,09	0	0
Stomach	4,35	4,59	0	0

Table 1: DVH for synthetic and reference CTs

3 Analysis of the results

3.1 Dose difference analysis

Offline analysis allowed quantitative comparison between the two treatment plans in terms of dose distribution. The maximum dose difference were measured to be $40.1\,Gy$, at coordinates [247 284 87] in correspondence of an air bubble region, as shown in Figure 4.



(a) (b) (c)

Figure 4: Maximum dose difference point plotted on the CT (a) and on the sCT (b), along with dose difference distribution (c) in the slice corresponding to the maximum dose difference.

3.2 Gamma analysis

Gamma analysis results provided a quantitative assessment of the agreement between the CT-based and the sCT-based plans in terms of dose distribution accuracy. A pass/fail criterion was established based on specific tolerance values for the dose difference and the distance-to-agreement. If the calculated gamma index was within the specified criteria, it was considered to pass. Otherwise, it was considered as failed. A good agreement means that the sCT-based approach is reliable.

The threshold, dose difference and distance to agreement (DTA) were modified to evaluate different scenarios. The threshold refers to the dose difference that is considered acceptable for a given comparison between the measured and reference dose distributions. It is typically defined as a percentage of the prescribed dose. Any dose difference below the threshold is considered within acceptable limits. The dose difference, represents the numerical disagreement between the two distributions. DTA measures the spatial agreement between the distributions. It specifies the maximum distance allowable between corresponding points in the two distributions for them to be considered in agreement. DTA is usually expressed in millimeters $[mm]$. The pass rate is a measure of the agreement between the measured and calculated dose distributions and represents the percentage of points or pixels that meet the predefined criteria for dose difference and DTA. It indicates the quality of agreement. Usually, an acceptable pass rate should be higher than 90%.

The parameters chosen for the analysis are listed in Table 2. The analysis carried out with $3\,mm$ - 3% parameters showed a resulting pass rate within the acceptance range, both when setting the dose threshold to 10% and to 90%. A more stringent analysis was then performed, by using $1\,mm$ - 1% constraints, which resulted in a much lower pass rate in both cases.

Threshold [%]	**Dose difference** [%]	**DTA** [mm]	**Pass Rate** [%]
10	3	3	97,38
90	3	3	92.86
10	1	1	81.33
90	1	1	54.73

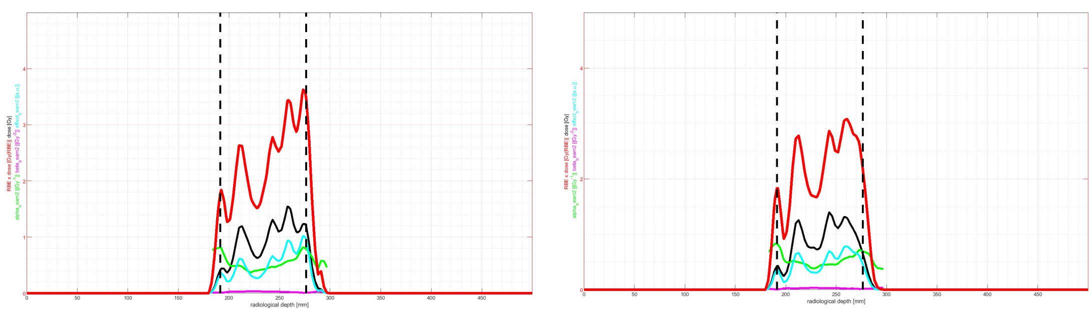
Table 2: Gamma Analysis Setup

3.3 Range shift analysis

The purpose of range shift analysis is to account for uncertainties or variations in the range of radiation in the patient's body. The range of carbon ions in tissue depends on their energy, and it is critical to accurately determine the range of ions to ensure that the tumor receives the desired dose while minimizing radiation exposure to surrounding healthy tissues and organs. Several factors can affect the range of carbon ions, such as changes in tissue density, anatomical variations, and internal organ movements

To evaluate the range shift, a beam and a slice must be chosen. The choice of the slice depends on the specific treatment site and the region to be examined. Some criteria for slice and beam selection include coverage of the target volume, adjacent organs at risk and air bubble regions or regions of varying density. In this plan beam 2 was chosen since it encounters all of the formerly mentioned relevant structures. Following the same reasoning, the slice was chosen in the axial plane corresponding to $z = 154\,mm$.

The difference between the beam ranges in the two plans, computed at 80% of the more distal dose peak from the dose profiles shown in Figure 5, was then calculated. The value of the range shift resulted equal to 5,4 mm, therefore within the acceptance range.



(a) (b)

Figure 5: Depth-dose profiles of the 270° beam for the CT-based plan (a) and the synthetic CT-based plan (b).