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Evaluation of dual-arc VMAT radiotherapy treatment plans automatically generated via dose-mimicking

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Introduction

Dose-mimicking allows for the automatic creation and optimization of coplanar/non-coplanar three dimensional conformal radiation therapy (3DCRT), step-and-shoot intensity-modulated radiation therapy (IMRT), sliding window IMRT, and volumetric modulated arc therapy (VMAT) treatment plans that mimics a reference radiotherapy treatment plan of any modality. The algorithm is currently used in multi-criteria optimization (MCO) to go from a navigated fluence-based plan to a plan that is actually deliverable [1, 2]. The algorithm is also used to create alternative treatment plans in various treatment planning systems (TPSs). Provided that the dose-mimicking algorithm is capable of creating deliverable treatment plans of high plan quality, it would ensure a high level of flexibility in clinical practice. The dose-mimicking algorithm would give clinics (with TPSs which have dose-mimicking capabilities) the ability of automated multi-modality optimization, which could be used to verify that a patient is always treated with the optimal treatment technique [3]. It would also supply alternative treatment plans if a treatment technique/machine becomes unavailable, ensuring continuous patient treatment, which is of great importance for therapeutic outcome [4].

Hence, the purpose of this study was to investigate the plan quality achieved for dual-arc VMAT plans, optimized via dose-mimicking. A second purpose was to verify that such plans can be accurately delivered at a clinically commissioned linear accelerator (linac).

Methods and Materials

Twelve patient cases with tumors in the head & neck (n=3), brain (n=3), abdominal (n=3) and pelvic regions (n=3) were used for the study. Numerous (>100 per case) dual-arc VMAT treatment plans (6 MV) were created and optimized in our clinical TPS (Eclipse™, Varian Medical Systems Incorporated, CA, USA) by varying the importance of sparing a key organ at risk (OAR) in the plans, while keeping doses to other OARs constant (acceptable variation < 1 Gy) and below our clinical dose-volume criteria. The trade-off between the mean dose to the key OAR and the volume of the planning target volume (PTV) receiving less than 95% of the prescribed dose was used to evaluate the plan quality. Sub-optimal plans were subsequently rejected leaving a total of 152 system-specific optimal plans [5-7], i.e. one front of optimal plans for each of the twelve patient cases. These original plans were then exported to the fallback module in RayStation® (RaySearch Laboratories AB, Stockholm, Sweden), where new corresponding dual-arc VMAT treatment plans (with similar settings) were automatically created and optimized via dose-mimicking. Details about the dose-mimicking algorithm can be found in the supplementary material.

By plotting the fronts of the original plans together with the corresponding data from the dose-mimicking plans, the plan quality could be evaluated and compared [8, 9]. All 304 plans (152 original plans and 152 dose-mimicking plans) were delivered with a TrueBeam™ (Varian Medical Systems Incorporated, CA, USA) linac and measured with a bi-planar diode array system (Delta^{4}®, ScandiDos AB, Uppsala, Sweden). Measurements were compared with TPS calculations using three-dimensional γ-analysis [10, 11] with the criteria set to 3%/2 mm and with a threshold of 15% of the maximum dose. A Wilcoxon signed-rank test (α=0.05) was used to

determine if there was a significant difference in the γ-analysis results between the corresponding (paired) original and dose-mimicking plans. Furthermore, the Pearson product-moment correlation method was used to determine if there was a correlation between the fraction of approved data points and the total number of monitor units (MUs) in a plan.

Results

The fronts consisting of the system-specific optimal original plans together with the corresponding dose-mimicking plans (one case per tumor site) are displayed in Figure 1 (fronts for all cases are displayed in the Supplementary material as Figures 1 and 2). There was a distinguishable difference in plan quality between plans optimized via the two techniques for seven of the twelve cases (H1, B1-B3, A1, and P2-P3). The difference was more pronounced for three of the twelve cases; two cases of brain tumors (B2 and B3), and for one case of tumor in the abdominal region (A1) (Figure 1 and Supplementary material).

Results from the plan delivery measurements showed that the fractions of approved data points from the γ-analysis were significantly higher ($p<0.01$) for the dose-mimicking plans compared to the original plans. The fractions varied between 93.0% and 100% for the original plans and between 98.6% and 100% for the dose-mimicking plans (see Figure 3 in the Supplementary material). In 66 of the 152 comparisons, the dose-mimicking plan had a higher fraction of approved data points than the corresponding original plan, while the original plan had a higher fraction in 7 comparisons. Lastly, the fractions were identical in 79 comparisons. The numbers of MUs needed to deliver the original plans were significantly higher ($p<0.01$, on average 29%) than the fallback plans. The highest numbers of MUs for a plan correlated with the lowest values in the γ-analysis ($r = -0.77$, $p<0.01$, see Figure 3 in the Supplementary material).

Discussion

There was a distinguishable difference in plan quality between the two treatment planning techniques for seven of the twelve patient cases. For two of these cases (B2 and A1), there was a pronounced superiority in plan quality for the dose-mimicking plans compared to the original plans due to better target coverage, and for one case (B3) an inferiority due to poorer target coverage (Figure 1 and Supplementary material). Although, the original VMAT treatment plans were supposed to be optimal, they could in some cases be dominated by the dose-mimicking plans. Hence, the optimality was only true among plans created in the clinical TPS, i.e. it was a system-specific optimality and not a general optimality for VMAT treatment plans. The quality of the plans was only evaluated for two parameters (PTV coverage vs. mean dose to key OAR), while doses to other OARs were kept constant and below our clinical dose-volume criteria. Even though all plan parameters were controlled, minor plan quality differences (other than those visible in the evaluation) may have been present because of the plans' multidimensional nature.

The three-dimensional γ-analysis of all dual-arc VMAT plans showed that the measurements of the plan delivery was significantly more similar to the dose calculations for the dose-mimicking plans than for the original plans. However, only three of the original plans did not fulfil our clinical quality control (QC) criterion of ≥ 95.0% approved data points. The optimizer in our

clinical TPS randomly and simultaneously varies the multileaf collimator (MLC) shapes, the dose rate, and gantry speed for every control point in search of an optimal solution [12, 13]. In contrast, the dose-mimicking optimizer employs a non-randomized gradient based optimization algorithm [14]. Furthermore, it promotes the segments (control points) with the highest number of open leaf pairs [14]. Consequently, the control points for the fallback plans have a higher number of open leaf pairs and also larger field openings compared to the control points for the original plans. Therefore, a lower QC result and a higher number of MUs, as seen in our results for the original plans, compared to the dose-mimicking plans were to be expected.

The fraction of approved data points correlated with the total number of MUs in a plan. Hence, if a plan with a high number of MUs is produced by the clinical TPS, further optimization is desirable (e.g. via dose-mimicking), with the purpose of lowering the number of MUs and thereby improving the QC result, while maintaining the plan quality. A feature (MU Objective) that controls the maximum number of MUs allowed in a plan is available in the clinical TPS and should be used to avoid creating plans with unreasonable amounts of MUs, thereby also avoiding poor QC results. The study by Mancosu et al. shows results similar to our study, i.e. that the fraction of approved data points decreases significantly when the total number of MUs increases [15]. Masi et al. found only a weak correlation (for a gantry control point separation of 2°) between the fraction of approved data points and the total number of MUs in a plan [16]. However, the maximum number of MUs for a plan in that study was 592 [16]. Similarly, if we remove data for the two cases (H2 and A2) which have plans with MUs well above that value, then our remaining data also expresses a weak correlation. Hence, there seems to exist a threshold value for the correlation.

This study clearly shows that the dose-mimicking algorithm is capable of producing dual-arc VMAT treatment plans of high quality. Consequently, clinics which have TPSs with dose-mimicking capabilities have the ability to perform automated multi-modality optimization. This study also illustrates that such treatment plans can be delivered at a clinically commissioned linac with higher accuracy than plans produced through conventional treatment optimization. Simply by applying the dose-mimicking algorithm to manually optimized treatment plans can result in more MU efficient plans, improved QC results, and improved plan quality for dual-arc VMAT treatment plans.

Conflict of interest notification

Any actual or potential conflicts of interest do not exist.

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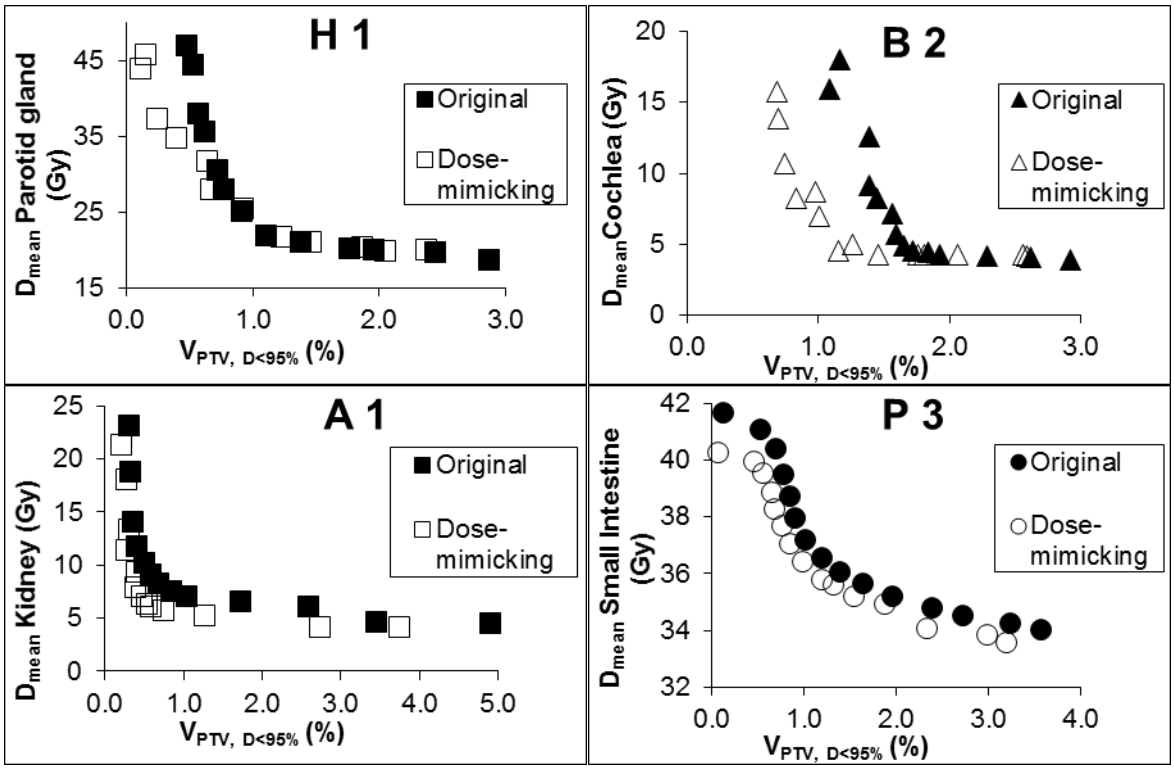

Figure 1:

Fronts consisting of system-specific optimal original plans and dose-mimicking treatment plans for one case of each tumor site: head & neck tumor (H1), brain tumor (B2), tumor in the abdominal region (A1), and in the pelvic region (P3).

Supplementary material

Details about the dose-mimicking algorithm

The composite objective function during generation of a dose-mimicking plan is a weighted sum of reference dose-volume histogram (DVH) functions that impose a one-sided quadratic penalty on DVH curve error. Functions associated with OARs are given unit weight while functions associated with targets are given a weight equal to a user-defined target priority. Reference DVH functions associated with OARs penalize overdosage with respect to the fallback DVH over the entire volume interval. Whereas, reference DVH functions associated with targets penalize overdosage for relative volumes in the interval [0, 0.5] and underdosage in the interval [0.5, 1.0]. All reference DVH functions are based on creating sets of DVH points for the reference dose and the present dose. These divide the volume interval into subintervals in which the dose levels of both curves are constant, e.g. for the subinterval $[V_{low}, V_{high}]$ with corresponding dose levels d and d_{ref} the contribution to the objective function value from the given subinterval will be:

Penalizing overdosage: $$\left(V_{high} - V_{low}\right) \cdot H\left(d - d_{ref}\right)^2 \quad (1)$$

Penalizing underdosage: $$\left(V_{high} - V_{low}\right) \cdot H\left(d_{ref} - d\right)^2 \quad (2)$$

where H is the Heaviside function.

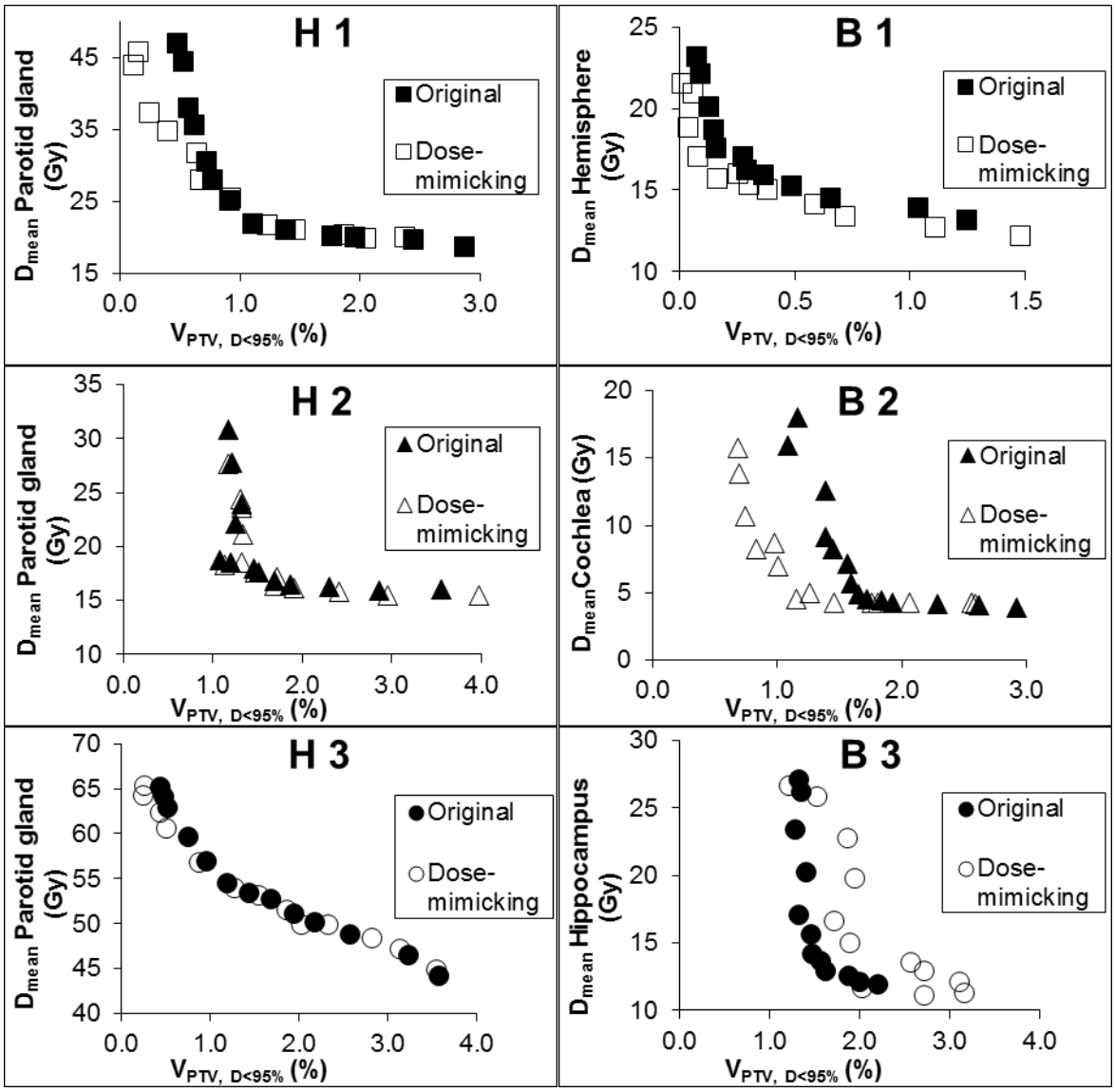

Figure 1:

Fronts consisting of system-specific optimal original plans and dose-mimicking treatment plans for three cases of head & neck tumors (H1-3) and three cases of brain tumors (B1-3).

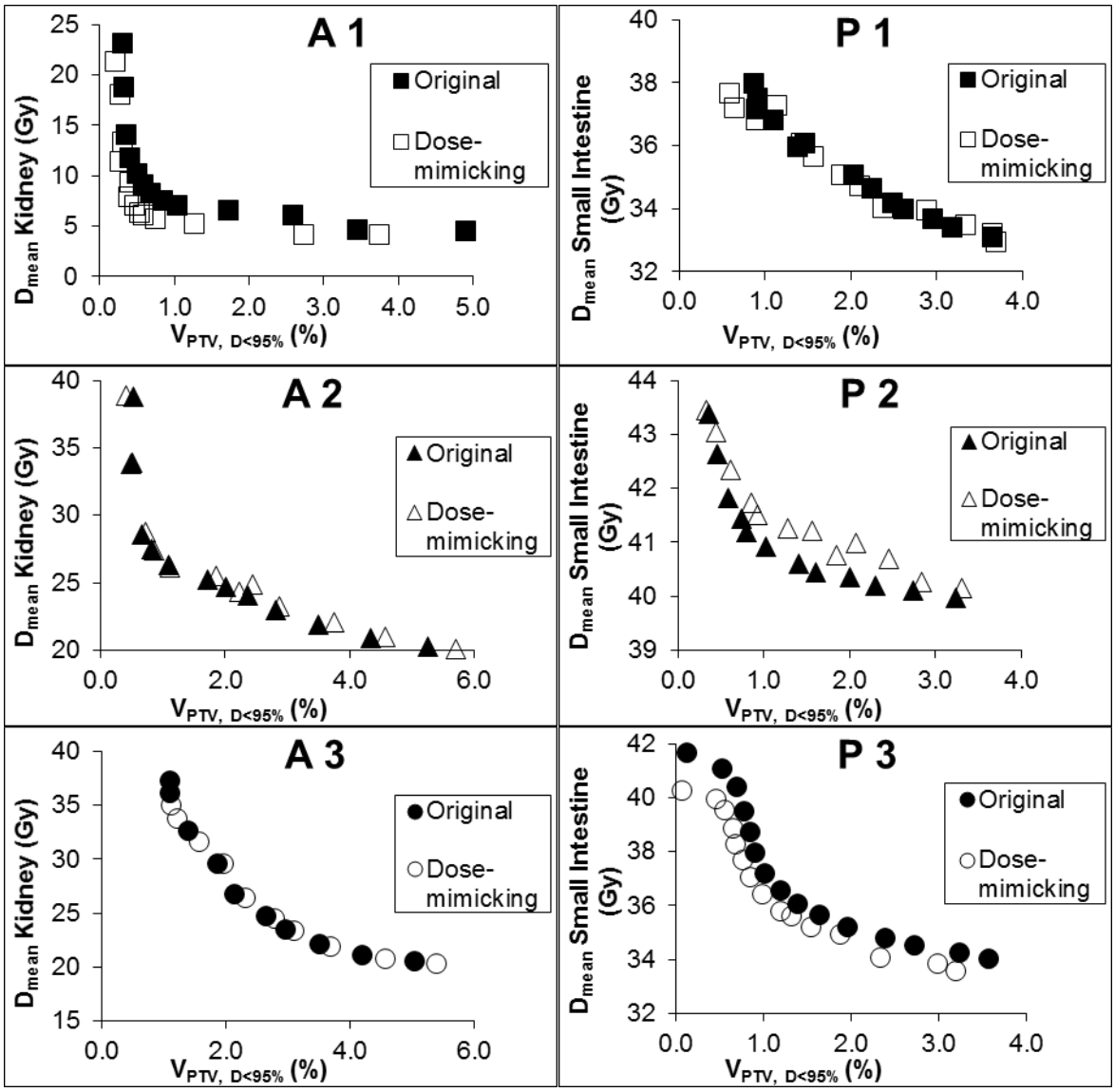

Figure 2:

Fronts consisting of system-specific optimal original plans and dose-mimicking treatment plans for three cases of tumors in the abdominal region (A1-3) and three cases of tumors in the pelvic region (P1-3).

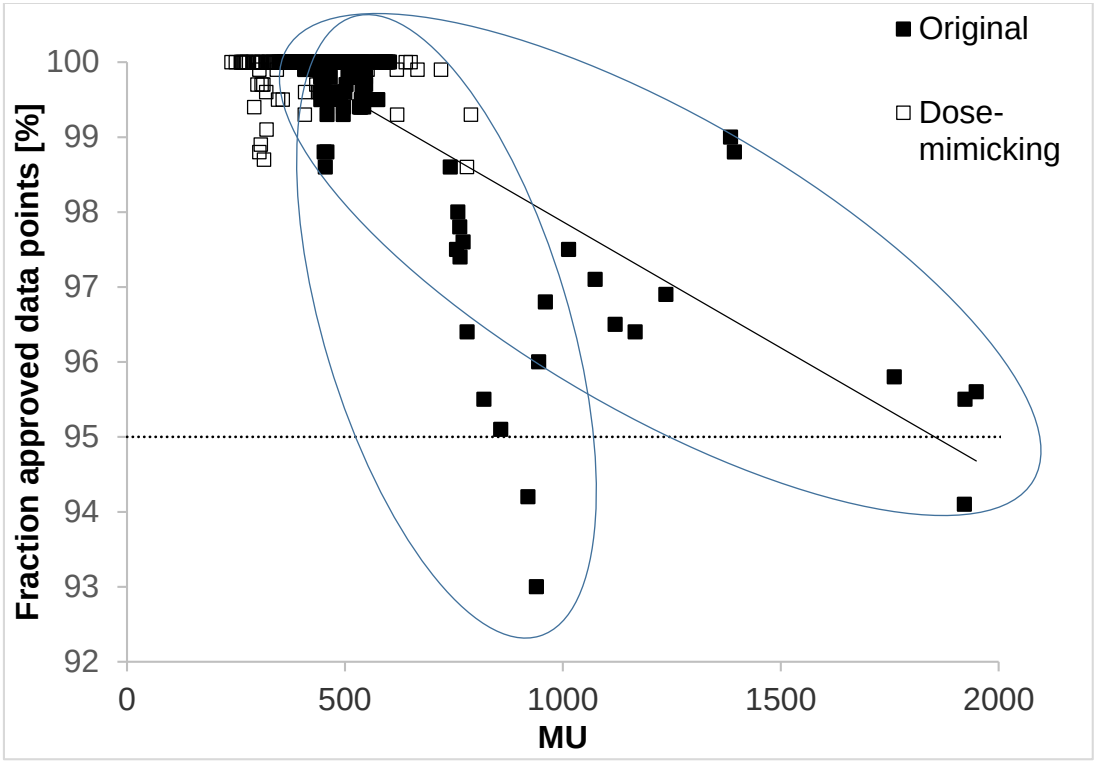

Figure 3:

Results from the 3%/2 mm γ-analysis for original plans as well as dose-mimicking treatment plans that illustrates how the results correlate (correlation line) with the total number of MUs in a plan. Our clinical quality control (QC) criterion of 95% approved data points for a plan is included in the figure as a dotted line. Also, ellipses are shown which encompasses plans for case H2 and A2.