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Node-positive left-sided breast cancer: does VMAT improve treatment plan quality with respect to IMRT?

Additional material online

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Since its introduction, intensity-modulated radiotherapy (IMRT) has been explored for the adjuvant treatment of breast cancer [4, 7, 31]. The use of IMRT can significantly improve dose distribution for the breast resulting in reduced heart, lung and contralateral breast doses as well as improving the cosmetic outcome when compared to 3D conformal radiotherapy [1, 4, 9].

There is great heterogeneity in what is defined as "breast-IMRT" [21], ranging from photon-only IMRT [1, 31] to mixed electron and photon IMRT techniques with 2 [21] to 16 fields [30] applying various photon and electron beam energies. Regarding breast irradiation including regional lymph nodes, conventional 3- or 4-field conformal approaches fail to cover a volume that wraps around the chest wall in close proximity to the heart, lungs and spinal cord [22]. Dogan et al. [3] investigated the number of beams necessary for optimal dose coverage of regional lymph nodes in breast and found that 4-field IMRT was a good choice. However, 9 and more beams are considered advantageous by others [14, 21, 31].

Rotational IMRT techniques have been demonstrated to achieve not only better or comparable plan quality but also largely improve delivery efficiency when compared to step-and-shoot IMRT in various indications (e.g., [6]). Although IMRT and VMAT have been in clinical use for some time, the majority of studies evaluate breast only or breast/chest wall with internal mammary node (IMN) coverage [14, 21]. Few publications to date have addressed the role of IMRT in lymph node-positive breast cancer, and fewer involved investigation of VMAT (e.g., [28]).

Furthermore, 6 MV is considered the general purpose IMRT energy [3]. Regarding obese patients or patients with oversize breast volume (>2,000 cm^3 and breast thickness >7 cm), higher photon beam energy may show advantages over 6 MV. This aspect has not yet been addressed in VMAT or IMRT planning studies for breast cancer including axillary and supraclavicular nodes. The aim of the present treatment planning study was to explore 4-field IMRT and VMAT plans with 6, 10, and 15 MV photon beams for patients with node-positive left-sided breast cancer.

Methods and materials

Target volume delineation and organs at risk

We selected ten CT scans of patients with left-sided breast cancer, who underwent breast conserving surgery. Five patients were considered obese with a breast thickness larger than 7 cm (range 7–10.5 cm) and a breast volume larger than 2,000 cm^3 (range 2,000–3,750 cm^3). Patients were positioned in the supine position with arms raised above the head (BreastSTEP™, IT-V Medizintechnik GmbH, Austria).

For all cases, the clinical target volume (CTV) consisted of the left breast, infraclavicular lymph nodes (level III) and supraclavicular lymph nodes. The planning target volume (PTV_{MC+LN}) was defined to include a 10 mm margin around the CTV in all directions except the posterior direction towards the lung, where a 7 mm margin was added. The boost PTV_B was defined to include a 7–20 mm margin around the tumour bed in all directions.

The left and right lung as well as the spinal cord were auto-contoured in the treatment planning system (TPS) Pinnacle[3] (V9.0, Philips Radiation Oncology Systems, Fitchburg, WI, USA) using the model based segmentation option. Additionally, the heart, contralateral breast and the oesophagus were considered as critical structures.

Treatment planning

Plans for both VMAT and IMRT were generated using the same TPS, isocenter, dose grid (4×4×4 mm^3), prescriptions, and optimisation objectives in order to ensure fair treatment plan comparison. A primary plan for the PTV_{MC+LN} and a separate, sequential plan for the PTV_B were generated for each patient. The composite plan was evaluated, con-

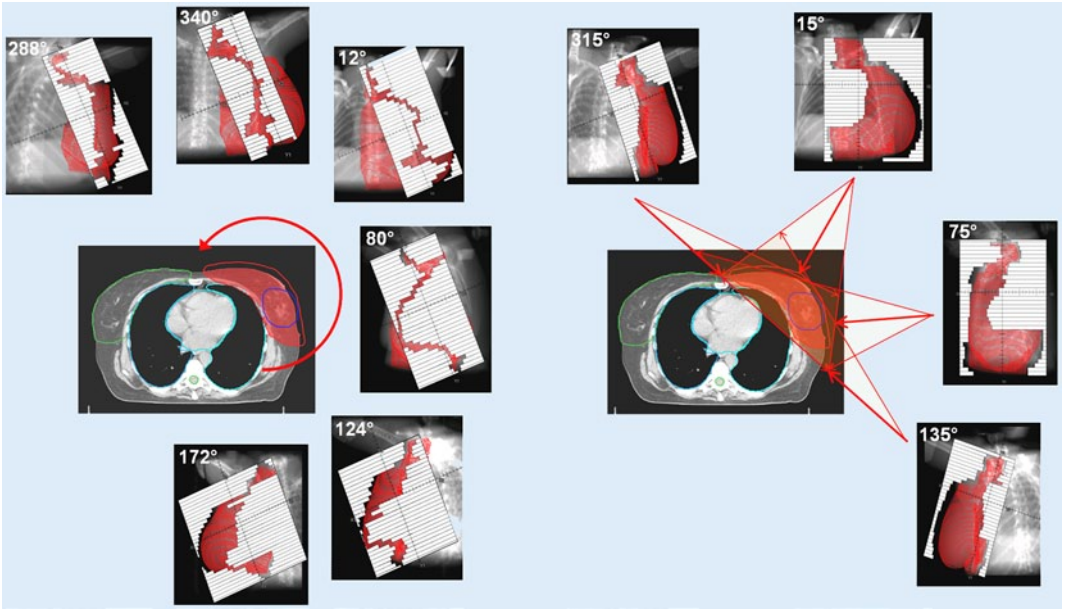

Fig. 1 ◀ Illustration of VMAT (*left*) and four-field IMRT (*right*) treatment plans with corresponding examples of segment shapes and digitally reconstructed radiographs for left-sided breast cancer (*red*: PTV_{MC+LN})

sisting of PTV_{MC+LN} and PTV_B. The prescription dose was 50.4 Gy to PTV_{MC+LN} in 1.8 Gy fractions and additional 10 Gy in 2 Gy fractions for PTV_B.

Optimisation aid structures in terms of rings around the target volumes were applied as described previously [20]. For IMRT planning, PTV_{MC+LN} was extended by 10 mm beyond the patient surface (PTV_{large}) to accommodate the variation due to setup uncertainties and patient breathing. This helping structure was considered during the optimisation with very low weighting, yielding extension of fluence for tangential fields without influencing plan quality. As illustrated in **Fig. 1**, the SmartArc algorithm produces elongated segments sweeping across the target volume and optimisation of PTV_{large} would therefore result in inhomogeneous dose distribution. Since flash margins are currently not established for SmartArc, optimisation was performed directly on the PTV_{MC+LN} structure. Dose constraints for target volumes and organs at risk (OAR) are listed in **Tab. 1**.

All plans were generated for an Elekta Synergy accelerator (DesktopPro Rel.7.01; MLCi with 1 cm leaf width) using the collapsed cone algorithm of Pinnacle[3].

IMRT plans were generated using four coplanar fields, consisting of two tangential beams and two additional, equidistant fields as illustrated in **Fig. 1**. An average of 60 and 15 segments were optimised in typically 25–30 iterations for PTV_{MC+LN} and PTV_B, respectively, using the direct machine parameter optimisation (DMPO) method [2]. Finally, 6, 10 and 15 MV photon beam IMRT plans were created for each patient and target volume.

VMAT plans were generated using a single rotation including an arc segment of up to 250° at a maximum allowed gantry rotation time of 90 s and gantry spacing at 4°. SmartArc plan optimisation was performed during 100 iterations; 6, 10 and 15 MV photon beam VMAT plans were created for each patient and target volume.

Plan comparison/plan evaluation

All plans were normalised to PTV_{MC+LN} and PTV_B mean doses, respectively. Dose–volume histograms (DVH) were analysed both manually and automatically using ArtiView™ (Aquilab GmbH, Germany) for each plan and results for DVH metrics were compared. $D_{98\%}$, $D_{50\%}$ and $D_{2\%}$, indicating dose to 98% (near-minimum dose), 50% and 2% (near-maximum dose) of both target volumes, were recorded. The homogeneity index (HI) was calculated according to ICRU 83 [13]: $HI = (D_{2\%}-D_{98\%})/D_{50\%}$. The conformity index (CI) as proposed by Paddick et al. [19] was evaluated: $CI_{Paddick}=TV^2_{PI}/(PI\times TV)$, where TV_{PI} is the target volume (TV) within the prescribed isodose volume (PI).

The dose to normal tissue was quantified by a volume V_{ring} which was introduced earlier [20]. V_{ring} was defined as the volume inside the body contour excluding the PTV_{MC+LN} plus a margin of 0.7 cm ($R_{90\%}$) in all directions. Further, surrogates for low dose volumes, i.e. the relative volumes of the 10, 30 and 50% isodoses ($V_{x\%}/V_{Body}=V_{Tissuex\%}$) were assessed. $D_{2\%}$ and D_{mean} were determined for all OAR and V_{ring} from the composite plan.

Delivery efficiency was determined in terms of total treatment delivery time (TT, time between the start of the first beam and the end of the last beam) and number of monitor units (MU) for each target volume per fraction.

Plan verification

For dose measurements, a 2D ionisation chamber array (seven29, PTW-Freiburg, Germany) was inserted vertically into an octagonal solid water phantom (Octavius, PTW-Freiburg) [33]. For calculation of the 2D gamma (γ) index, measured and recalculated plans were exported to the VeriSoft® software (PTW Freiburg). The percentage of detectors with γ index <1 and the mean γ were evaluated [17] applying the 3%/3 mm criteria (dose difference/distance to agreement) to quantify dosimetric accuracy.

All results were recorded as continuous variables; mean and standard deviations were calculated. We considered superiority of one photon beam energy if results were improved in at least 8 of 10 patients or 4 of 5 patients in the subgroups (normal and obese breast size patients).

Results

Treatment plan evaluation

Both techniques achieved good target coverage and excellent OAR sparing for both obese and normal patients (**Tab. 2, 3, Fig. 2**). Photon energy had no significant influence on CI and HI for VMAT, and in IMRT plans 6 MV showed a moderate benefit (**Tab. 2**). For normal patients, the VMAT plan results showed no considerable difference in OAR sparing between the investigated photon energies. For IMRT, 6 MV plans indicated improvements over 10 and 15 MV plans in 26 out of 37 parameters. For obese patients, IMRT plan results for OAR showed best metrics in 6 MV plans, especially for the contralateral breast and lung. Large variations were found between plans, especially concerning low dose exposure, caused by differences in patient geometry, size and position of target volumes and OARs. Results for the oesophagus show 4 Gy higher mean dose for obese breast size patients (D_{mean}=30.7 Gy) compared to normal breast size patients (D_{mean}=26.3 Gy) for both techniques.

Averaging all 10 patients, all target volume metrics of VMAT plans showed negligible differences between high and low energy photon beams. For IMRT plans, 6 MV again achieved best results in 17 out of 37 dose parameters, especially in $D_{2\%}$ for both target volumes and OARs.

VMAT plans were equal or superior in a pairwise comparison with IMRT plans with respect to target coverage, homogeneity and delivery efficiency. We found on average 2% more normal tissue irradiated with low doses in VMAT than in IMRT.

The manual and ArtiView™ plan evaluation coincided accurately (difference <1%) for most of the observed dose metrics. However, slightly increased discrepancies were determined for OAR where steep dose gradients occurred, e.g. $V_{30\,Gy}$ for the heart was found to be up to 8% smaller and $D_{98\%}$ was found to be on average 2.6% higher in the TPS when compared to ArtiView™ results, respectively.

Plan verification

Results for the γ-index analysis are presented in **Fig. 3**. Most of the plans met

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Node-positive left-sided breast cancer: does VMAT improve treatment plan quality with respect to IMRT?

Abstract

Purpose. The aim of the present work was to explore plan quality and dosimetric accuracy of intensity-modulated radiotherapy (IMRT) and volumetric modulated arc therapy (VMAT) for lymph node-positive left-sided breast cancer.

Methods. VMAT and IMRT plans were generated with the Pinnacle^3 V9.0 treatment planning system for 10 lymph node-positive left-sided breast cancer patients. VMAT plans were created using a single arc and IMRT was performed with 4 beams using 6, 10, and 15 MV photon energy, respectively. Plans were evaluated both manually and automatically using ArtiView™. Dosimetric plan verification was performed with a 2D ionization chamber array placed in a full scatter phantom.

Results. Photon energy had no significant influence on plan quality for both VMAT and IMRT. Large variability in low doses to the heart was found due to patient anatomy (range $V_{5\,Gy}$ 26.5–95%). Slightly more normal tissue dose was found for VMAT (e.g., $V_{Tissue30\%}$=22%) than in IMRT ($V_{Tissue30\%}$=18%). The manual and ArtiView™ plan evaluation coincided very accurately for most dose metrics (difference <1%). In VMAT, 96.7% of detector points passed the 3%/3 mm gamma criterion; marginally better accuracy was found in IMRT (98.3%).

Conclusion. VMAT for node-positive left-sided breast cancer retains target homogeneity and coverage when compared to IMRT and allows maximum doses to organs at risk to be reduced. ArtiView™ enables fast and accurate plan evaluation.

Keywords

Volumetric modulated arc therapy · Intensity-modulated radiotherapy · Breast neoplasms · Lymph nodes

Linksseitiges Mammakarzinom inklusive Lymphabfluss: Verbessert VMAT die Planqualität gegenüber IMRT?

Zusammenfassung

Ziel. Ziel der Studie war die Evaluierung der Planqualität und der dosimetrischen Genauigkeit von intensitätsmodulierter Strahlentherapie (IMRT) und volumetrisch modulierter Rotationstherapie (VMAT) für Patientinnen mit lymphknotenpositivem linksseitigem Mammakarzinom.

Methodik. VMAT- und IMRT-Pläne wurden mit dem Pinnacle^3-Bestrahlungsplanungssystem (V9.0) für 10 Patientinnen mit lymphknotenpositivem linksseitigem Mammakarzinom generiert. VMAT-Pläne wurden mit einer Rotation, IMRT-Pläne mit 4 Feldern mit jeweils 6, 10 und 15 MV erstellt. Die Planauswertung erfolgte sowohl manuell als auch automatisch mittels ArtiView™. Die Planverifikation wurde mit einer 2-D-Ionisationskammer-Matrix in einem Festkörperphantom durchgeführt.

Ergebnisse. Die Photonenenergie hat keinen signifikanten Einfluss auf die VMAT- und IMRT-Planqualität. Es wurden aufgrund unterschiedlicher Anatomien große Variationen im Niedrigdosisvolumen des Herzens festgestellt ($V_{5\,Gy}$ 26,5–95%). In VMAT-Plänen wurde ein geringfügig höheres Niedrigdosisvolumen (z. B. $V_{Tissue30\%}$=22%) als in IMRT-Plänen ($V_{Tissue30\%}$=18%) ermittelt. Manuelle und automatische Auswertung stimmten für die meisten Parameter sehr genau überein (Abweichung <1%). VMAT-Pläne erreichten einen Gamma-Index <1 (3 mm Abstand und 3% Dosis) für 96,7% der Detektorpunkte, geringfügig bessere Präzision erzielten die IMRT-Pläne mit 98,3%.

Schlussfolgerung. VMAT liefert eine ähnliche Dosishomogenität und -abdeckung der Zielvolumina wie IMRT und ermöglicht eine Reduktion der Risikoorgan- und Maximaldosen. Mittels ArtiView™ können Bestrahlungspläne schnell und genau evaluiert werden.

Schlüsselwörter

Volumenmodulierte Arc-Therapie · Intensitätsmodulierte Strahlentherapie · Brustneoplasien · Lymphknoten

Tab. 1 Dose constraints for target volumes, helping structures and organs at risk. $R_{90\%}$ is a ring of 0.7 cm around the target volume, where 90% of the prescribed dose is allowed. $R_{80\%}$ covers the area from 0.7 cm to 2 cm around the target volume, with maximum dose (D_{max}) <80% of the prescribed dose

Structure	Dose constraint
PTV_{MC+LN}	D_{mean}=100%
	D_{min}≥95%
	D_{max}≤107%
PTV_{Boost}	D_{mean}=100%
	D_{max}≤107%
$R_{80\%}$	D_{max}≤80%
$R_{90\%}$	D_{max}≤90%
PTV_{large}	D_{mean}=100% (weight 0.1)
Composite plan constraints	
Lung left	$D_{20\%}$<30 Gy
	$D_{30\%}$<20 Gy
	D_{mean}<16 Gy
Oesophagus	D_{mean}<28 Gy
	D_{max}<48 Gy
Heart	D_{mean}<9 Gy
	D_{max}<40 Gy
	$D_{10\%}$<20 Gy
	$D_{30\%}$<3 Gy
Spinal cord	D_{max}<30 Gy
Lung right	D_{mean}<4 Gy
	D_{max}<10 Gy
Breast right	D_{mean}<3 Gy
	D_{max}<6 Gy
V_{ring}	D_{mean}<7 Gy
	D_{max}<35 Gy

Tab. 2 Overview of all investigated dose–volume histogram parameters and delivery efficiency metrics as mean values and standard deviations (***SD***). Better (+/++) or worse (−/−−) results in at least 8/9 of 10 treatment plans are indicated; no difference between techniques is shown with ***0***. Analysis of subgroups (normal/obese breast patients) is provided as supplementary material (*Tables 2a*, *b*, online)

	VMAT						IMRT		
	6 MV		10 MV		15 MV		6 MV	10 MV	15 MV
	Mean ± SD		Mean ± SD		Mean ± SD		Mean ± SD	Mean ± SD	Mean ± SD
PTV_{MC+LN}									
D_{med} [Gy]	51.7 ± 0.6	0	51.8 ± 0.4	0	51.5 ± 0.5	++	51.7 ± 0.4	51.9 ± 0.5	51.9 ± 0.6
$D_{98\%}$ [Gy]	35.4 ± 1.5	0	34.4 ± 1.4	0	35.5 ± 1.7	++	35.2 ± 1.8	34.3 ± 2.3	34.2 ± 2.3
$D_{02\%}$ [Gy]	55.9 ± 0.6	0	55.5 ± 1.6	0	56.6 ± 0.4	0	55.6 ± 0.8	56.0 ± 0.6	56.2 ± 0.6
CI	0.78 ± 0.03	0	0.77 ± 0.04	+	0.77 ± 0.05	+	0.76 ± 0.05	0.75 ± 0.05	0.74 ± 0.04
HI	0.40 ± 0.03	0	0.41± 0.05	0	0.41 ± 0.03	+	0.40 ± 0.04	0.42 ± 0.04	0.42 ± 0.04
MU	397.5 ± 39.9	++	403.7 ± 37.1	++	469.3 ± 78.4	++	671.9 ± 115.5	801.1 ± 169.7	861.2 ± 163.1
TT [min]	1.7±0.2	++	1.7±0.1	++	1.6±0.0	++	8.7 ± 0.5	8.7 ± 0.5	8.1 ± 0.4
PTV_{Boost}									
D_{med} [Gy]	61.9 ±0.8	+	62.3 ±0.7	0	62.0 ±1.1	0	62.3 ±0.8	62.5 ±1.1	62.8 ±1.2
$D_{98\%}$ [Gy]	46.7 ±9.2	0	45.7 ±9.2	0	46.5 ±9.0	++	47.9 ±9.4	46.5 ±9.9	43.7 ±9.1
$D_{02\%}$ [Gy]	64.1 ±1.0	0	64.5 ±0.4	0	65.4 ±1.4	0	65.5 ±1.0	65.5 ±1.3	65.9 ±1.2
CI	0.46 ±0.13	0	0.48 ±0.23	0	0.44 ±0.12	+	0.43 ±0.13	0.40 ±0.11	0.40 ±0.12
HI	0.28 ±0.14	0	0.30 ±0.15	0	0.31 ±0.14	+	0.28 ±0.15	0.30 ±0.16	0.35 ±0.15
MU	301.2 ±81.1	++	355.9 ±115.6	0	351.3 ±109.3	0	311.8 ±90.6	320.1 ±66.3	365.4 ±114.6

the clinical specification of γ<1 for 95% of detector points passing the γ-index criterion for 3%/3 mm (range 87.3–100%). In general, IMRT plans showed slightly higher dosimetric accuracy than VMAT plans.

Discussion

This study compared IMRT and VMAT plans for node-positive left-sided breast cancer patients using 6, 10 and 15 MV high photon energy beams. Target coverage and homogeneity were comparable for both techniques. No energy dependence could be found in target or in associated organs at risk for VMAT. For IMRT, 6 MV photon plans showed slight benefits over 10 and 15 MV photon energy beams. Comparing VMAT vs. IMRT, hot spots decreased while peripheral doses increased for VMAT plans due to lower dose gradients. This issue has been addressed by several authors [20, 21, 28, 35], but the clinical consequences are unknown at present.

The large variations found in low doses, especially regarding the heart, might be explained by large variations in patient anatomy. Similar findings have been reported by Taylor et al. [29]. The mean heart dose for VMAT (D_{mean}=8.5 Gy) and IMRT (D_{mean}=8.2 Gy) was comparable to the findings of Fogliata et al. [8] (IMRT 10.1 Gy) as well as Goddu et al. [12] (Tomotherapy 12.2 Gy). Although there is great awareness of the potential damage to the heart in left-sided breast cancer RT [16], the radiobiology of the heart damage is only partially understood [23]. There are no known 'safe' levels of radiation to the heart at present [14].

Low dose irradiation raises the concern of developing a secondary malignancy [1, 5], especially regarding the contralateral breast [27]. We found comparable exposure of the right breast in VMAT and IMRT. High dose regions in contralateral structures are similar (e.g. $D_{2\%}$ for right breast) or smaller ($D_{2\%}$ and $V_{10\,Gy}$ for the right lung) in VMAT compared to IMRT for normal breast sizes. This effect was not found in patient plans with large breast size.

The dose to the ipsilateral lung was found slightly increased in VMAT plans; however, $V_{20\,Gy}$ and $V_{30\,Gy}$ were always within the tolerance. Clinical evidence

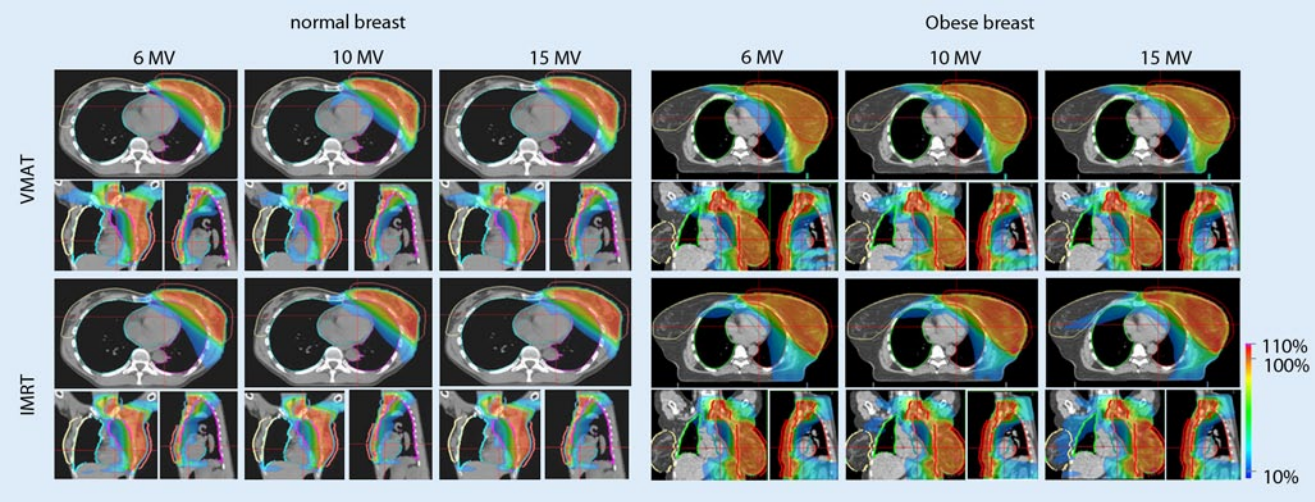

Fig. 2 ▲ Sample isodose distributions in transverse, coronal and sagittal planes (ArtiView™) for VMAT and IMRT plans of a normal (*left*) and an obese (*right*) patient at 6, 10 and 15 MV

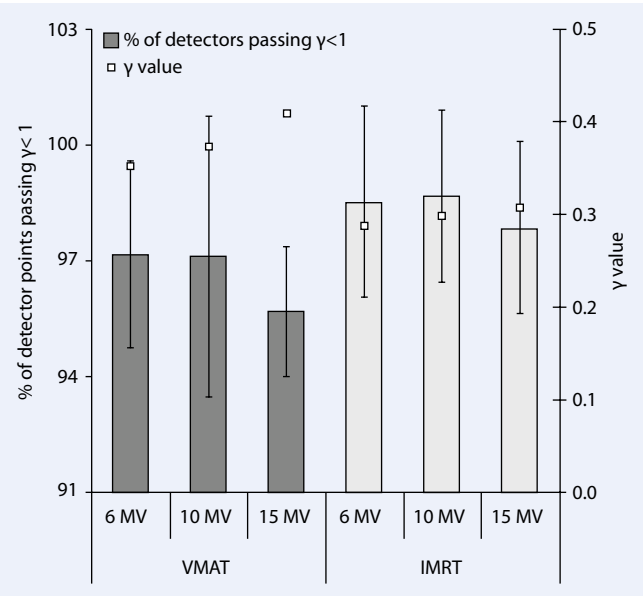

Fig. 3 ▲ Results of γ-index analysis: *bars* represent percent of detector points passing γ<1, *error bars* show the corresponding standard deviation and *squares* display γ values. Boxes indicate γ values

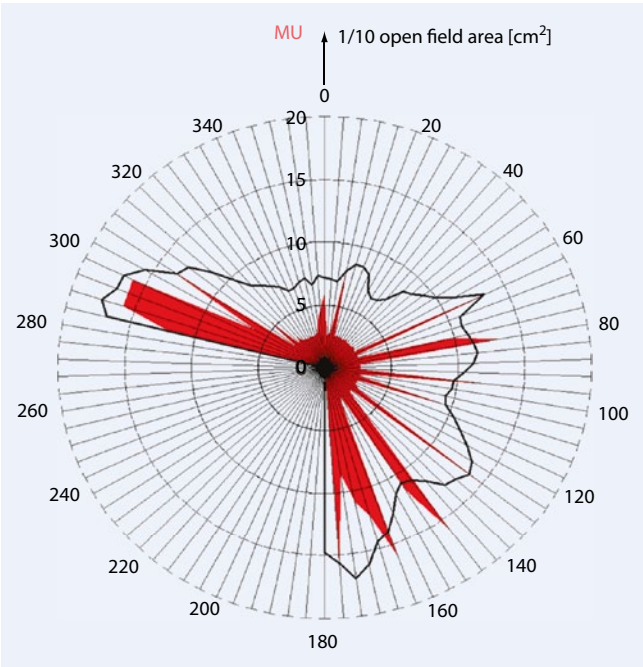

Fig. 4 ▲ Polar diagram of monitor unit distribution (*red*) and the corresponding 1/10 open field area (*black*) for a representative VMAT plan

of pulmonary complications in radiation treatment for breast cancer is reported to be rare within this tolerance [15].

Oesophageal toxicity has been correlated with mean doses greater than 34 Gy [24]. Our VMAT and IMRT results were well within this limit (D_{mean}<31.5 Gy). However, larger target volumes of obese breast size patients were found to correlate with higher mean dose to the oesophagus compared to normal breast size patients, again due to unfavourable geometry.

In this study, intrafraction motion was taken into account for IMRT by using adequate margins in the plan optimisation. For SmartArc optimisation, such options are currently not established. Artificial soft-tissue equivalent expansion of 2 cm of the body in the region of the breast was therefore proposed to account for breast motion during rotational IMRT [18, 30].

The monitor unit distribution for a representative VMAT plan and the corresponding open field area are illustrated in **Fig. 4**. As can be seen, high dose rate fluctuation occurs throughout the plan and only a minimal MU contribution comes from gantry angles 340° to 50° because of OAR constraints. This low-MU segment could be avoided by restricting VMAT beam angles. However, in Pinnacle[3] V9.0 it is not possible to optimise VMAT arcs smaller than 90°. In Pinnacle[3] V9.2, the minimum arc angle is 24° which allows avoiding critical structures more efficiently and reducing unnecessary low dose irradiation.

Tab. 3 Results for organs at risk. The mean values and standard deviations (***SD***) for the 10 patients are shown. Better (+/++) or worse (−/−−) results in at least 8/9 of 10 treatment plans are indicated; no difference between techniques is shown with ***0***. Analysis of subgroups (normal/obese breast patients) is provided as supplementary material (*Tables 3 a, b*, online)

	VMAT						IMRT		
	6 MV		10 MV		15 MV		6 MV	10 MV	15 MV
	Mean ±SD		Mean ±SD		Mean ±SD		Mean ±SD	Mean ±SD	Mean ±SD
Lung left									
D_{mean} [Gy]	14.6 ±0.6	0	14.8 ±0.8	0	14.8 ±0.7	0	14.6 ±1.0	14.7 ±1.3	15.0 ±1.5
$D_{02\%}$ [Gy]	49.7 ±2.9	0	49.7 ±2.2	0	49.1 ±2.8	+	49.6 ±3.7	50.0 ±3.3	49.8 ±4.1
$V_{20\,Gy}$ [%]	26.8±2.2	–	27.7 ±2.9	–	27.0 ±2.9	0	23.9 ±3.6	25.6 ±4.1	26.6 ±4.4
$V_{30\,Gy}$	16.6 ±1.8	0	17.4 ±1.8	0	16.7 ±2.1	+	16.9 ±3.3	17.8 ±3.3	17.8 ±3.6
Heart									
D_{mean} [Gy]	8.9 ±1.4	0	8.8 ±1.1	0	8.6 ±1.3	0	8.6 ±1.5	8.6 ±1.8	8.4 ±1.5
$D_{02\%}$ [Gy]	32.4 ±5.1	+	33.6 ±6.7	0	32.4 ±7.7	++	36.0 ±10.8	36.0 ±10.6	36.7 ±10.2
$V_{5\,Gy}$ [%]	73.0 ±23.4	0	72.4 ±19.7	0	75.6 ±23.8	0	69.2 ±21.0	65.5 ±21.2	66.0 ±21.7
$V_{10\,Gy}$ [%]	24.5 ±9.6	0	21.5 ±7.1	0	20.1 ±7.1	+	19.4 ±5.7	21.4 ±6.6	22.0 ±4.8
$V_{30\,Gy}$ [%]	2.7 ±1.7	+	3.0 ±2.3	0	2.7 ±2.4	++	4.2 ±3.5	4.4 ±3.6	4.0 ±3.0
Oesophagus									
D_{mean} [Gy]	28.4 ±6.2	0	28.0 ±6.2	+	27.8 ±6.6	+	28.1 ±5.1	28.9 ±5.2	29.3 ±5.9
$D_{02\%}$ [Gy]	47.5 ±7.3	0	46.4 ±7.5	0	45.7 ±8.8	0	45.0 ±5.7	45.7 ±5.0	44.8 ±6.0
Myelon									
D_{mean} [Gy]	8.7 ±5.4	0	7.9 ±5.0	+	8.7 ±5.1	+	8.6 ±3.3	9.9 ±4.4	10.1 ±4.1
$D_{02\%}$ [Gy]	25.7 ±7.4	0	24.3 ±7.3	+	24.7 ±6.9	0	24.4 ±7.0	26.6 ±7.5	27.0 ±7.0
V_{ring}									
D_{mean} [Gy]	5.6 ±1.0	–	5.4 ±1.2	0	5.6 ±1.0	0	4.9 ±1.0	5.2 ±1.1	5.4 ±1.2
$D_{02\%}$ [Gy]	32.1 ±4.8	0	31.6 ±5.6	0	31.6 ±5.7	–	27.9 ±4.9	27.0 ±4.0	27.3 ±4.5
$V_{Tissue50\%}$	15.1% ±3.3%	–	14.8% ±3.2%	–	15.0% ±3.1%	0	13.9% ±2.7%	13.9% ±2.7%	14.0% ±2.6%
$V_{Tissue30\%}$	21.8% ±4.5%	–	21.1% ±4.0%	–	21.6% ±4.2%	–	17.9% ±3.4%	18.8% ±3.4%	19.3% ±3.4%
$V_{Tissue10\%}$	38.6% ±6.7%	0	38.0% ±7.4%	0	40.6% ±7.9%	0	37.9% ±6.5%	40.1% ±6.5%	41.4% ±7.6%
Lung right									
D_{mean} [Gy]	3.9±1.0	0	3.4 ±1.1	0	4.5 ±1.6	0	4.2 ±2.3	4.4 ±2.3	4.5 ±2.5
$D_{02\%}$ [Gy]	11.4 ±3.0	0	9.4 ±3.6	0	12.4 ±4.4	0	9.8 ±4.1	12.1 ±5.9	13.1 ±6.3
$V_{5\,Gy}$ [%]	23.0 ±12.3	0	17.7 ±13.6	0	28.7 ±19.2	0	20.2 ±18.0	24.6 ±19.0	25.6 ±19.7
$V_{10\,Gy}$ [%]	4.3 ±3.0	–	2.6 ±3.4	0	7.1 ±6.8	0	5.7 ±11.5	7.7 ±10.7	8.6 ±12.7
Breast right									
D_{mean} [Gy]	2.8 ±1.0	–	2.9 ±1.2	0	3.2 ±1.3	0	2.8 ±1.0	3.3 ±1.6	3.3 ±1.5
$D_{02\%}$ [Gy]	5.8 ±0.9	0	7.1 ±2.6	0	7.2 ±2.7	0	6.0 ±2.1	7.0 ±2.8	7.1 ±3.0

The major features of VMAT over IMRT are the reduction in treatment time and monitor units. Our results showed that VMAT can achieve a similar plan quality while limiting treatment time to less than 2 min (compared to 8 min in IMRT) and reducing monitor units up to 90% (**Tab. 2**).

Another purpose of this study was the dosimetric verification of IMRT and VMAT plans. Ionisation chamber array measurements were within the tolerance limits of the γ-index criterion of 3%/3 mm for both VMAT (96.7%) and IMRT (98.3%) plan delivery. Similar results were previously reported for IMRT (e.g. [34]) and VMAT (e.g. [32]). Deviations between measurements and calculations were higher for VMAT compared to IMRT [20]. This may originate from the fact that SmartArc uses continuous, variable dose-rates in the optimisation process, whereas the linac under study is bound to binned dose-rates. Such uncertainties might be reduced by interpolation of the control point vectors from 4° to 2° final gantry spacing. Today, the gold standard for VMAT plan verification is still a dose measurement reporting the γ index [26]. In future, independent monitor unit verification will be an attractive option for static and rotational IMRT [10]. Besides manual evaluation of plan quality criteria, automated evaluation was investigated. ArtiView™ provides fast and accurate plan evaluation.

In this study, photon beam energy variation in IMRT and VMAT for left-sided node-positive breast cancer plans was investigated for the first time. Further experience has to be gained regarding new linac control systems with improved dynamic parameters, such as continuous variable dose rates and MLC interdigitation. Recently, flattening filter free approaches (FFF) [11] became clinically available and provide promising results for chest wall radiotherapy [25, 28], which should

be further investigated for large and complex target volumes.

Conclusion

VMAT for node-positive left-sided breast cancer allows the maximum doses to OAR, especially the heart to be reduced, while retaining target homogeneity and coverage when compared to IMRT. For most patients, 6 MV plans showed the best results in both static and rotational IMRT. Patient age and anatomical geometry should be considered when determining which technique and energy to use.

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References

1. Abo-Madyan Y, Polednik M, Rahn A et al (2008) Improving dose homogeneity in large breasts by IMRT: efficacy and dosimetric accuracy of different techniques. Strahlenther Onkol 184:86–92
2. Cotrutz C, Xing L (2003) Segment-based dose optimisation using a genetic algorithm. Phys Med Biol 48:2987–2998
3. Dogan N, Cuttino L, Lloyd R et al (2007) Optimized dose coverage of regional lymph nodes in breast cancer- the role of intensity modulated radiotherapy. Int J Radiat Oncol Biol Phys 68:1238–1250
4. Donovan E, Bleakley N, Denholm E et al (2007) Randomised trial of standard 2D radiotherapy (RT) versus intensity modulated radiotherapy (IMRT) in patients prescribed breast radiotherapy. Radiother Oncol 82:254–264
5. Dörr W, Herrmann T (2002) Second primary tumors after radiotherapy for malignancies. Treatment-related parameters. Strahlenther Onkol 178:357–362
6. Eppinga E, Lagerwaard F, Verbakel W et al (2010) Volumetric modulated arc therapy for advanced pancreatic cancer. Strahlenther Onkol 186:382–387
7. Evans PM, Donovan EM, Partridge M et al (2000) The delivery of intensity modulated radiotherapy to the breast using multiple static fields. Radiother Oncol 57:79–88
8. Fogliata A, Clivio A, Nicolini G et al (2007) A treatment planning study using non-coplanar static fields and coplanar arcs for whole breast radiotherapy of patients with concave geometry. Radiother Oncol 85:346–354
9. Freedman GM, Li T, Nicolaou N et al (2009) Breast intensity-modulated radiation therapy reduces time spent with acute dermatitis for women of all breast sizes during radiation. Int J Radiat Oncol Biol Phys 74:689–694
10. Georg D, Nyholm T, Olofsson J et al (2007) Clinical evaluation of monitor unit software and the application of action levels. Radiother Oncol 85:306–315
11. Georg D, Knöös T, McClean B (2011) Current status and future perspective of flattening filter free photon beams. Med Phys 38:1280–1293
12. Goddu SM, Chaudhari S, Mamalui-Hunter M et al (2009) Helical tomotherapy planning for left-sided breast cancer patients with positive lymph nodes: comparison to conventional multiport breast technique. Int J Radiat Oncol Biol Phys 73:1243–1251
13. International Commission on Radiation Units and Measurements (ICRU). ICRU Report No. 83: Prescribing, Recording, and Reporting Photon-Beam Intensity-Modulated Radiation Therapy (IMRT)
14. Jagsi R, Moran J, Marsh R et al (2010) Evaluation of four techniques using intensity-modulated radiation therapy for comprehensive locoregional irradiation of breast cancer. Int J Radiat Oncol Biol Phys 78:1594–1603
15. Lind PA, Wennberg B, Gagliardi G, Fornander T (2001) Pulmonary complications following different radiotherapy techniques for breast cancer, and the association to irradiated lung volume and dose. Breast Cancer Res Treat 68:199–210
16. Lohr F, Heggemann F, Papavassiliu T et al (2009) Is cardiotoxicity still an issue after breast-conserving surgery and could it be reduced by multifield IMRT? Strahlenther Onkol 185:222–230
17. Low DA, Harms WB, Mutic S, Purdy JA (1998) A technique for the quantitative evaluation of dose distributions. Med Phys 25:656–661
18. Nicolini G, Fogliata A, Clivio A et al (2011) Planning strategies in volumetric modulated arc therapy for breast. Med Phys 38:4025–4031
19. Paddick I (2000) A simple scoring ratio to index the conformity of radiosurgical treatment plans. Technical note. J Neurosurg 93:219–222
20. Pasler M, Georg D, Wirtz H, Lutterbach J (2011) Effect of photon-beam energy on VMAT and IMRT treatment plan quality and dosimetric accuracy for advanced prostate cancer. Strahlenther Onkol 187:812–819
21. Popescu CC, Olivotto IA, Beckham WA et al (2010) Volumetric modulated arc therapy improves dosimetry and reduces treatment time compared to conventional intensity-modulated radiotherapy for locoregional radiotherapy of left-sided breast cancer and internal mammary nodes. Int J Radiat Oncol Biol Phys 76:287–295
22. Rabinovitch R, Ballonoff A, Newman F, Finlayson C (2008) Evaluation of breast sentinel lymph node coverage by standard radiation therapy fields. Int J Radiat Oncol Biol Phys 70:1468–1471
23. Sardaro A, Petruzzelli MF, D'Errico MP et al (2012) Radiation-induced cardiac damage in early left breast cancer patients: risk factors, biological mechanisms, radiobiology, and dosimetric constraints. Radiother Oncol 103:133–142
24. Singh AK, Lockett MA, Bradley JD (2003) Predictors of radiation-induced esophageal toxicity in patients with non-small cell lung cancer treated with three-dimensional conformal radiotherapy. Int J Radiat Oncol Biol Phys 55:337–341
25. Spruijt KH, Dahele M, Cuijpers JP et al (2012) Flattening filter free vs flattened beams for breast irradiation. Int J Radiat Oncol Biol Phys 85:506–513
26. Stock M, Kroupa B, Georg D (2005) Interpretation and evaluation of the gamma index and the gamma index angle for the verification of IMRT hybrid plans. Phys Med Biol 50:399–411
27. Stovall M, Smith S, Langholz B et al (2008) Dose to the contralateral breast from radiotherapy and risk of second primary breast cancer in the WECARE study. Int J Radiat Oncol Biol Phys 72:1021–1030
28. Subramaniam S, Thirumalaiswamy S, Srinivas C et al (2012) Chest wall radiotherapy with volumetric modulated arcs and the potential role of flattening filter free photon beams. Strahlenther Onkol 188:484–491
29. Taylor CW, Nisbet A, McGale P, Darby SC (2007) Cardiac exposures in breast cancer radiotherapy: 1950s–1990s. Int J Radiat Oncol Biol Phys 69:1484–1495
30. Thilmann C, Zabel A, Nill S et al (2002) Intensity-modulated radiotherapy of the female breast. Med Dosim 27:79–90
31. Thilmann C, Zabel A, Kuhn S et al (2002) Inversely planned intensity modulated radiotherapy for irradiation of a woman with breast cancer and funnel chest. Strahlenther Onkol 178:637–643
32. Vandecasteele K, De Neve W, De Gersem W et al (2009) Intensity-modulated arc therapy with simultaneous integrated boost in the treatment of primary irresectable cervical cancer. Strahlenther Onkol 185:799–807
33. Van Esch A, Clermont C, Devillers M et al (2007) On-line quality assurance of rotational radiotherapy treatment delivery by means of a 2D ion chamber array and the Octavius phantom. Med Phys 34:3825–3837
34. Wiezorek T, Banz N, Schwedas M et al (2005) Dosimetric quality assurance for intensity-modulated radiotherapy. Feasibility study for a filmless approach. Strahlenther Onkol 181:468–474
35. Wiezorek T, Schwahofer A, Schubert K (2009) The influence of different IMRT techniques on the peripheral dose: a comparison between sMLM-IMRT and helical tomotherapy. Strahlenther Onkol 185:969–702