Reirradiation of Spinal Column Metastases

Comparison of Several Treatment Techniques and Dosimetric Validation for the Use of VMAT

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Background: For reirradiation of spinal column metastases, intensity-modulated radiation therapy (IMRT) reduces the dose to the spinal cord, while allowing longer treatment times. We analyzed the potential of volumetric modulated arc therapy (VMAT) to reduce treatment time and number of monitor units (MU).
Patients and Methods: In CT datasets of 9 patients with spinal column metastases, the planned target volume (PTV) encompassed the macroscopic tumor including the spinal cord or medullary cone, respectively. The prescribed dose for the target was 40 Gy, but median spinal cord dose was intended to be < 26 Gy. We compared a posterior (3D-PA) static field technique, a two-field wedge technique (3D-wedge) and 5-/7-beam IMRT with VMAT. Conformity index (CI), homogeneity index (HI40), dose volume histogram (DVH) parameters, treatments delivery time (T), and MU were analyzed. Dosimetry was validated with EDR2-film/ionization chambers.
Results: PTV coverage was insufficient for 3D-conformal radiotherapy (3D-CRT) when spinal cord tolerance was respected. The IMRT approach provided excellent results but has the longest treatment time. VMAT produced dose distributions similar to IMRT with shorter treatment times (VMAT: mean 4:49 min; IMRT: mean 6:50 min) and fewer MU (VMAT: 785; IMRT: 860). Reduced conformity and increased homogeneity for VMAT when compared to IMRT were observed. An absolute deviation between measured and calculated dose of +0.70 ± 3.69% was recorded. γ-Index analysis showed an agreement of 91.33 ± 3.53% for the 5%/5 mm criteria.
Conclusion: For this paradigm, VMAT produces high quality treatment plans with homogeneity/conformity similar to static IMRT, shorter treatment times, and fewer MU. Verification measurements showed good agreement between calculation and delivered dose, leading to clinical implementation.

Key Words: Volumetric intensity modulated arc therapy · Intensity-modulated radiation therapy · 3D conformal radiation therapy · Spinal column metastases

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Rebestrahlung von paraspinalen Metastasen: Vergleich verschiedener Bestrahlungstechniken und dosimetrische Validierung von VMAT

Ziel: Die Intensitätsmodulierte Radiotherapie (IMRT) ermöglicht bei der Rebestrahlung von Wirbelsäulenmetastasen eine Reduktion der Dosis im Spinalkanal bei gleichzeitig längerer Bestrahlungszeit im Vergleich zur konventionellen 3D-Technik. Wir analysierten das Potential der volumetrisch modulierten Rotationstherapie (VMAT), um die Bestrahlungszeit und die Anzahl der Monitor-Einheiten (MU) zu reduzieren.
Patienten und Methoden: 9 CT-Datensätze von Patienten mit Wirbelsäulenmetastasen wurden untersucht, bei denen das Zielvolumen (ZV) den makroskopischen Tumor inklusive Spinalkanal umfasste. Verschreibungsdosis für das ZV waren 40 Gy unter Berücksichtigung der medianen Spinalkanaldosis von < 26 Gy. Wir verglichen eine posteriore 3D-Technik (3D-PA), eine 2-Felder-Technik mit Keilen (3D-Wedge) und 5/7-Felder-IMRT mit VMAT. Konformitätsindex (CI), Homogenitätsindex (HI40), Dosis-Volumen-Histogramme (DVH), Bestrahlungszeit (T) und MU wurden verglichen. Die Dosimetrie wurde mit EDR2 Filmen und Ionistationskammer überprüft.
Ergebnisse: Die ZV-Abdeckung für die 3D-Techniken war insuffizient, wenn die Toleranzdosis des Spinalmarks berücksichtigt wurde. Der IMRT-Ansatz ergab exzellente Resultate, allerdings mit der längsten Bestrahlungszeit. Mit VMAT ließen sich ähnliche Dosisverteilungen wie mit IMRT mit kürzeren Bestrahlungszeiten (VMAT Mittel 4:49 Min., IMRT Mittel 6:50 Min.) und weniger MU (VMAT:785, IMRT:860) realisieren. Eine geringere Konformität und höhere Homogenität von VMAT wurde im Vergleich zu IMRT beobachtet. Die absolute Abweichung zwischen gemessener und berechneter Dosis betrug +0,70±3,69%. Die γ-Analyse zeigte eine Übereinstimmung von 91,33 ± 3,53% für 5%/5 mm.

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Schlussfolgerung: Für dieses Paradigma erzeugt VMAT qualitativ hochwertige Bestrahlungspläne mit zu IMRT vergleichbarer Homogenität/Konformität, kürzeren Bestrahlungszeiten und weniger MU. Verifikationsmessungen zeigten gute Übereinstimmungen zwischen errechneten und gemessenen Dosen und erlaubten die klinische Implementierung.

Schlüsselwörter: Volumetrisch intensitätsmodulierte Rotationstherapie · Intensitätsmodulierte Radiotherapie · 3D konformale Radiotherapie · Wirbelsäulenmetastasen

Introduction

Spinal column metastases can cause morbidity, including pain and compression of the spinal cord with resulting neurologic deficits and fractures of the vertebral bones. Radiotherapy (RT) is a proven therapy to prevent complications and reduce pain [10]. With longer survival secondary to improving systemic therapy, clinicians are now faced with a need for a longer duration of local control [13, 26]. Either primary dose escalation or reirradiation of bone lesions may provide this prolonged control. Guckenberger et al. [11] recently suggested primary dose-escalated RT based on excellent safety and local control. Milker-Zabel et al. [15] reported a local control rate of 94.7% after a median follow-up of 12.3 months for the reirradiation of vertebral bone metastases with stereotactic conformal radiotherapy (4–14 beam directions) or intensity-modulated radiotherapy (IMRT). The limiting factor both in primary dose escalation and reirradiation of spinal column metastases is spinal cord tolerance. Using 3D-conformal radiotherapy (3D-CRT) without any elements of fluence modulation for retreatment exceeds the radiation tolerance to the spinal cord when target doses of > 30 Gy are intended [18]. IMRT provides sufficient PTV coverage while respecting spinal cord dose [22]. Multiple gantry angles and several segments per beam are used, thus, paying for plan quality with longer treatment times. Given that spinal column metastases are often painful when the patient is positioned prone or supine on the treatment couch, these patients might benefit from short treatment times. We, therefore, explored the possibility of establishing volumetric modulated arc therapy (VMAT) clinically to treat this target paradigm. Several earlier studies have shown that VMAT may reduce treatment time and primary monitor units (MU) for several target types with dose distributions similar to IMRT [1, 19, 21, 25, 28, 29, 32–33], although the benefit is not easy to quantify theoretically, since only preliminary attempts at a comprehensive theory of VMAT have been made [31].

We report the analysis of different treatment techniques regarding plan quality, treatment efficiency, and dosimetric delivery accuracy of VMAT for this target paradigm as evaluated prior to clinical implementation.

Materials and Methods

Retreatments were planned based on CT datasets of 9 patients with spinal column metastases who had previously been treated with 3D-CRT to spinal cord tolerance. The planning target volume (PTV; 497 ± 247 cm^2) encompassed the macroscopic tumor (complete vertebral body plus anterior elements and margin; the mean number of vertebral bodies was 3.44 (range 3–4) and included tge spinal cord (SC) or medullary cone, respectively. The SC/medullary cone was contoured separately for the length encompassed by the PTV (SC(PTV)) and outside the PTV area. The PTV included the SC(PTV). Although that caused the PTV DVH to show some systematic underdosage which in reality does not exist, this was the only technical way all treatment planning could be compared on exactly the same volumes. The median volume for PTV was 495 ± 251 cm^3 (range 144–857 cm^3). We chose a prescription dose for the target of 40 Gy with a fraction dose of 2 Gy, planned for a 6 MV synergy linear accelerator (Elekta, UK) with a maximum dose rate of 600 MU per minute. Median dose to the SC was intended not to exceed 26 Gy based on available data for retreatment tolerance [17, 30].

Two different 3D-CRT strategies were assessed in this study: a single posterior (3D-PA) static field (180°) and a two-field wedge technique (3D-wedge) with two beams at angles of around 160° and 200°, respectively, depending on patient anatomy. Masterplan 3.1 (Nucletron, The Netherlands) was used as treatment planning system (TPS) for 3D-CRT. Plans were normalized to 26 Gy as the median dose of the SC in order to stay within the SC tolerance. As reference modulated treatment, we created an isotropically distributed 5-beam IMRT (IMRT-5B) and an isotropically distributed 7-beam IMRT (IMRT-7B) plan, respectively, using the TPS Hyperion (University of Tübingen, Germany). A total of 40 Gy were prescribed as the median dose to the PTV. VMAT plans were generated with ERGO++ 1.7.2 (Elekta-Software, Saint Louis, MO, USA) with two complete 360° rotations (clockwise and counter clockwise) to increase the modulation depth (the first rotation focused on the whole PTV excluding the SC, the second focused on the part of the target immediately adjacent to the SC) and were normalized as described for static IMRT plans.

For statistical analyses, exact Wilcoxon signed-rank tests were used to assess any differences between the treatment paradigms. In general, a p value below 0.05 was considered significant. All computations were performed using the IBM SPSS Statistics program (version 18, SPSS Inc., Chicago, IL, USA).

The conformity index (CI) and homogeneity index (HI40) were used to compare conformity and homogeneity between treatment plans[20]. Due to the fact that we prescribe dose to the median dose level in the PTV, we had to modify the CI as follows:

$$CI = \frac{V_{D99\%}}{V_{PTV}} \quad (1)$$

where V_{PTV} describes the target volume in cm³ and $V_{D99\%}$ is the total volume in cm³ which receives the *effective* minimal target dose (dose encompassing 99% of the PTV). The CI definition is characterized by the *effective* minimal dose applied to the PTV which follows the idea of the CI definition by the RTOG.

HI is defined as follows according to the RTOG guidelines [24]:

$$HI = \frac{D_{\max}}{D_{presc}} \quad (2)$$

where D_{presc} is the prescription dose and D_{max} is the maximum dose in the treatment plan. In addition, we compared two special dose volume histogram (DVH) parameters for the PTV and SC. $C_{95\%PD}$ describes the percentage coverage of the PTV by the isodose representing 95% of the prescription dose (PD) and SC_{PTV} is the median dose to the spinal cord inside the PTV. The treatment efficiency was quantified by the number of MU and total treatment time (TTT). For all approaches, TTT was measured on the unit with the same measuring device (stopwatch) and under the same circumstances (first beam on to last beam off).

To assess dosimetric accuracy, verification measurements were performed using radiographic films and ionization chambers in a homogenous RW3 phantom as described previously [7], following the suggestions of Rhein et al. [23] and Ezzell et al. [8]. Dose matrices as calculated in the TPS and measured by film were compared. We performed profile analyses and γ-index analyses [6].

Results

Figure 1 displays the essential differences of the dose distributions generated by the different techniques. For the 3D-CRT approaches (3D-PA and 3D-wedge) shown in Figure 1, nontarget tissue volume exposed to primary beams is small. The 26 Gy isodose line covers only approximately 50% of the PTV. It has to be taken into account that the 3D approaches were normalized according to the limitation of the spinal cord of 26 Gy. Therefore, an adequate PTV coverage is not possible (dose range in PTV: 12.7–30 Gy). The IMRT approaches as shown in Figure 1 show excellent PTV coverage with adequate sparing of the spinal cord, at the expense of a larger non-PTV volume exposed to primary beam. Similar to IMRT, the VMAT approach in Figure 1 shows a very good PTV coverage and OAR sparing but exposes an even larger volume outside the PTV to primary beam.

In Table 1 the numeric comparison values of the different approaches are shown. Because of the normalization of the 3D approach based on the spinal cord constraint a HI and CI analysis was not possible. With a HI of 1.13 ± 0.07 VMAT showed a better homogeneity in the PTV than IMRT with 5 beams (HI: 1.23 ± 0.06) or 7 beams (HI: 1.21 ± 0.06). On the other hand, IMRT yielded with both primary beam geometries a higher conformity (IMRT-5B: 1.60 ± 0.34; IMRT-7B: 1.79 ± 0.26) than VMAT (1.96 ± 0.35).

Both 3D-CRT techniques used a low number of MU with 241 ± 21 MU for 3D-PA and 526 ± 137 MU for 3D-wedge. VMAT plans (785 ± 92 MU) were delivered with fewer MU than IMRT (IMRT-5B: 843 ± 133; IMRT-7B: 878 ± 102).

Looking at the treatment time as second efficiency aspect, 3D-PA (25 ± 2 s) and 3D-wedge (88 ± 7 s) are, of course, the fastest treatments. Comparing the modulated techniques the VMAT approach is with a mean treatment time of 289 ± 69 s 20% faster than IMRT-5B (348 ± 72 s) and 40% faster than IMRT-7B (472 ± 82 s).

Table 1 also reports the mean percentage coverage of the PTV with 95% of the PD ($C_{95\%PD}$). For the 3D approaches, two $C_{95\%PD}$ values are reported, one for the plan normalized to 26 Gy as the median SC dose and the other one normalized to 40 Gy as the median PTV dose. It is obvious that $C_{95\%PD}$ for the plans normalized according to SC constraints are 0% because the PTV doses are dramatically lower than 40 Gy. The alternative $C_{95\%PD}$ reports possible PTV coverage when not respecting SC tolerance. With values of 47.9 ± 9.89% for 3D-PA and 55.3 ± 1.93% for 3D-wedge the 3D approaches are clearly less conformal than the modulated techniques VMAT (83.82 ± 2.68%), IMRT-5B (83.99 ± 2.59%), and IMRT-7B (83.98 ± 2.15%). In comparison to IMRT, VMAT further slightly reduced the mean dose to the SC encompassed by PTV.

Figure 2 displays DVHs for a typical case. VMAT and IMRT resulted in comparable PTV coverage with higher maximum PTV doses for IMRT as also indicated by the HI. Due to the necessary normalization based on SC constraints, 3D-CRT results in insufficient target coverage. VMAT has a slightly larger volume exposed to lower doses (5–25% of prescription dose (PD)) as shown by the DVH for the volume encompassed by the external contour. IMRT in contrast exposed slightly larger volumes to intermediate doses (30–60% of PD). Exposure of OARs such as lungs, complete SC and SC encompassed by the PTV were similar for the modulated techniques.

Figure 3 displays the mean DVHs of PTV and spinal cord inside the PTV (SC(PTV)) with a confidence interval (CINT) of 95%. Expectedly, the DVHs for the 3D approaches do not show a large interval range because of the simple beam geometry and the missing modulation which lead to similar results. The CINT range for VMAT is wider than for the IMRT techniques because the forward planning step in ERGO++ leads to larger variations among the VMAT plans.

The differences between the introduced delivery techniques regarding the most relevant comparison parameters are reported with respective significance levels in Table 2. The small standard deviations lead to homogeneous results within the delivery techniques and to the majority of differences between techniques being statistically significant despite occasionally small absolute differences.

Validation of the new treatment paradigm started with assessing the accuracy of plan data transfer from the TPS to the R&V system. We found slight variations regarding the

number of MU because of required numerical rounding. The deviations were, however, within a tolerance limit of < 0.5%. On absolute dosimetry with an ionization chamber, an absolute deviation between the measured and calculated dose of 0.70 ± 3.69% was recorded. Artifacts such as marker holes on the films or the area where the films were cut were excluded from the calculation. For a γ-index based on a 5% dose criterion and a 5 mm DTA acceptance criterion, 91.33 ± 3.53% of points were within the acceptance criteria and (78.56 ± 5.34% for 3%/3 mm). Sample dose profiles and maps of the distribution of pixels passing and failing the respective γ-criteria are shown in Figure 4.

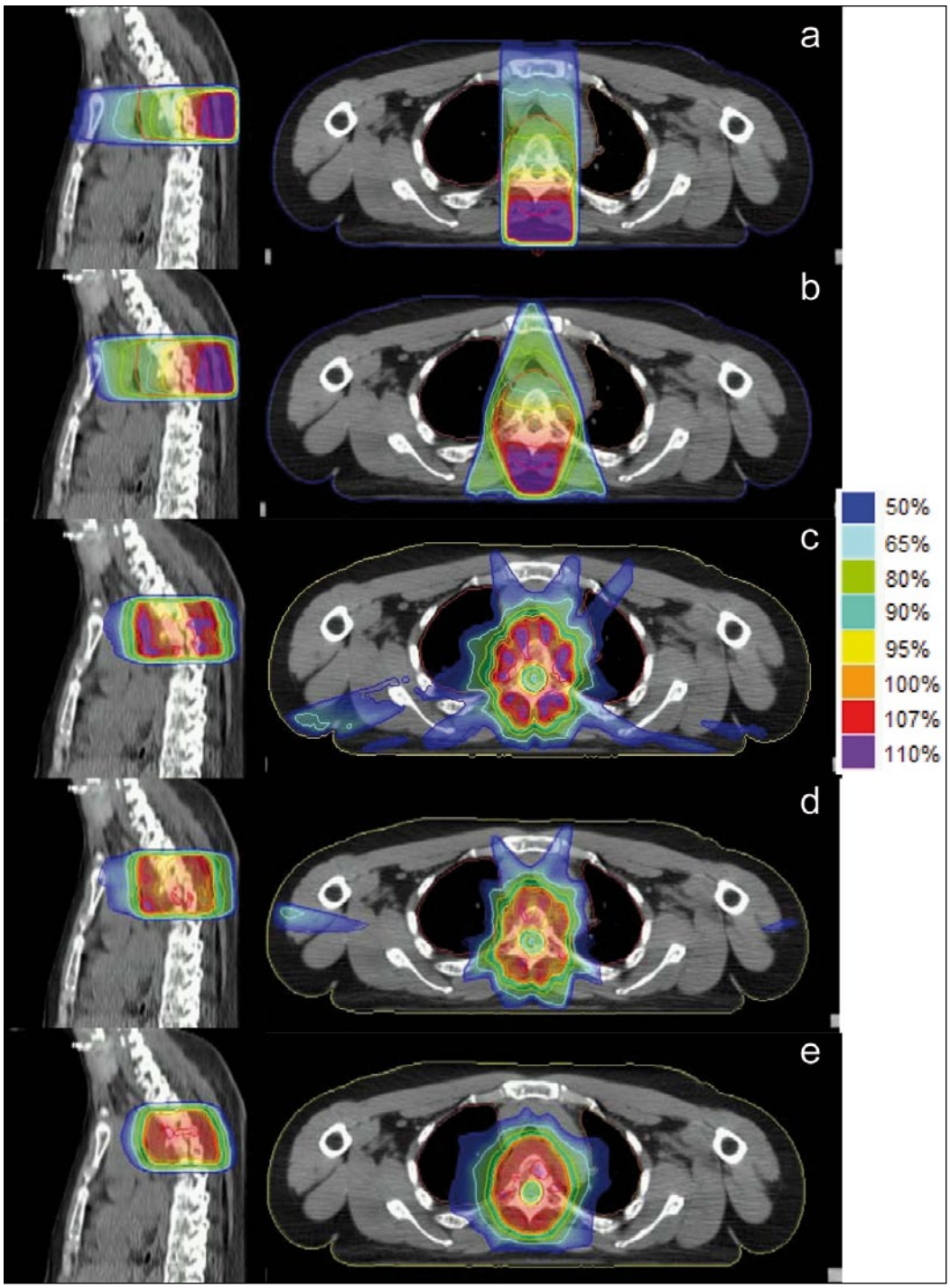

Figure 1. Sagittal and transversal dose distribution for 3D-PA (**a**), 3D-wedge (**b**), IMRT-5B (**c**), IMRT-7B (**d**), and VMAT (**e**).

Abbildung 1. Sagittale und transversale Dosisverteilung für 3D-PA (**a**), 3D-Wedge (**b**), IMRT-5B (**c**), IMRT-7B (**d**), und VMAT (**e**).

Discussion

The potential benefits of modulated techniques for spinal column tumors were shown in earlier publications [5, 11, 15, 22, 35] when spinal cord tolerance was an issue [30]. An early study by Pirzkall et al. [22] demonstrated the advantages of a manually created multiple arc segment (MAS) technique in this situation. PTV coverage and OAR exposure of MAS already had the characteristics of IMRT treatment which, in fact, was not inversely planned [22]. Milker-Zabel et al. [15] showed in their publication that this technique and, later, inversely planned IMRT are safe and effective in the treatment of recurrent spinal column tumors. Due to technical limitations at the time of the study, treatment delivery was still slow [15].

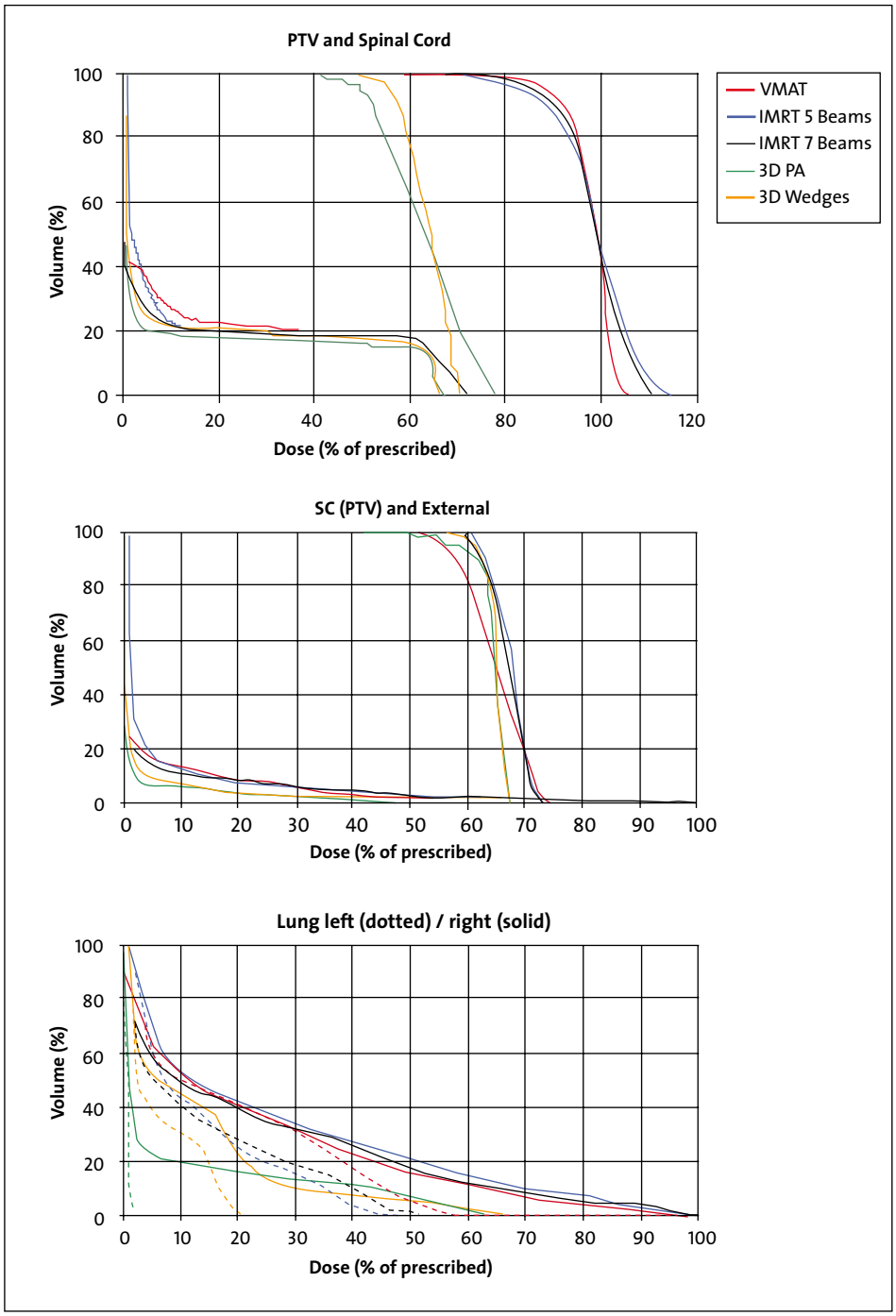

Figure 2. DVHs of PTV and OARs (lungs and SC encompassed by PTV) for a typical case dataset.

Abbildung 2. DVHs für PTV und OARs (Lungen und SC vom PTV umschlossen) für einen repräsentativen Datensatz.

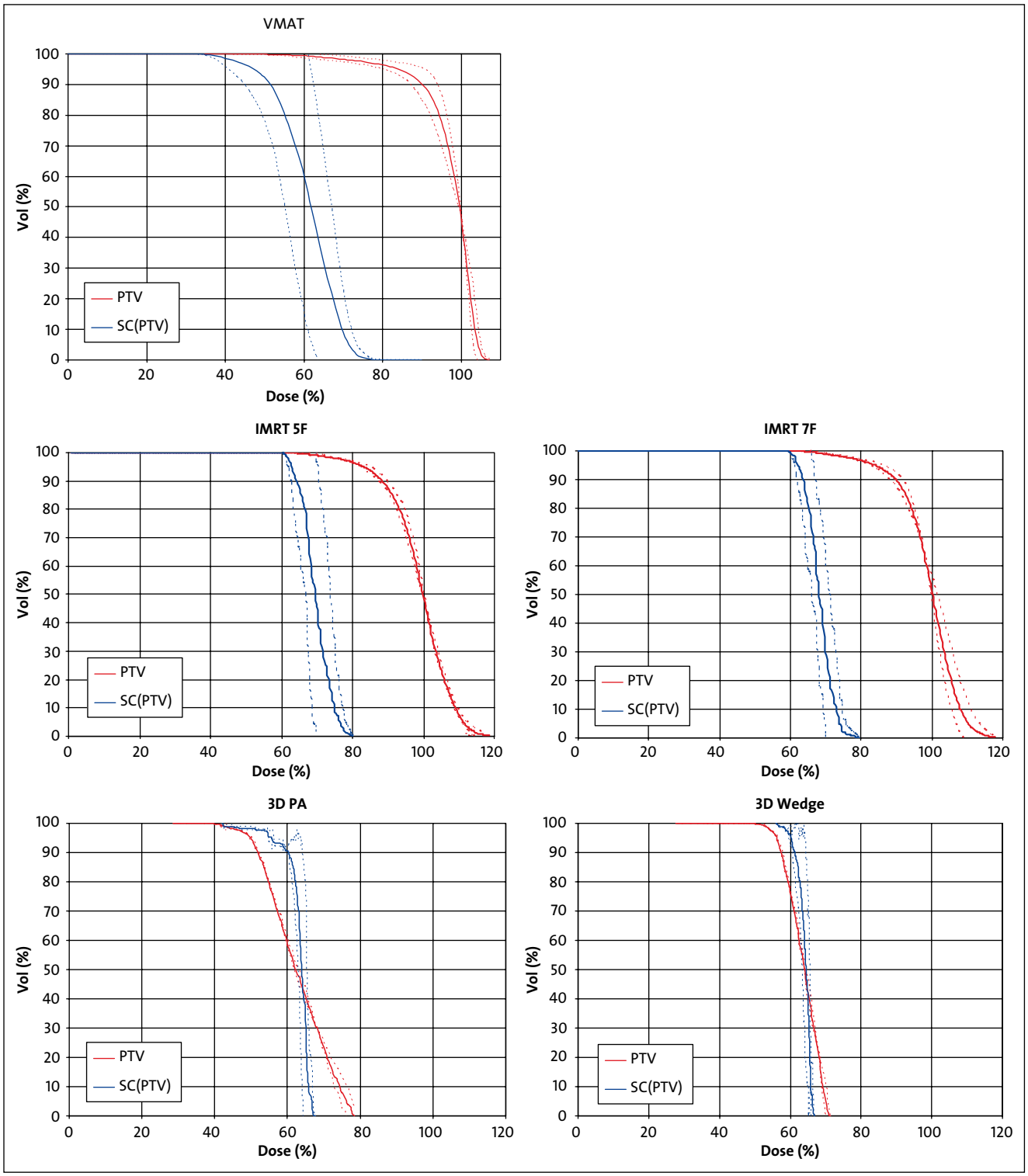

Figure 3. DVHs of PTV and SC(PTV) with 95% confidence interval.

Abbildung 3. DVHs von PTV und SC(PTV) mit 95%-Konfidenzintervall.

We have shown that VMAT provides the possibility to create treatment plans that are similar to static/dynamic IMRT with discrete beam angles in plan quality but are more efficient (shorter treatment time, fewer primary MU) for this particular treatment paradigm, approaching a mean treatment time of less than 5 min. This study clearly shows that higher tumor doses can be applied with modulated techniques such as VMAT than with simple 3D techniques while still respecting cord tolerance and should, therefore, be preferred in patients with good prognosis where longer term control is the treatment goal.

Table 1. Mean values ± standard deviations for homogeneity (HI40), conformity (CI), number of monitor units (MU), and treatment time (Time) for the three different techniques. In addition, the mean 99% dose in the PTV ($D_{99\%PTV}$), the mean percentage coverage of the PTV with 95% of the PD ($C_{95\%PD}$), and mean spinal cord (encompassed by the PTV) dose (SC_{PTV}).

Tabelle 1. Mittelwerte ± Standardabweichungen für Homogenität (HI40), Konformalität (CI), Anzahl von Monitoreinheiten (MU) und Bestrahlungszeit (Time) für die 3 Techniken. Zusätzlich: mittlere 99%-PTV-Dosis ($D_{99\%PTV}$), mittlere prozentuale Abdeckung des PTV mit 95% der PD ($C_{95\%PD}$) und mittlere Spinalkanal-(umschlossen vom PTV)-Dosis (SC_{PTV}).

	3D-PA	3D-wedge	IMRT 5B	IMRT 7B	VMAT
HI40	–	–	1.23 ± 0.06	1.21 ± 0.06	1.13 ± 0.07
CI	–	–	1.60 ± 0.34	1.79 ± 0.26	1.96 ± 0.35
MU	241 ± 21	526 ± 137	843 ± 133	878 ± 102	785 ± 92
Time, s	25 ± 2	88 ± 7	348 ± 72	472 ± 82	289 ± 69
D99%PTV	17.11 ± 4.72Gy	20.09 ± 3.24Gy	27.52 ± 1.48Gy	26.42 ± 1.73Gy	24.48 ± 2.34Gy
$C_{95\%PD}$	0% / 47.92 ± 9.89%	0% / 55.33 ± 1.93%	82.59 ± 4.56%	81.22 ± 4.37%	81.28 ± 4.25%
SC_{PTV}	26.11 ± 0.33Gy	25.98 ± 0.06Gy	26.91 ± 0.93Gy	25.67 ± 1.51Gy	23.54 ± 2.35Gy

Table 2. Differences reported with respective significance levels between delivery methods. n.s.: not significant, p value: significance.

Tabelle 2. Unterschiede mit respektiven Signifikanzstufen zwischen den Bestrahlungstechniken. n.s.: nicht significant, p-Wert: Signifikanz.

	3D-Wedge	IMRT 5B	IMRT 7B	VMAT
Target $D_{99\%}$				
3D-PA	3D-PA < 3D-wedge (p = 0.078)	3D-PA < IMRT 5B (p = 0.004)	3D-PA < IMRT 7B (p = 0.004)	3D-PA < VMAT (p = 0.004)
3D-wedge	–	3D-wedge < IMRT 5B (p = 0.004)	3D-wedge < IMRT 7B (p = 0.004)	3D-wedge < VMAT (p = 0.004)
IMRT 5B	–	–	IMRT 5B > IMRT 7B (p = 0.008)	IMRT 5B > VMAT (p = 0.008)
IMRT 7B	–	–	–	IMRT 7B > VMAT (p = 0.002)
SC(PTV) D_{Mean}				
3D-PA	n.s.	3D-PA < IMRT 5B (p = 0.027)	n.s.	3D-PA > VMAT (p = 0.023)
3D-wedge	–	3D-wedge < IMRT 5B (p = 0.004)	n.s.	3D-wedge > VMAT (p = 0.020)
IMRT 5B	–	–	IMRT 5B > IMRT 7B (p = 0.055)	IMRT 5B > VMAT (p = 0.004)
IMRT 7B	–	–	–	IMRT 7B > VMAT (p = 0.039)
MU				
3D-PA	3D-PA < 3D-wedge (p = 0.004)	3D-PA < IMRT 5B (p = 0.004)	3D-PA < IMRT 7B (p = 0.004)	3D-PA < VMAT (p = 0.004)
3D-wedge	–	3D-wedge < IMRT 5B (p = 0.004)	3D-wedge < IMRT 7B (p = 0.004)	3D-wedge < VMAT (p = 0.004)
IMRT 5B	–	–	n.s.	n.s.
IMRT 7B	–	–	–	IMRT 7B > VMAT (p = 0.012)
CI				
3D-PA	3D-PA > 3D-wedge (p = 0.055)	3D-PA > IMRT 5B (p = 0.004)	3D-PA > IMRT 7B (p = 0.027)	3D-PA > VMAT (p = 0.098)
3D-wedge	–	3D-wedge > IMRT 5B (p = 0.020)	n.s.	n.s.
IMRT 5B	–	–	IMRT 5B < IMRT 7B (p = 0.016)	IMRT 5B < VMAT (p = 0.004)
IMRT 7B	–	–	–	IMRT 7B < VMAT (p = 0.066)
HI				
3D-PA	n.s.	3D-PA < IMRT 5B (p = 0.004)	3D-PA < IMRT 7B (p = 0.004)	3D-PA < VMAT (p = 0.004)
3D-wedge	–	3D-wedge < IMRT 5B (p = 0.004)	3D-wedge < IMRT 7B (p = 0.004)	3D-wedge < VMAT (p = 0.004)
IMRT 5B	–	–	IMRT 5B > IMRT 7B (p = 0.047)	IMRT 5B > VMAT (p = 0.004)
IMRT 7B	–	–	–	IMRT 7B > VMAT (p = 0.004)

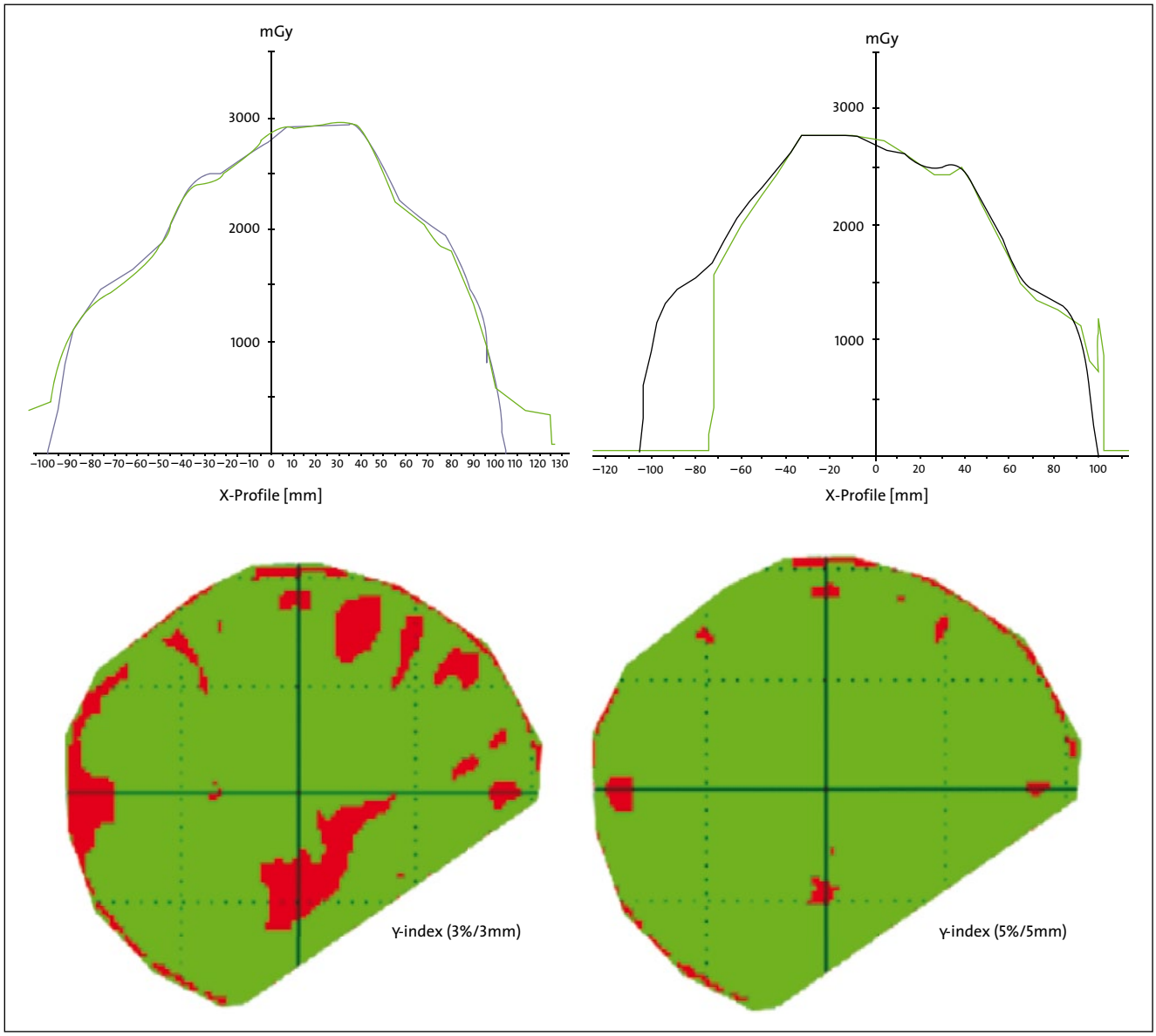

Figure 4. Two dose profiles examples provided by Verisoft and two γ-index plots with 3%/3 mm and 5%/5 mm for a typical plan dataset.

Abbildung 4. Exemplarische Dosisprofile (aus Verisoft) und zwei γ-Index-Bilder mit 3%/3 mm und 5%/5 mm für einen repräsentativen Fall.

Guckenberger et al. [11] recently evaluated the clinical outcome of dose-escalated image-guided radiotherapy with IMRT. Most of their patients were treated to a median dose of 60 Gy to the PTV in 20 fractions. They reported rapid and long-term pain relief with low acute and late toxicity using IMRT with a median of 7 incident beams (range, 6–14). The mean treatment time was not reported but a low number of segments (median total of 29 segments) were used. Chawla et al. [5] examined the efficiency and the possible advantages of single fraction stereotactic radiosurgery (SRS) using helical tomotherapy in the treatment of a patient with spinal column metastases in a case report. The prescribed dose to the PTV was 9 Gy and the treatment plan resulted in an excellent dose reduction down to 2.15 Gy at the spinal cord center. The PTV consisted only of the T6 vertebral bone and the treatment time was 13.6 min. The long treatment time resulted from the high fraction dose; thus, a lower fraction dose, e.g., 2 Gy, would reduce treatment time accordingly. It depends, however, linearly on target length. Treatment time for targets encompassing several vertebral bodies is, therefore, longer while it does not change for a VMAT approach [5]. The absence of a 40 cm field length limit (as it applies to VMAT) is a theoretical advantage

for tomotherapy but it is of negligible clinical relevance in the retreatment of spinal lesions that will normally be restricted to lesions < 40 cm in length.

A first report by Wu et al. [35] compared a volumetric treatment technique, Varian's RapidArc™, to sliding window IMRT for vertebral body radiotherapy. Treatment plans were generated with the TPS Eclipse (Varian Medical Systems, USA) in conjunction with a Novalis Tx linear accelerator with a maximal dose rate of 1000 MU/min and a single fraction dose of 16 Gy. Therefore, direct comparison of their results with our results regarding plan efficiency is not possible. They analyzed the CI for IMRT and VMAT with 1 and 2 arcs. They found a better conformity with VMAT than with IMRT and also suggested the necessity to use 2 arcs for optimal plan quality. Similar to our results they found a reduction of MU (24%) and also of treatment time (52%), interestingly with the two-arc treatment being delivered faster than the one-arc treatment and with fewer MU. Dosimetric data of their approach, however, are missing because their technique had not been implemented clinically at the time of publication [35].

We performed dosimetry with EDR2 films and ionization chambers because this method is stable and has been extensively validated. With increasing patient load based on the possible acceleration of modulated treatments, verification with 2D detector arrays will soon gain importance. Early reports indicate their reliability and validity [2, 14, 27] and this approach is currently validated for VMAT at our department [3].

An important issue for dosimetric accuracy is the distance of the control points (CP) during the setup of our VMAT plans. A larger number of CP not only results in better plan quality because of more degrees of freedom for modulation but also results in better dosimetric accuracy. This is because the TPS uses a pencil-beam algorithm for dose calculation in a static fashion at every CP. Consequently the dose calculation is performed in a discrete way but the delivery is dynamic, which leads to disagreements in measurements against calculation especially in the low dose region outside the PTV at the border of the phantom. We chose a distance between the CP of 5° which is sufficient to create plans of excellent plan quality but led to a lower number of pixels passing the γ-test with the criteria 3%/3 mm (78.56 ± 5.34%) than usually expected. Since Figure 3 clearly indicates that this disagreement was only in the low dose region with percentage differences translating into only small absolute differences, this trade-off was accepted to keep treatment times low while still obtaining excellent target coverage and organ at risk sparing. Continuous Monte Carlo dose calculation instead of a static approximation would solve this issue.

As a positive collateral result, a constant reduction in treatment time and MU while maintaining plan quality of modulated treatments as indicated in this manuscript and by others reduces the concern that secondary tumors might be caused by a high number of MU with modulated techniques [12]. Similarly, potentially detrimental effects of treatment protraction [4, 9, 16] are less likely with these fast modern techniques.

Conclusion

With plan quality being similar to static IMRT, VMAT is an efficient treatment technique for target volumes with a central avoidance structure. The increased treatment efficiency reduces the treatment time without imaging for the patient down to less than 5 min. This efficient treatment approach is dosimetrically sound and has successfully been implemented clinically.

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References

1. Alvarez Moret J, Kolbl O, Bogner L. Quasi-IMAT study with conventional equipment to show high plan quality with a single gantry arc. Strahlenther Onkol 2009;185:41–8.
2. Bedford JL, Lee YK, Wai P et al. Evaluation of the Delta4 phantom for IMRT and VMAT verification. Phys Med Biol 2009;54:N167–76.
3. Boggula R. Validation of novel 2D (helical dosimetry®) and 3D (COMPASS®) QA tools for VMAT. In Medical Physic and Biomedical Engineering World Congress 2009. Munich. 2009.
4. Brenner DJ, Hlatky LR, Hahnfeldt PJ et al. The linear-quadratic model and most other common radiobiological models result in similar predictions of time-dose relationships. Radiat Res 1998;150:83–91.
5. Chawla S, Abu-Aita R, Philip A et al. Stereotactic radiosurgery for spinal metastases: case report and review of treatment options. Bone 2009;45:817–21.
6. Depuydt T, Van Esch A, Huyskens DP. A quantitative evaluation of IMRT dose distributions: refinement and clinical assessment of the gamma evaluation. Radiother Oncol 2002;62:309–19.
7. Dobler B, Lorenz F, Wertz H et al. Intensity-modulated radiation therapy (IMRT) with different combinations of treatment-planning systems and linacs: issues and how to detect them. Strahlenther Onkol 2006;182:481–8.
8. Ezzell GA, Galvin JM, Low D et al. Guidance document on delivery, treatment planning, and clinical implementation of IMRT: report of the IMRT Subcommittee of the AAPM Radiation Therapy Committee. Med Phys 2003;30: 2089–115.
9. Fowler JF, Welsh JS, Howard SP. Loss of biological effect in prolonged fraction delivery. Int J Radiat Oncol Biol Phys 2004;59:242–9.
10. Freundt K, Meyners T, Bajrovic A et al. Radiotherapy for oligometastatic disease in patients with spinal cord compression (MSCC) from relatively radioresistant tumors. Strahlenther Onkol 2010;186:218–23.
11. Guckenberger M, Goebel J, Wilbert J et al. Clinical outcome of dose-escalated image-guided radiotherapy for spinal metastases. Int J Radiat Oncol Biol Phys 2009;74:828–35.
12. Hall EJ, Wuu CS. Radiation-induced second cancers: the impact of 3D-CRT and IMRT. Int J Radiat Oncol Biol Phys 2003;56:83–8.
13. Katagiri H, Takahashi M, Wakai K et al. Prognostic factors and a scoring system for patients with skeletal metastasis. J Bone Joint Surg Br 2005;87: 698–703.
14. Li JG, Yan G, Liu C. Comparison of two commercial detector arrays for IMRT quality assurance. J Appl Clin Med Phys 2009;10:2942.

15. Milker-Zabel S, Zabel A, Thilmann C et al. Clinical results of retreatment of vertebral bone metastases by stereotactic conformal radiotherapy and intensity-modulated radiotherapy. Int J Radiat Oncol Biol Phys 2003;55:162–7.
16. Mu X, Lofroth PO, Karlsson M et al. The effect of fraction time in intensity modulated radiotherapy: theoretical and experimental evaluation of an optimisation problem. Radiother Oncol 2003;68:181–7.
17. Nieder C, Grosu AL, Andratschke NH et al. Update of human spinal cord reirradiation tolerance based on additional data from 38 patients. Int J Radiat Oncol Biol Phys 2006; 66:1446–9.
18. Nieder C, Grosu AL, Andratschke NH et al. Proposal of human spinal cord reirradiation dose based on collection of data from 40 patients. Int J Radiat Oncol Biol Phys 2005;61:851–5.
19. Otto K. Volumetric modulated arc therapy: IMRT in a single gantry arc. Med Phys 2008;35:310–7.
20. Paddick I. A simple scoring ratio to index the conformity of radiosurgical treatment plans. Technical note. J Neurosurg 2000;93(Suppl 3):219–22.
21. Palma D, Vollans E, James K et al. Volumetric modulated arc therapy for delivery of prostate radiotherapy: comparison with intensity-odulated radiotherapy and three-dimensional conformal radiotherapy. Int J Radiat Oncol Biol Phys 2008;72:996–1001.
22. Pirzkall A, Lohr F, Rhein B et al. Conformal radiotherapy of challenging paraspinal tumors using a multiple arc segment technique. Int J Radiat Oncol Biol Phys 2000;48:1197–204.
23. Rhein B, Haring P, Debus J et al. [Dosimetric verification of IMRT treatment plans at the German Cancer Research Center (DKFZ)]. Z Med Phys 2002;12:122–132.
24. RTOG. Phase IB study of radiosurgery and etanidazole (sr-2508) for the treatment of recurrent primary brain tumors or CNS metastases. 1997, Radiation Therapy Oncology Group
25. Stieler F, Wolff D, Lohr F et al. A fast radiotherapy paradigm for anal cancer with volumetric modulated arc therapy (VMAT). Radiat Oncol 2009;4:48.
26. Tokuhashi Y, Matsuzaki Y, Toriyama S, et al. Scoring system for the preoperative evaluation of metastatic spine tumor prognosis. Spine (Phila PA 1976) 1990;15:1110–3.
27. Van Esch A, Clermont C, Devillers M et al. On-line quality assurance of rotational radiotherapy treatment delivery by means of a 2D ion chamber array and the Octavius phantom. Med Phys 2007;34:3825–37.
28. Vanetti E, Clivio A, Nicolini G et al. Volumetric modulated arc radiotherapy for carcinomas of the oro-pharynx, hypo-pharynx and larynx: a treatment planning comparison with fixed field IMRT. Radiother Oncol 2009;92:111–7.
29. Vandecasteele K, De Neve W, De Gersem W et al. Intensity-modulated arc therapy with simultaneous integrated boost in the treatment of primary irresectable cervical cancer. Treatment planning, quality control, and clinical implementation. Strahlenther Onkol 2009;185:799–807.
30. Wara WM, Phillips TL, Sheline GE et al. Radiation tolerance of the spinal cord. Cancer 1975;35:1558–62.
31. Webb S, McQuaid D. Some considerations concerning volume-modulated arc therapy: a stepping stone towards a general theory. Phys Med Biol 2009;54:4345–60.
32. Weber DC, Peguret N, Dipasquale G et al. Involved-node and involved-field volumetric modulated arc vs. fixed beam intensity-modulated radiotherapy for female patients with early-stage supra-diaphragmatic Hodgkin lymphoma: a comparative planning study. Int J Radiat Oncol Biol Phys 2009;75:1578–86.
33. Wolff D, Stieler F, Hermann B et al. Clinical implementation of volumetric intensity-modulated arc therapy (VMAT) with ERGO++. Strahlenther Onkol 2010; 186:280–8.
34. Wolff D, Stieler F, Welzel G et al. Volumetric modulated arc therapy (VMAT) vs. serial tomotherapy, step-and-shoot IMRT and 3D-conformal RT for treatment of prostate cancer. Radiother Oncol 2009;93:226–33.
35. Wu QJ, Yoo S, Kirkpatrick JP et al. Volumetric arc intensity-modulated therapy for spine body radiotherapy: comparison with static intensity-modulated treatment. Int J Radiat Oncol Biol Phys 2009;75:1596–604.

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