A Planning Comparison of Dynamic IMRT for Different Collimator Leaf Thicknesses with Helical Tomotherapy and RapidArc for Prostate and Head and Neck Tumors

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Purpose: A comparative analysis of the three most advanced intensity-modulated radiotherapy (IMRT) techniques currently commercially available was performed. Treatment plans made in rotational techniques (helical tomotherapy [HT] and RapidArc) were compared with sliding-window IMRT (dIMRT) on a conventional linear accelerator using different leaf thicknesses (2.5 mm, 5 mm, and 10 mm). The influence of the different planning techniques on the coverage of planning volume and sparing of organs at risk (OARs) was investigated.
Patients and Methods: Nine patients with localized prostate and nine patients with head and neck cancer were chosen for this study. Treatment planning was performed in Eclipse (Varian) and in Tomotherapy planning software. Treatment plans were compared according to target volume coverage and sparing OARs, as well as by conformity and homogeneity index.
Results: For both investigated tumor sites, the dosimetric effects of leaf widths between 2.5 mm, 5 mm and 10 mm were shown to be small in regard to target coverage. Tomotherapy plans had better target coverage (higher minimum dose). For prostate cancer, better sparing of bladder and rectum was achieved with RapidArc and dIMRT plans. For head and neck cancer, best sparing of parotid glands was achieved in HT plans. There was no significant difference ($p > 0.05$) in sparing of OARs between the dIMRT plans with different leaf widths neither for prostate cancer nor for head and neck cancer.
Conclusion: For prostate and head and neck cases, all investigated IMRT techniques provide highly conformal treatment plans in terms of both target coverage and critical structure sparing.

Key Words: IMRT · RapidArc · Helical tomotherapy · Prostate cancer · Head and neck cancer

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Planvergleich zwischen dynamischer IMRT für unterschiedliche Leafbreiten, helikaler Tomotherapie und RapidArc am Beispiel von Prostatakarzinom und Kopf-Hals-Tumoren

Ziel: Es wurde eine Vergleichsanalyse der drei modernsten für die Photonentherapie kommerziell erhältlichen IMRT-Techniken (intensitätsmodulierte Radiotherapie) durchgeführt. Bestrahlungspläne, die mit Rotationstechnik erstellt wurden (helikale Tomotherapie [HT] und RapidArc) wurden mit dynamischer („sliding-window") IMRT (dIMRT) für einen konventionellen Linearbeschleuniger mit unterschiedlichen Lamellenbreiten (2,5 mm, 5 mm und 10 mm) verglichen. Der Einfluss der unterschiedlichen Planungstechniken auf Parameter für die Zielvolumenabdeckung und die Schonung von Risikoorganen wurde untersucht.
Patienten und Methodik: Es wurden jeweils neun Patienten mit Prostatakarzinom und mit Kopf-Hals-Tumor für die Untersuchung ausgewählt. Die Bestrahlungsplanung erfolgte mittels Eclipse (Fa. Varian) und der Tomotherapie-Planungssoftware. Bestrahlungspläne wurden hinsichtlich der Zielvolumenabdeckung und der Schonung von Risikoorganen sowie anhand des Konformitätsindex und des Homogenitätsindex verglichen.
Ergebnisse: Für beide untersuchten Tumorentitäten war der dosimetrische Effekt unterschiedlicher Leafbreiten (2,5 mm, 5 mm und 10 mm) hinsichtlich der Zielvolumenabdeckung gering. Mittels Tomotherapie konnte die beste Zielvolumenabdeckung erreicht werden (höheres Dosisminimum). Bei Patienten mit Prostatakarzinom ließ sich mittels RapidArc und dIMRT eine bessere Schonung der Harnblase und des Rektums erzielen. Bei Patienten mit Kopf-Hals-Tumoren wurde in den HAT-Plänen eine bessere Schonung der Speicheldrüsen erreicht. Weder für Prostatakarzinome noch für Kopf-Hals-Tumoren zeigte sich ein signifikanter Unterschied bezüglich der Schonung der Risikoorgane zwischen den dIMRT-Plänen unter Verwendung unterschiedlicher Lamellenbreiten ($p > 0{,}05$).

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Schlussfolgerung: Mit allen untersuchten IMRT-Techniken war es für Patienten mit lokalisiertem Prostatakarzinom und für Patienten mit Kopf-Hals-Tumor möglich, hochkonformale Bestrahlungspläne mit guter Schonung der Risikoorgane zu erzeugen.

Schlüsselwörter: IMRT · RapidArc · Helikale Tomotherapie · Prostatakarzinom · Kopf-Hals-Tumoren

Introduction

An appropriate choice of the irradiation technique may significantly improve the patient's quality of life after treatment without compromising the effect on the tumor. Intensity-modulated radiotherapy (IMRT) presents the most advanced commercially available conformal treatment technique. Delivery of IMRT is possible using different methods: for example, in slice-by-slice rotational therapy using binary collimation like tomotherapy [17] or computer-controlled multileaf collimators (MLCs) in static (SMLC for segmental MLC) [12] or dynamic (DMLC or sliding-window) mode [16, 31]. Another rotational IMRT technique was proposed by Otto [19] combining one gantry rotation and aperture changes for intensity-modulated arc therapy (RapidArc, Varian).

The influence of the MLC leaf width on radiotherapy treatment planning has been studied by several authors. Fiveash et al. [10] compared IMRT plans between 5 and 10 mm MLC leaf width in three cranial head and neck cases, observing better sparing of parotid gland and optic structures when using 5-mm leaf MLC. Dvorak et al. [7] found better conformity when using micro MLC for IMRT stereotactic radiotherapy of lung and liver. Kubo et al. [15] investigated the impact of leaf width on stereotactic radiosurgery and three-dimensional prostate planning. They showed advantage of micro MLC in sparing more bladder and rectum.

Rotational delivery has a number of potential advantages: in being able to deliver radiation from 360°, it may offer more conformal dose distributions relative to IMRT using only a limited number of fields and gantry directions. By obviating questions of beam number and direction, plan optimization becomes simpler.

Several studies have been published comparing helical tomotherapy (HT) with other IMRT modalities [2, 3, 6, 9, 20, 21, 23]. Most of these comparisons have been done between HT and multibeam static step-and-shoot IMRT. HT has generally yielded better results in terms of plan quality due to higher target dose homogeneity and superior normal-tissue sparing compared to these static IMRT techniques.

Several planning studies comparing between RapidArc and HT plans [2] or RapidArc and IMRT plans [11] have been published. Those studies have shown that both techniques have an ability to produce highly conformal plans with high target dose homogeneity. RapidArc showed improvements in organs at risk (OARs) and healthy tissue sparing with uncompromised target coverage when double arcs are applied. Up to now, there is no study comparing all three IMRT techniques for the same patients.

Prostate and head and neck cancer belong to the cancer sites typically treated with the IMRT technique [26]. The goal of this study is to distinguish strengths and weaknesses of three intensity-modulated delivery techniques: dynamic IMRT technique (dIMRT) with three different MLC leaf width thicknesses (2.5 mm, 5 mm, and 10 mm), RapidArc and HT for those cancer sites.

Patients and Methods

The IMRT plans for different MLC leaf widths and RapidArc plans were retrospectively recreated for nine patients with prostate and nine patients with head and neck cancer. Treatment plan comparisons, according to the target dose coverage and critical structure sparing, were performed.

Patients

All patients were randomly selected from patients with prostate and head and neck cancer that had received radiation therapy treatment between 2007 and 2008 at our department. They were scanned on a helical CT (computed tomography) scanner (Siemens Sensation 16, Siemens Medical Solutions, Erlangen, Germany) with 3 mm slice thickness.

For nine prostate cancer patients, irradiation plans containing a simultaneous integrated boost (SIB) were generated. The planning target volume (PTV) was defined as prostate gland and base of seminal vesicles with narrow safety margins (PTV_{70}). An additional PTV was defined within the PTV_{70} (PTV_{76}). The prescription dose was 70 Gy prescribed to 95% of the PTV_{70} (95% of the PTV_{70} are getting 70 Gy), and 76 Gy to 95% of the PTV_{76} (95% of the PTV_{76} are getting 76 Gy) in 35 fractions.

Nine patients with adjuvant radiotherapy for head and neck tumors were selected. The PTV was defined as region of the primary tumor and lymph node levels I–V bilaterally adding 1 cm safety margin in all directions. The dose was prescribed so that 95% of the PTV are getting 50 Gy in 25 fractions.

Helical Tomotherapy Planning

For each patient, plans were calculated using two jaw widths of 10 mm and 25 mm and a same pitch of 0.287. Dose was calculated using normal calculation grid (2 mm). The modulation factor is defined by the ratio of maximum leaf open time in a plan over the average leaf open time for all nonzero leaf open times. The actual modulation factor, however, is determined by the optimization process and is usually lower than the nominal modulation factor [17]. All optimizations were done by interactively adapting the objectives and their priorities, keeping the modulation factor constant. The primary aim was to produce the most optimal target coverage and sparing OARs. Plans were optimized using an inverse treatment-planning process (based on least squares optimization) determining

MLC aperture times, and the dose was calculated using a superposition/convolution approach. The software version used for this study was HiART TomoPlan 2.0 (Tomotherapy Inc., Madison, WI, USA). Details on the HT optimization process can be found in [2, 21, 31] and references therein.

IMRT Planning

The sliding-window IMRT plans were generated with seven coplanar equidistant fields of 15-MV and 6-MV photons for prostate and head and neck cancer patients, respectively. Optimizations and dose calculations were performed using Eclipse Version 8.2 (Varian Medical Systems, Palo Alto, CA, USA). Plans were optimized to meet a set of dose constraints to various critical structures and the prescribed doses to the target volumes. After optimization, the dose calculation was performed in Eclipse with the anisotropic analytical algorithm (AAA) photon dose calculation algorithm [8, 11] using a calculation grid of 2.5 mm.

Plans were optimized using three different MLCs: HD 120, Millenium 120 and Standard 80 (Varian) with leaf sizes 2.5 mm, 5 mm, and 10 mm, respectively.

The beamlet size used by the treatment-planning system is determined by the leaf width. The MLC Millenium HD 120 produced a beamlet size of 2.5 × 2.5 mm in the center of the field but 5 × 2.5 cm in the periphery. The MLC HD 120 produced a beamlet size of 5 × 2.5 mm in the center of the field but 10 × 2.5 cm in the periphery. In this work, for prostate cases, primary target volumes and OARs were within the central portion of the field, but for the head and neck cases, the whole field was used in order to cover the target. The MLC Standard 80 produced beamlets of 10 × 2.5 mm. All beam-modeling parameters were identical for the three MLCs. Optimal beam fluences were converted to MLC files for dynamic "sliding-window" delivery.

Treatment-planning parameters, such as isocenter location, number of fields, MLC margin, gantry and collimator angles for each beam, and the prescription dose, were the same for each case.

Constraints for calculation of the IMRT plans were chosen to lead to an optimal solution. This set of constraints was selected by multiple planning attempts with the leaf thickness 2.5 mm. When one optimal set of constraints for each patient was found, it was saved as a protocol which was then used for generating plans with other leaf thickness. In all three cases, the number of iterations was kept constant. In that way, all three IMRT plans were made using the same inverse planning constraint conditions and the same number of iterations was used and this number of iterations was chosen in the way that the result was no further dependent very much on the number of iterations (i.e., further iterations have not changed the dose-volume histograms [DVHs]).

Target coverage was given the highest priority during treatment planning for all techniques. For OARs, comparisons were made using mean and maximum doses.

RapidArc

For all patients, plans were optimized with Version 8.6.14 of RapidArc software. After optimization, the dose distribution was calculated with Eclipse using the AAA, with a calculation grid of 2.5 mm. The RapidArc plan consists of a single counterclockwise full arc from gantry angles 179° to 181° for prostate cancer patients and of two full arcs (counterclockwise 179° to 181° and clockwise 181° to 179°) for head and neck cancer patients. The application of two independent arcs that are simultaneously optimized might allow the optimizer to achieve higher target homogeneity and lower the dose in OARs. The collimator angle was chosen between 35° and 45°, allowing us to cover large PTVs up to almost 30 cm in length. The same dose objectives as in the IMRT plan were used for PTVs and OARs.

Evaluation Tools

DVHs were used to provide quantitative comparisons between plans for different techniques. For PTV, the minimum (D_{min}) and maximum (D_{max}) doses were calculated as dose received by 98% and 2% of the volume, D_{98} and D_2, and consequently reported. Target D_{95} coverage was calculated as dose that covered 95% of the PTV. The homogeneity of the treatment was expressed in terms of homogeneity index HI = $(D_2 – D_{98}) / D_P$ (difference between the dose covering 2% and 98% of the PTV divided with the prescription dose) [30]. The degree of conformality of the plans was measured with a conformity index, $CI_{90\%}$, defined as the ratio between the patient volume receiving at least 90% of the prescribed dose and the volume of the PTV [8].

For OARs, the analysis included the mean dose, the maximum dose, and a set of appropriate V_X and D_Y values: for patients with prostate cancer, values D_{50} (dose received by 50% of the volume) and V_{70} (volume that receives 70% of the prescribed dose) for bladder and rectum were evaluated, and for patients with head and neck cancer, V_{20} (volume that receives < 20% dose) for the left and right parotid were evaluated.

Beam-on times for dIMRT and RapidArc plans were calculated in RT Chart, ARIA (Varian Medical Systems, Palo Alto, CA, USA), assuming the dose rate of 600 MU/min. For HT, beam-on time were given by the Tomotherapy planning software.

Statistical Analysis

Significance of the difference between results obtained for OARs for investigated planning techniques was tested. Analysis of variance with repeated measures was used as global test and in case of significance followed by paired Student's t-tests. Data was summarized with means and standard error of the mean and plotted with error bars defined as mean and 95% confidence interval for mean. All tests were performed two-sided. Significance was set to 5%. The analysis was performed with SPSS V18.

Results

Case 1: Prostate Cancer

In Table 1, the minimum, maximum and mean target coverage for analyzed prostate cancer plans are summarized. All dIMRT plans showed equally good coverage of the PTV for all leaf thicknesses. No significant difference in D_{mean}, D_{min} and D_{max} could be observed between IMRT plans for MLC thicknesses 2.5 mm, 5 mm, and 10 mm. The same target coverage was achieved in RapidArc plans, by having the advantage of gradually lower D_{max} than in dIMRT plans. Both variants of HT plans generally have the lowest maximum dose and better PTV coverage (gradually higher minimum dose) compared to the IMRT plans. PTV_{70} and PTV_{76} DVHs are presented in Figure 1.

Small differences were observed for the main OARs, with the IMRT DVH curves being generally below those of the HT for both jaw sizes. Examples of DVHs for bladder and rectum for three patients are presented in Figures 2a to 2f. The values D_{50} (dose received by 50% of the volume) and V_{70} (volume that receives 70% of the prescribed dose) for bladder and rectum are shown in Table 1 for all plans and patients. The best sparing of the bladder was achieved in RapidArc plans for all patients. There was no large difference found in the bladder sparing between dIMRT plans with different MLC widths. For some patients, a slightly better rectum sparing was achieved when smaller leafs (2.5 mm and 5 mm) were used. Within HT plans, using smaller jaws made some improvements in DVHs for bladder and rectum possible. D_{50} and V_{70} for bladder and rectum between dIMRT plans with different MLC widths and with tomotherapy plans with jaw width 1 cm were not significantly different ($p > 0.05$).

Also homogeneity and conformity indices did not differ significantly ($p > 0.05$ for both HI and CI) between dIMRT plans with different leaf widths (Table 1). Dose distribution

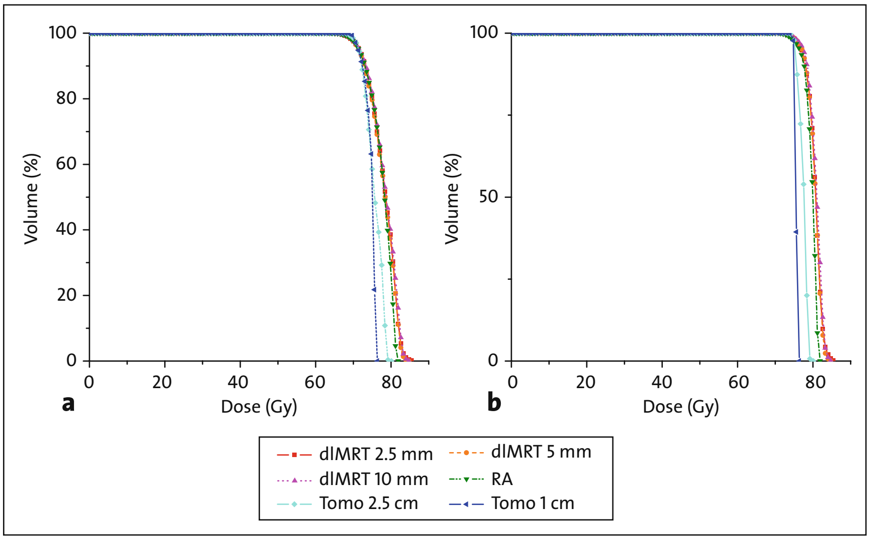
Table 1. Summary of mean dosimetric parameters for prostate cancer patients for all plans: averaged minimum (D_{min}), maximum (D_{max}) and mean (D_{mean}) doses for PTV_{70} and PTV_{76}; mean D_{50} and mean V_{70} for bladder and rectum, mean homogeneity (HI) and conformity indices (CI), mean beam-on time. Ranges for those values are given in parentheses. dIMRT: dynamic intensity-modulated radiotherapy; PTV: planning target volume; Tomo: tomotherapy.

Tabelle 1. Zusammenfassung der Mittelwerte der dosimetrischen Parameter aller Pläne für Patienten mit Prostatakarzinom: durchschnittliche minimale (D_{min}), maximale (D_{max}) und mittlere (D_{mean}) Dosis für PTV_{70} und PTV_{76}; mittlere D_{50} und mittleres V_{70} für Harnblase und Rektum, mittlere Homogenitäts- (HI) und Konformitätsindizes (CI), mittlere Strahlzeit. Intervall in Klammern. dIMRT: dynamische intensitätsmodulierte Radiotherapie; PTV: Planungszielvolumen; Tomo: Tomotherapie.

Prostate	dIMRT 2.5 mm	dIMRT 5 mm	dIMRT 10 mm	RapidArc	Tomo 1 cm	Tomo 2.5 cm
PTV_{70} D_{mean} (Gy)	71.5 (70.0–72.1)	71.4 (70.0–72.1)	71.3 (70.0–71.6)	71.3 (68.6–72.8)	70.9 (70.2–71.4)	71.1 (70.8–71.4)
PTV_{76} D_{mean} (Gy)	77.0 (76.0–77.8)	77.0 (76.5–77.8)	76.7 (75.3–77.7)	76.8 (73.0–79.8)	75.5 (75.0–77.4)	76.0 (75.2–77.3)
PTV_{70} D_{min} (Gy)	68.2 (66.7–68.6)	68.5 (68.3–68.8)	68.5 (68.1–68.7)	68.1 (64.7–68.9)	69.5 (68.9–70.1)	69.3 (68.8–69.9)
PTV_{76} D_{min} (Gy)	75.3 (74.2–77.8)	75.4 (73.5–77.8)	74.8 (73.8–76.8)	74.6 (73.0–77.9)	74.6 (73.9–76.4)	75.0 (72.6–77.0)
PTV_{76} D_{max} (Gy)	84.5 (82.6–86.1)	84.2 (83.3–86.1)	83.0 (80.5–84.7)	83.0 (78.4–84.7)	77.5 (77.3–79.8)	78.9 (77.0–81.2)
Rectum D_{50} (Gy)	26.4 (21.0–33.9)	27.8 (18.9–36.4)	27.9 (15.4–36.9)	23.8 (11.8–37.1)	30.2 (20.2–43.7)	37.5 (24.8–45.0)
Rectum V_{70} (%)	23.8 (15.3–27.2)	24.8 (16.2–29.8)	24.2 (15.5–28.9)	22.9 (14.5–32.8)	27.8 (18.3–40.0)	32.3 (20.3–41.2)
Bladder D_{50} (Gy)	24.8 (8.6–51.5)	25.7 (9.2–51.5)	27.4 (10.5–49.0)	20.8 (9.1–46.2)	24.3 (12.2–33.6)	33.7 (20.4–53.4)
Bladder V_{70} (%)	28.0 (12.0–53.7)	29.0 (11.8–53.4)	29.9 (12.1–53.4)	24.2 (9.9–46.7)	29.3 (12.4–61.0)	32.2 (13.0–58.0)
CI	0.73 (0.69–0.77)	0.72 (0.7–0.75)	0.71 (0.64–0.77)	0.8 (0.78–0.86)	0.78 (0.76–0.81)	0.8 (0.75–0.83)
HI	0.09 (0.08–0.11)	0.09 (0.08–0.11)	0.075 (0.07–0.11)	0.09 (0.05–0.1)	0.04 (0.01–0.06)	0.02 (0.01–0.03)
Mean beam-on time (s)	97.3 (87.1–103.9)	88.9 (76.0–107.5)	81.3 (74.0–97.1)	74.8 (62.4–79.2)	647.5 (488.0–807.6)	268.6 (211.1–345.0)

conformity was slightly better for RapidArc and HT plans. Dose distribution homogeneity was better for HT plans compared with dIMRT and RapidArc plans.

The beam-on time necessary to deliver the total number of MUs for the prescribed dose per fraction for all patients and respective treatment plans are presented in Table 1. The shortest beam-on time was achieved in RapidArc plans. Beam-on time of dIMRT plans was slightly shorter than the beam-on time on the tomotherapy machine. It has to be considered that the treatment time for dIMRT is longer than the calculated beam-on time, as additional time is necessary for moving the gantry to the next position and also for loading the fields.

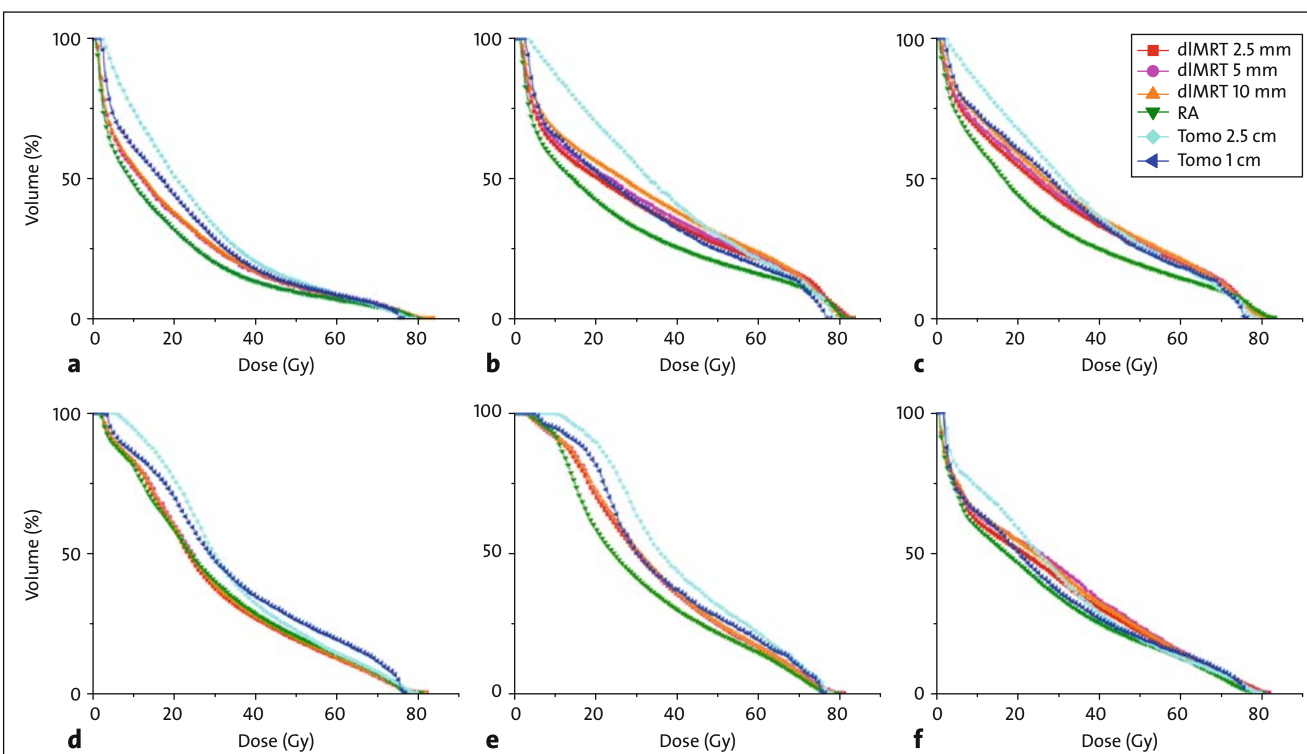


Figures 1a and 1b. DVHs for PTV_{70} (a) and PTV_{76} (b) for one of the patient with prostate cancer.

Abbildungen 1a und 1b. DVHs für PTV_{70} (a) und PTV_{76} (b) eines Patienten mit Prostatakarzinom.

Case 2: Head and Neck Cancer

Table 2 summarizes the mean target coverage for analyzed head and neck cancer patients. All plans showed equally good coverage of the PTV for all leaf thicknesses. No significant difference in D_{mean}, D_{min} and D_{max} could be observed between IMRT plans for MLC thicknesses 2.5 mm and 5 mm. The same target coverage was achieved in RapidArc plans, having slightly lower D_{max} than in dIMRT plans. The HT plans generally had the lowest D_{max} and better PTV



Figures 2a to 2f. DVHs for bladder (a–c) and rectum (d–f) for three of nine investigated patients with prostate cancer.

Abbildungen 2a bis 2f. DVHs für Harnblase (a–c) und Rektum (d–f) für drei von neun untersuchten Patienten mit Prostatakarzinom.

Table 2. Summary of mean dosimetric parameters for head and neck cancer patients for all plans: averaged minimum (D_{min}), maximum (D_{max}) and mean (D_{mean}) doses for PTV; mean V_{20} for left and right parotid gland, mean maximum dose in spinal cord, mean homogeneity (HI) and conformity indices (CI), mean beam-on time. Ranges for those values are given in parentheses. dIMRT: dynamic intensity-modulated radiotherapy; PTV: planning target volume; Tomo: tomotherapy.

Tabelle 2. Zusammenfassung der Mittelwerte der dosimetrischen Parameter aller Pläne für Patienten mit Kopf-Hals-Tumoren: durchschnittliche minimale (D_{min}), maximale (D_{max}) und mittlere (D_{mean}) Dosis für PTV; mittleres V_{20} für die linke und rechte Speicheldrüse, mittlere Maximaldosis im Rückenmark, mittlere Homogenitäts- (HI) und Konformitätsindizes (CI), mittlere Strahlzeit. Intervall in Klammern. dIMRT: dynamische intensitätsmodulierte Radiotherapie; PTV: Planungszielvolumen; Tomo: Tomotherapie.

Head and neck	dIMRT 2.5 mm	dIMRT 5 mm	dIMRT 10 mm	RapidArc	Tomo 1 cm	Tomo 2.5 cm
PTV D_{mean} (Gy)	47.5 (47.3–48.0)	47.5 (47.3–47.5)	47.4 (47.2–47.5)	46.7 (46.2–47.5)	49.1 (48.3–49.5)	48.6 (47.9–48.9)
PTV D_{min} (Gy)	45.8 (45.5–46.3)	46.0 (45.5–48.0)	45.8 (45.5–46.3)	45.2 (45.5–47.3)	48.5 (47.6–49.0)	47.5 (46.5–48.4)
PTV D_{max} (Gy)	54.3 (53.5–55.0)	54.0 (53.0–55.0)	54.0 (53.0–55.0)	54.9 (52.5–58.0)	53.5 (52.2–55.8)	52.7 (51.6–53.4)
Spinal cord D_{max} (Gy)	38.7 (36.5–42.5)	39.2 (37.0–43.0)	39.6 (37.0–44.5)	37.4 (36.5–40.0)	29.6 (24.6–33.6)	33.3 (27.6–36.0)
Par left V_{20} (%)	82.7 (55.6–95.8)	82.5 (55.4–97.7)	84.6 (62.4–100.0)	83.2 (55.4–100.0)	53.1 (36.6–62.1)	56.6 (40.0–68.9)
Par right V_{20} (%)	84.3 (46.3–99.8)	83.9 (46.5–99.7)	85.2 (50.2–99.8)	75.5 (61.1–91.9)	55.3 (35.2–72.7)	61.6 (40.2–70.8)
CI	0.82 (0.62–0.97)	0.82 (0.62–0.9)	0.82 (0.62–0.89)	0.79 (0.65–0.89)	0.82 (0.66–0.86)	0.83 (0.63–0.89)
HI	0.12 (0.10–0.13)	0.12 (0.10–0.13)	0.12 (0.10–0.13)	0.11 (0.04–0.52)	0.06 (0.04–0.08)	0.05 (0.04–0.06)
Mean beam-on time (s)	359.3 (227.0–470.5)	348.3 (223.8–458.8)	341.9 (216.6–469.9)	150.2 (148.8–157.2)	1193.2 (834.4–2,465.8)	476.7 (389.7–709.1)

coverage (higher D_{min}) compared to the IMRT plans. The PTV DVH for one investigated patient is presented in Figure 3.

For all patients, the clinical requirements for minimizing the dose to brainstem, chiasm, and eyes were met (data not shown). In this comparison, we focused on the spinal cord and the parotid glands, because using IMRT techniques enables good sparing of these organs. Also, it could have an impact on patients' quality of life [5, 9, 23]. V_{20} (volume that receives < 20% dose) for the left and right parotid for all patients is shown in Table 2. Tomotherapy lowered the dose to the parotid glands, while maintaining the dose distribution to the target volumes. In a parotid gland that overlaps with a target volume, the parotid dose reduction depends on the dose gradient achievable with the IMRT technique used. DVHs for right parotid gland for three patients are presented in Figures 4a to 4c.

D_{max} in spinal cord for all patients and techniques are presented in Table 2. HT showed lower maximum dose for all patients, although maximum doses in all plans and for all patients were clinically acceptable. DVHs of spinal cord for three patients are presented in Figures 4d to 4f. V_{20} for parotid glands and D_{max} in spinal cord were not significantly different between dIMRT plans with different MLC widths and RapidArc plans ($p > 0.05$).

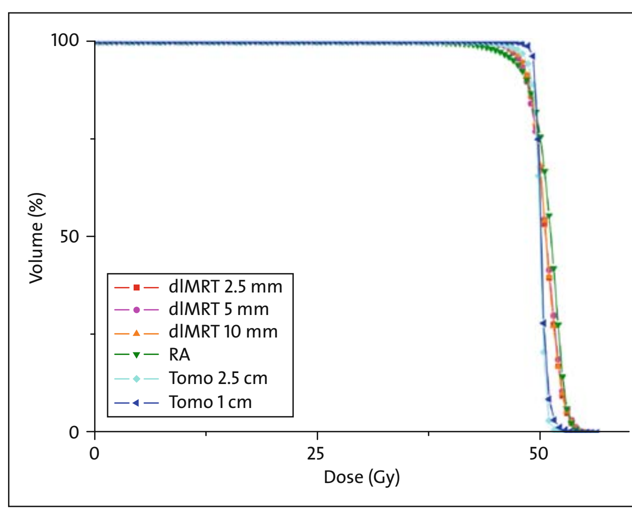
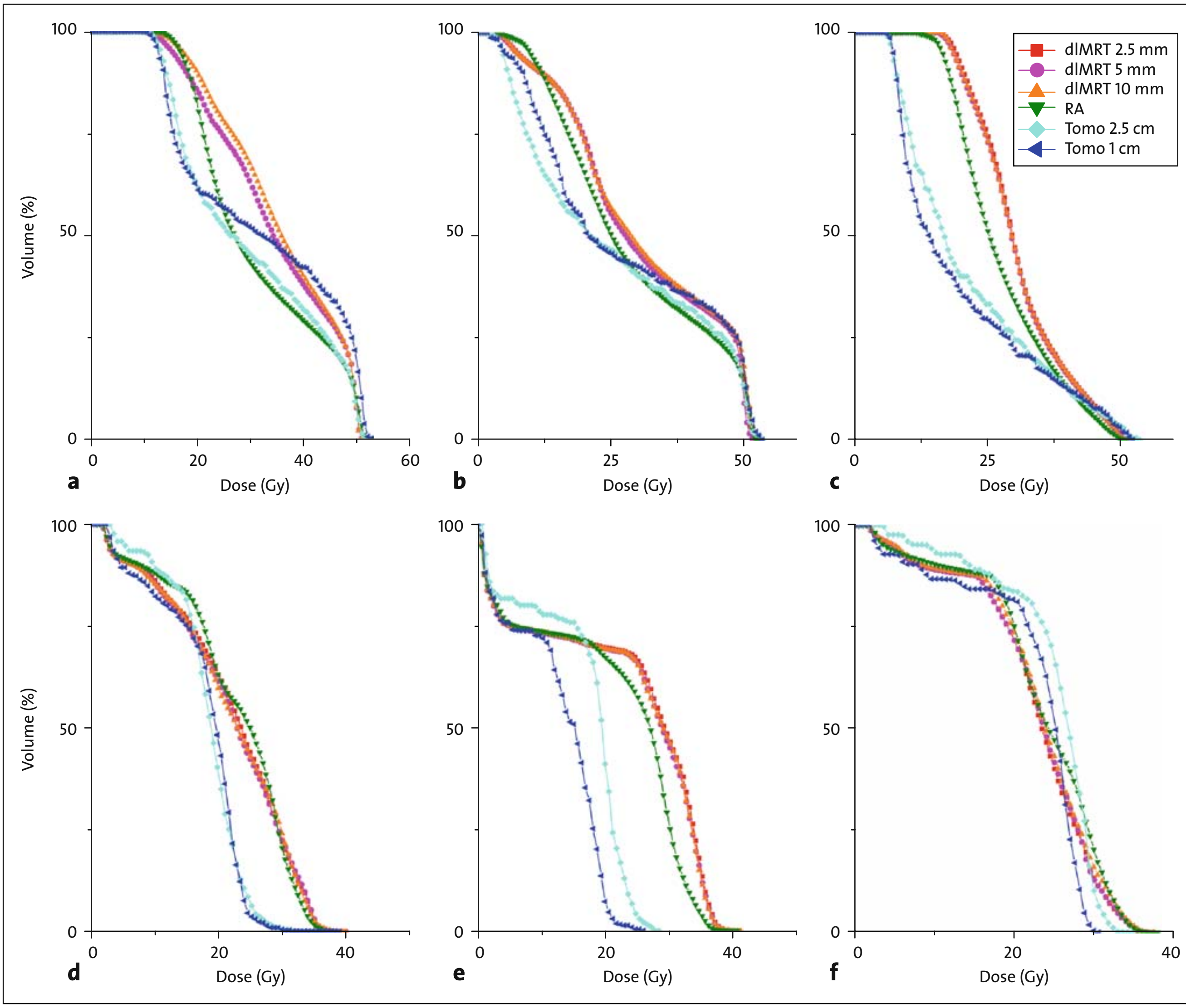


Figure 3. DVH for PTV for one patient with head and neck cancer.

Abbildung 3. DVH für PTV eines Patienten mit Kopf-Hals-Tumor.

Looking at the dose to the PTV (Table 2), we found slightly more homogeneous dose distributions in the tomotherapy plans. The conformity index (Table 2) showed no difference



Figures 4a to 4f. DVHs for right parotid gland (a–c) and spinal cord (d–f) for three of nine investigated patients with head and neck cancer.

Abbildungen 4a bis 4f. DVHs für die rechte Speicheldrüse (a–c) und das Rückenmark (d–f) für drei von neun untersuchte Patienten mit Kopf-Hals-Tumor.

for the different planning modalities ($p > 0.05$). Generally, tomotherapy plans show better conformity [24] which could be of benefit when dose escalation to small subvolumes is desirable.

The mean beam-on times necessary to deliver the total number of MUs for the prescribed dose per fraction for all patients and respective treatment plan category are presented in Table 2. The beam-on time of dIMRT and RapidArc plans is shorter than the beam-on time on the tomotherapy machine. The treatment time for dIMRT plans is longer than the beam-on time, because of the time necessary to move the gantry to the next position. The shortest irradiation times were calculated for RapidArc treatments.

Discussion

The results of this study demonstrate that all used IMRT techniques are able to provide highly conformal treatment plans in terms of both target coverage and critical structure sparing for both prostate and head and neck cases. We have shown that for both investigated tumor sites, the dosimetric effects of leaf widths between 2.5 mm, 5 mm and 10 mm are small with regard to target coverage as already found in previously reported studies [1, 4, 14, 18, 25]. The general observation is that dIMRT has more difficulties to match the locally prescribed doses than HT. The minimum dose in the PTV by the tomotherapy plans is higher than in the dIMRT plans. This is consistent with the findings in [6]. The maximum dose in the PTV in the dIMRT and RapidArc plans is higher than for tomotherapy, although those volumes with higher doses ("hot spots") are very small.

For prostate cancer patients, the dIMRT and RapidArc plans provide improved sparing of the critical structures, especially for the bladder and rectum. dIMRT and RapidArc show plans of similar quality which is in agreement with previous findings [20, 32]. The somewhat worse DVHs for bladder and rectum in both tomotherapy plans could be explained by the fact that tomotherapy beam shape has a helical form which adds doses in OARs in the vicinity of the cranial and caudal end of the PTV.

In the case of head and neck tumors, the differences in DVHs for PTV and OARs are minor for the dIMRT plans made with different leaf widths. The best sparing of parotid glands has been achieved in HT plans followed by dIMRT, for all investigated patients. The homogeneity and conformity indices show no differences for plans with different leaf widths.

For both investigated tumor sites, no advantage of thin leaves is found. The negligible influence of leaf width on the mean OAR dose for dIMRT application can be explained by the relatively large volume ratio between PTV and OAR. This was also shown by Dvorak et al. [7] and Jin et al. [14].

By tomotherapy, the helical nature of the system allows the beamlets to overlap, thus minimizing the disadvantage of the large width, especially if the pitch of the helix is maintained to be sufficiently small.

One advantage of RapidArc over dIMRT and HT plans is that the patient-averaged MUs are significantly reduced. Dose to healthy organs not in the proximity of the PTV arises largely from collimator transmission and scatter radiation from the linac, and this dose is proportional to the number of MUs [28]. Such scattered doses might increase the risk of secondary tumors [13]. The collimator transmission and scatter radiation from the linac are the same for the dIMRT and RapidArc plans, but beam-on time is significantly shorter in RapidArc plans. The actual physical dose delivered to patients could be affected by many other factors such as beam penumbra modeling, setup uncertainty, organ motions, impact of MLC design on peripheral doses [29], source to MLC distance, etc. This work is a dosimetric study based purely on treatment planning.

In addition, the decreased delivery time of RapidArc plans has the potential to reduce the effects of intrafractional motion by prostate cancer patients, as conventional doses of radiation can be delivered in about 1 min.

Although beam-on times are shorter for dIMRT compared to HT for 2.5 cm jaw size, the irradiation times for prostate plans are comparable for these two modalities, because of additional time needed for dIMRT to move the gantry to the next position and to load the fields. For head and neck cases, irradiation time is shorter for dIMRT plans compared to the HT plans. Generally, HT plans with jaw size 1 cm have significantly longer irradiation times, without proportional benefit of sparing OARs.

Besides the physical and clinical advantages, reduced beam-on times and, consequently, reduced effective treatment times have a strong impact on the clinical routine.

Conclusion

This is the first study that describes the quantitative dosimetric differences in dIMRT plans using three different leaf widths, tomotherapy and RapidArc plans. Presented results indicate that dIMRT plans for all three collimator leaf thicknesses are equally suitable for conformal coverage of the target volume and sparing OARs. HT plans show steeper DVHs for the PTV and plans appear to be more conformal and more homogeneous than dIMRT plans for all leaf widths and RapidArc plans. The RapidArc technique can reduce beam-on time while maintaining dosimetric quality comparable to that of the dIMRT approach.

If improvements in DVHs of OARs achieved in the investigated planning and irradiation techniques are clinically relevant has to be tested and confirmed through long-term follow-up studies.

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