



HALFMOON TomoTherapy (Helical ALtered Fractionation for iMplant partial Omission): implant-sparing post-mastectomy radiotherapy reshaping the clinical target volume in the reconstructed breast

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Abstract

Purpose To report the dosimetric feasibility of the radiation technique HALFMOON (Helical ALtered Fractionation for iMplant partial Omission) for post-mastectomy radiation therapy (PMRT) in intermediate–high-risk breast cancer patients with implant-based immediate breast reconstruction, where the clinical target volume (CTV) does not include the whole implant (implant-sparing approach).

Methods In the HALFMOON technique, the CTV consisted of skin, subcutaneous tissues, and pectoralis major muscle, excluding the implant, chest wall muscles, and rib plane. The HALFMOON plans were compared with conventionally contoured CTV plans, in which the whole implant, chest wall muscles, and ribs plane were included in the CTV, in a ratio 1:3. All patients underwent hypofractionated treatment of 40.05 Gy/15 fractions, using helical Tomotherapy[®].

Results Eighteen patients undergoing HALFMOON technique were compared to 54 subjects treated with conventionally contoured CTV plans. No difference was found in the planning target volume coverage between the two groups. Conversely, a statistically relevant dose reduction in HALFMOON patients was observed for ipsilateral lung ($D_{15\%}$, $p < 0.0001$; $D_{20\%}$, $p < 0.0001$; $D_{35\%}$, $p = 0.003$), contralateral lung ($D_{20\%}$, $p = 0.048$), contralateral breast ($D_{15\%}$, $p = 0.031$; $D_{20\%}$, $p = 0.047$), and stomach (D_{mean} , $p = 0.011$). Regarding the implant, $V_{90\%}$ and $D_{50\%}$ decreased by 46% and 8%, respectively, in the HALFMOON plans ($p < 0.0001$).

Conclusion The HALFMOON approach is technically feasible and resulted in high-dose conformity of the target with a significant reduction of radiation dose delivered to implant and other organs. A clinical study is needed to assess the impact on reconstruction cosmetic outcome and local control.

Keywords Hypofractionation · Intensity-modulated radiotherapy · Dosimetry · Post-mastectomy radiation therapy · Immediate breast reconstruction

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Introduction

Indications for post-mastectomy radiation therapy (PMRT) in breast cancer (BC) have been recently broadened (Recht et al. 2017; EBCTCG (Early Breast Cancer Trialists' Collaborative Group) et al. 2014). Given the growing use of immediate breast reconstruction (IBR) after mastectomy (Frasier et al. 2016; Sabino et al. 2016), its interaction with PMRT has become a subject of great interest.

Although there is no consensus about the most appropriate technique of breast reconstruction in relation to PMRT,

implant-based techniques, including both one-stage (direct to implant) and two-stage procedures, using tissue expanders (TE) prior to the placement of permanent implant (PI), are known to carry a higher rate of complications compared to autologous ones (El-Sabawi et al. 2016; Cordeiro et al. 2014; Brennan et al. 2016; Barry and Kell 2011; Fowble et al. 2015).

Besides the potential radiation-induced toxicity, the reconstructed breast may interfere with radiation therapy (RT) delivery, challenging the proper target coverage and the optimal sparing of organs at risk (OARs) (Buchholz et al. 2002; Schechter et al. 2005; Motwani et al. 2006). In addition, there is no consensus on the definition of the clinical target volume (CTV) for chest wall (CW) irradiation. The European Society for Radiotherapy and Oncology (ESTRO) consensus guidelines (Offersen et al. 2015) on target volume delineation for BC stated that there is no reason for routinely including the major pectoral muscle and ribs in the CTV of the thoracic wall, provided that they are not involved by the tumor. Therefore, the ESTRO panelists (Offersen et al. 2015) suggest limiting the CTV to the subcutaneous tissues and to the skin in slim patients, while the Breast Cancer Atlas released by the American Society for Radiation Oncology (ASTRO) (White et al. 2019) and by the Italian Association of Radiotherapy and Clinical Oncology (AIRO) (AIRO 2013) recommend including skin, subcutaneous tissues, pectoralis muscles, CW muscles, and ribs in the CTV posterior margin. However, these guidelines do not specifically address issues related to the target volume delineation in the presence of IBR. Due to the submuscular position of the implant in oncological plastic surgery and the concave shape of the reconstructed breast, the three-dimensional conformal radiation technique (3D-CRT) necessarily involves the whole breast reconstruction.

Taking advantage of intensity-modulated radiotherapy (IMRT), dose distribution can be tailored to the tissues overlying the reconstruction without including the whole implant into the prescribed isodose and sparing, as a result, the adjacent underlying OARs (Caudrelier et al. 2014; Jagsi et al. 2010; De Neve et al. 2012).

The dosimetric results of this technique called HALFMOON (Helical ALtered Fractionation for iMplant partial Omission), performed with helical tomotherapy, are reported in this feasibility study as part of the European Institute of Oncology (IEO) breast research project.

Materials and methods

This is a prospective single-cohort pilot study carried out within the research project entitled “Adjuvant radiation treatments with intensity-modulated radiotherapy and/or hypofractionated schedules for breast cancer”, notified to

the IEO Ethics Committee (26 May 2016, Milan, Italy). Patients’ data are recorded in a dedicated databank (RTP R039-000-Tomotherapy-breast) which allows both retrospective and prospective analyses. All patients gave written informed consent for the treatment and anonymous use of their data for educational and research purposes.

The HALFMOON technique, using TomoTherapy® Hi-Art System (Tomotherapy Inc., Madison, WI) in helical modality (TomoHelical), has been addressed to patients with intermediate–high-risk BC, treated with mastectomy, either total or nipple sparing, and immediately reconstructed with implants (TE or PI). All the implants were placed beneath the pectoral muscle. As for our clinical practice, TE was fully inflated before RT.

HALFMOON CTV plans were matched by implant volume ($\pm 50 \text{ cm}^3$) in a 1:3 ratio with Conventional CTV TomoHelical plans (Conv-CTV-HT), which were consecutively selected from the RT databank, keeping the same proportion between right- and left-sided breasts. In a further analysis, the HALFMOON patients were compared in a ratio 1:1 to those of the same age (± 2 years) in the Conv-CTV-HT group. In addition, the latter were also re-planned with 3D-CRT.

CT scanning and target volume delineation

Simulation computed tomography scan of supine patients lying on a breast board, with 2.5 mm-thick slices, was acquired from the neck to the upper abdomen. Target volume and OARs were contoured using the treatment planning system Eclipse®, version 8.6 (Varian Medical System, Palo Alto, CA). Bolus was not used. All patients underwent locoregional treatment, including chest wall, second and third axillary nodal levels, and supraclavicular fossa.

The CTV for the HALFMOON technique comprised the skin, the subcutaneous tissues down to the tissue/implant interface, including the major pectoral muscle and, therefore, excluding the implant, CW muscles, and the rib plane. The PTV was obtained by 3D isotropic expansion of 0.5 cm from the CTV.

The HALFMOON CTV plans were dosimetrically compared to plans (conventionally contoured CTV plans, which acted as a control group) in which the CTV was delineated according to ASTRO (White et al. 2019) and AIRO (2013) guidelines, more specifically comprising skin, subcutaneous tissues, major pectoral muscle, implant, and the rib plane. The PTV was obtained by 3D expansion of 0.5 cm of the conventional CTV.

Conventionally contoured CTVs were also used for 3D-CRT re-planning. The 3D-CRT fields encompassed the CW CTV with a cranio-caudal margin of 1.5 cm and an extension of 2.5 cm into the air, while on the posterior margin, the central lung distance was ≤ 2.5 cm.

Prescription dose and plan design

The Hi-Art System, TomoTherapy Planning Station® (Accuray Inc., Sunnyvale, CA) was used to optimize helical IMRT plans with 6 MeV photon beams. A jaw width of 2.5 cm was used with a mean pitch of 0.39 and mean actual modulation factor of 1.43 ± 0.16 . Plan optimization was fulfilled adjusting dose–volume histogram (DVH) points and priorities to best meet OAR dose constraints without compromising the PTV coverage.

The treatment plans were validated according to dose/volume constraints, as shown in Table 1.

The 3D-CRT plans were performed using Eclipse®, according to ICRU 50 recommendations (ICRU report 1993), applying either the single- or different isocenter techniques. The 3D-CRT fields encompassed the CW CTV via medial and lateral opposed tangential beams, using multileaf collimator to spare OARs. The nodal region was treated through an anterior, 5°-angled field and covered by

Table 1 Dosimetric/volumetric parameters for organs at risk (OARs): HALFMOON versus Conv-CTV-HT plans (median values, interquartile range) and HALFMOON versus 3D-CRT plans (median values, min–max)

OARs	Constraints	HALFMOON plans (Gy), (n = 18)	Conv-CTV-HT plans (Gy), (n = 54)	p value	3D-CRT plans (Gy), (n = 18)	p value
Heart	$D_{15\%} < 8$ Gy	6.5 (5.9–6.8)	6.8 (5.7–7.2)	0.340	NC	NC
	$D_{20\%} < 6$ Gy	5.5 (5.3–5.9)	5.4 (4.5–6.0)	0.243	NC	NC
	$D_{\text{mean}} < 5$ Gy	4.5 (4.1–4.6)	4.5 (4.0–4.8)	0.197	2.5 (0.5–5.8)	< 0.001
	$D_{5\%}$	10.4 (9.5–12.1)	16.4 (12.5–17.4)	0.003	5.0 (1.5–36.8)	0.57
Ipsilateral lung	$D_{15\%} < 31$ Gy	22.7 (19.9–24.4)	27.2 (26.0–28.0)	< 0.0001	NC	NC
	$D_{20\%} < 26.4$ Gy	20.6 (17.9–22.3)	24.0 (23.0–25.0)	< 0.0001	NC	NC
	$D_{35\%} < 17.6$ Gy	14.9 (14.0–16.4)	16.4 (15.1–17.0)	0.003	NC	NC
	$D_{50\%} < 13$ Gy	11.5 (9.9–12.5)	11.40 (10.1–12.0)	0.682	NC	NC
Contralateral lung	$D_{5\%}$	29.5 (27.0–31.7)	34.8 (33.3–35.5)	< 0.0001	37.3 (34.2–39.2)	< 0.001
	$D_{20\%} < 13$ Gy	5.5 (5.0–6.6)	6.8 (5.5–8.9)	0.048	NC	NC
	$D_{35\%} < 10.6$ Gy	4.4 (3.9–4.8)	4.9 (4.0–6.5)	0.349	NC	NC
	$D_{50\%} < 9$ Gy	3.6 (3.1–3.9)	3.2 (2.6–4.7)	0.329	1.0 (0.4–1.3)	< 0.001
Contralateral breast	$D_{5\%}$	8.0 (7.6–10.1)	12.3 (10.1–13.5)	0.004	NC	NC
	$D_{\text{mean}} < 10$ Gy	8.6 (7.9–9.5)	9.3 (8.6–9.9)*	0.128	NC	NC
	$D_{15\%} < 17.6$ Gy	7.2 (5.9–8.1)	8.2 (6.9–9.7)	0.031	NC	NC
	$D_{20\%} < 9$ Gy	6.1 (5.2–7.2)	7.00 (6.0–8.2)	0.047	NC	NC
Liver	$D_{35\%} < 6$ Gy	4.6 (4.0–5.2)	5.0 (4.5–5.3)	0.161	NC	NC
	$D_{50\%} < 4.4$ Gy	3.9 (3.3–4.2)	4.0 (3.6–4.1)	0.891	NC	NC
	$D_{5\%}$	10.0 (8.4–12.5)	12.3 (10.4–14.4)	0.054	2.4 (2.2–4.2)	< 0.001
	$V_{13\text{ Gy}} < 10\%$	1.1 (0–3.1)	0.7 (0–4.0)	0.742	NC	NC
Stomach	$D_{\text{mean}} < 4.4$ Gy (acceptable 5.2 Gy)	2.6 (1.4–3.9)	2.0 (1.0–3.3)	0.491	NC	NC
	$D_{\text{mean}} < 2.4$ Gy (acceptable 4.4 Gy)	1.0 (0.8–1.7)	1.7 (1.0–3.0)	0.011	NC	NC
	$D_{\text{max}} < 8$ Gy (acceptable 13 Gy)	7.7 (4.4–9.0)	6.0 (3.9–13.3)	0.424	NC	NC

HALFMOON: Helical ALtered Fractionation for iMplant partial Omission; Conv-CTV-HT: Conventional Clinical Target Volume TomoHelical; 3D-CRT: Three-dimensional conformal radiation therapy; NC: not comparable (different constraints used); $D_{x\%}$: dose delivered to x% of OAR volume; D_{mean} : mean dose; $V_{x\text{Gy}}$: OAR volume percentage receiving xGy; D_{max} : maximum dose

* Data available for 24 (48.4%) patients

at least 80% isodose line. Dose homogeneity was optimized by means of wedges and mixed energy 6–18 MV. OARs' constraints are shown in Table 1.

The radiation scheme consisted of 40.05 Gy in 15 fractions of 2.67 Gy each over 3 weeks.

Clinical outcome

In the HALFMOON group, acute and intermediate toxicity, according to RTOG and LENT/SOMA scales, and status of disease at the last follow-up were reported. Reconstruction failure rate was evaluated in both the HALFMOON group and the Conv-CTV-HT group in terms of major revisions (removal of PI or conversion to autologous reconstruction) and minor revisions (substitution of the PI with another PI or prosthesis repositioning).

Statistical analysis

Statistical analysis was performed with the MedCalc® Software (Ostend, Belgium), version 16.8.4, for Windows. All data are expressed as median and interquartile range (IQR). The Mann–Whitney test was used for analysis of data. A *p* value of less than 0.05 was considered as statistical significance.

Results

Eighteen patients affected by stage II–IIIa stage BC were treated with the HALFMOON technique using TomoHelical from April 2016 to January 2018. They were matched with 54 controls, treated with TomoHelical in the same period of time. In a further analysis, the 18 patients in the HALFMOON group were compared to 18 out of 54 patients with conventional CTV of the same age (± 2 years). In addition, the latter group were also re-planned with 3D-CRT.

Median age was 48.7 ± 10 years for HALFMOON group and 45.6 ± 8.8 years for controls ($p = 0.27$). In both groups, the proportion of right- and the left-sided breast was 28% and 72%, respectively. For what concerns, the evaluation of the OARs, the dosimetric comparison between the HALFMOON group and the control group considered the contribution of both the nodal and CW PTVs, while for planning objectives, only the CW coverage was compared.

Distribution of the target dose

Median implant volume was 389 ± 128 cm³ in the HALFMOON group and 350 ± 128 cm³ in the conventional CTV group ($p = 0.44$). No significant difference was reported in the two groups regarding the type of implant (PI versus TE, $p = 0.73$). All the HALFMOON CTV plans fulfilled the predefined planning objectives, and no statistically

significant difference was found with the Conv-CTV-HT group, except for the metric $D_{0.03 \text{ cm}^3}$, which was significantly higher in the HALFMOON CTV plans. Regarding the median CW PTV values of the 18 patients re-planned with 3D-CRT, all the PTV planning objectives were significantly worse than those observed in the HALFMOON plans, except for better $D_{0.03 \text{ cm}^3}$ (Table 2).

Comparison of OARs' dosimetry

The median DVHs for main OARs and implant of the analyzed techniques are reported in Fig. 1, where the HALFMOON group (solid lines) was compared to 18 out of 54 patients with Conv-CTV-HT plans (dashed lines) and to the same patients re-planned with 3D-CRT (dotted lines). With respect to the dose distribution throughout the implant, the median implant $V_{90\%}$ and $D_{50\%}$ in the HALFMOON CTV plans compared with the Conv-CTV-HT plans decreased by 46% (100% versus 54%) and 8% (39.9 Gy versus 36.8 Gy), respectively, achieving statistical significance ($p < 0.0001$). An example of isodose distribution across the reconstructed breast is depicted in Fig. 2.

The median values of the dose distributions to the OARs are shown in Table 1. The dose constraints for each OAR met the planning directive in both groups. Comparing each single OARs' dose constraint, the HALFMOON technique presented significant lower doses to lungs, contralateral breast heart and stomach, in many respects. Table 1S reported median DVHs values by irradiated side.

The median DVHs of OARs of the 3D-CRT re-planned group are shown in Fig. 1 and Table 1, for low-dose region distribution and in Table 2S, for the remaining constraints.

Table 2 Planning target volume (PTV) of chest wall, including planning objectives and dosimetric results: HALFMOON versus Conv-CTV-HT (median values and interquartile range) and HALFMOON versus 3D-CRT plans (median values, min–max)

Chest wall PTV	Planning objectives	HALFMOON plans (%), (<i>n</i> = 18)	Conv-CTV-HT plans (%), (<i>n</i> = 54)	<i>p</i> value	3D-CRT plans (%), (<i>n</i> = 18)	<i>p</i> value
$V_{95\%}$	$V_{95\%} \geq 90\%$	95.10 (92.00–96.00)	94.00 (92.70–95.50)	0.478	76.5% (65.8–89.1)	< 0.001
$V_{90\%}$	$V_{90\%} \geq 95\%$ (ideal) $V_{90\%} \geq 90\%$ (acceptable)	99.20 (98.00–99.40)	98.00 (96.70–99.40)	0.197	86.3% (81.6–92.7)	< 0.001
D_{mean}	$D_{\text{mean}} \geq 99\%$ (ideal) $D_{\text{mean}} \geq 95\%$ (acceptable)	99.80 (99.60–99.90)	99.65 (99.40–100.00)	0.522	96.4% (92.6–98.9)	< 0.001
$D_{0.03 \text{ cm}^3}$	$D_{0.03 \text{ cm}^3} \leq 110\%$ (ideal) $D_{0.03 \text{ cm}^3} \leq 115\%$ (acceptable)	108.90 (108.00–109.30)	107.40 (106.00–108.60)	0.005	107.9% (106.2–112.8)	0.022

HALFMOON: Helical ALtered Fractionation for iMplant partial Omission; Conv-CTV-HT: Conventional Clinical Target Volume TomoHelical; 3D-CRT: Three-dimensional conformal radiation therapy; $V_x\%$: PTV percentage receiving *x*% of prescribed dose; D_{mean} : mean dose; $D_{0.03 \text{ cm}^3}$: dose percentage delivered to 0.03 cm³ of PTV

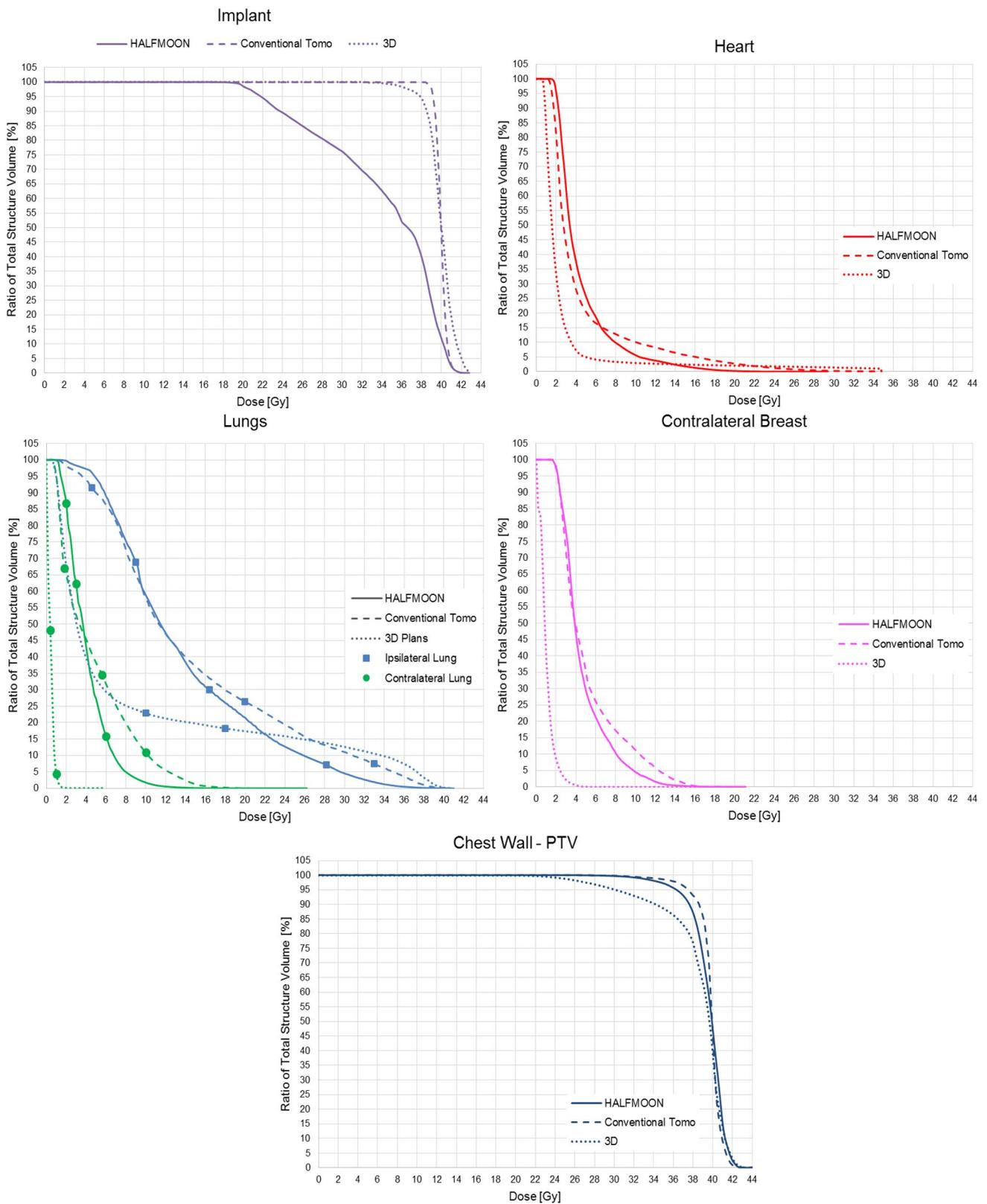


Fig. 1 Median dose–volume histogram of implant and organs at risk, and chest wall-planning target volume (PTV): HALFMOON plans (solid lines) versus Conventional CTV TomoHelical plans (dashed

lines) versus 3D-CRT plans (dotted lines). HALFMOON: Helical ALtered Fractionation for iMplant partial Omission

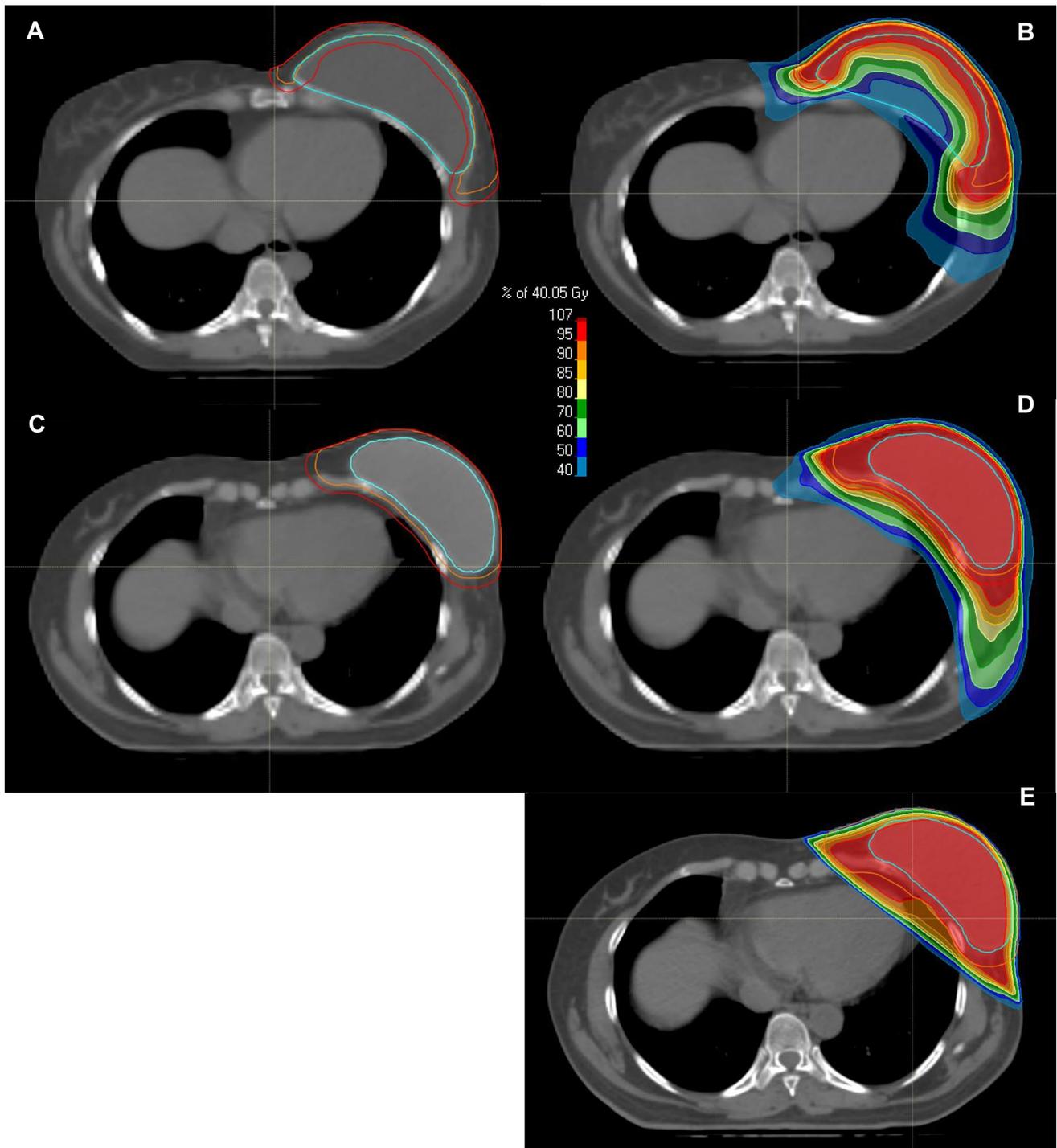


Fig. 2 Transversal computed tomography views of two representative matched patients. **a–c** Clinical Target Volume (CTV) (orange), Planning Target Volume (red) and implant (light blue) in HALFMOON and Conventional CTV TomoHelical plans; **b** HALFMOON plan

dose distribution; **d** conventional CTV TomoHelical plan dose distribution. **e** 3D-conformal plan dose distribution on the same patient in **c**. HALFMOON: Helical ALtered Fractionation for iMplant partial Omission

Clinical outcome

In the HALFMOON group, no grade ≥ 2 acute toxicity was observed during RT, while 1 case of Grade 2

hypopigmentation was recorded at 12 months (data available only in 9/18 patients). At a median follow-up time of 16 months (IQR: 10–23), all the HALFMOON patients

were alive and free from locoregional relapse, while one presented bone metastases.

Regarding outcome of IBR with TE, among the 9 patients in the HALFMOON group, 6 replaced TE with PI and 1 underwent major revision (conversion to autologous reconstruction), while 2 are still awaiting the planned substitution. Among the 33 patients in the Conv-CTV-HT group, 26 replaced TE with PI and 7 had major revision (2 conversion to autologous reconstruction and 5 removal for 2 disease progression, 1 infection, and 2 personal decision). Regarding outcome of IBR with PI, among the 9 patients in the HALFMOON group, 1 had minor revision (1 PI repositioning for asymmetry), while among the 21 patients in the Conv-CTV-HT group, 11 had minor revision (3 PI repositioning for asymmetry, 8 PI substitution for 7 capsular contracture, and 1 rupture) and 3 underwent major revision (2 conversion to autologous reconstruction and 1 removal for infection).

Discussion

To our knowledge, this is the first study reporting dosimetric details of implant-sparing RT plans, whose CTV includes tissues overlying the implant, excluding from the prescription isodose the implant, CW muscles, and the rib plane. Whether the irradiation of the soft tissues covering the implants, obtained with HALFMOON technique, might achieve better treatment tolerance or not will be a subject of further clinical investigations. As the CTV include skin and major pectoralis muscle, capsular contracture may be likely to occur anyway. On the other hand, sparing the implant/CW interface might reduce the fibrotic reactions which can contribute to greater adherence and fixity of the implants into the deep layers. Although in the HALFMOON group, the rate of major surgical revisions was lower than that in the Conv-CTV-HT group (6.2% versus 18.5%), this subject must be assessed in dedicated clinical trials, such as the Recon trial promoted by the Danish Breast Cancer Group (DBCG) (Nissen et al. 2018). Surely, by applying the HALFMOON technique, the dose distribution is more adherent to the true CTV, the PTV coverage is adequate ($V_{95\%} \geq 90\%$ and $V_{90\%} \geq 95\%$ in all cases) and the OARs' sparing, especially lung, might lead to a lower rate of radiation-induced toxicity. Even if small improvements in OARs dosimetry might be considered clinically irrelevant, they are expression of technological developments and RT conceptual evolution. Several studies described the impact of IBR on PMRT delivery using 3D-CRT, analyzing the difference in PTV coverage and OARs sparing between groups with or without IBR. The conclusions are not consistent. Some studies showed the technical difficulty of achieving satisfactory coverage of CW \pm nodal areas, while not increasing dose to OARs (Schechter et al. 2005; Motwani et al. 2006),

which prompted radiation oncologists to investigate the use of IMRT to improve treatment quality (Orecchia et al. 2018; Liljegren et al. 2014). In the current study, as shown in Fig. 1, compared to the TomoHelical, the 3D-CRT plans largely reduced dose to most of OARs. On the other hand, this benefit was obtained at the expense of a significantly reduced PTV coverage, in particular in the region of the match plane between breast tangential and axillary node fields (Miles et al. 2009). Conversely, other studies did not find that the implant was associated with increased dose to OARs as well as unsatisfactory PTV coverage (Ohri et al. 2012). Our analysis differs from the previous ones, since both the two groups had implant-based IBR and different CTV delineation, which influenced dosimetry to OARs. The comparison between the TomoHelical treatment plans revealed that HALFMOON technique was more advantageous for OARs dosimetry, in particular for ipsilateral lung (Table 1), and on the whole, there was no statistically significant difference in the PTV coverage (Table 2) compared to conventionally contoured CTVs. Regarding heart DVH, compared with the Conv-CTV-HT plans, HALFMOON technique had a statistical significance only in $D_{5\%}$, while D_{mean} and other parameters were similar, due to plan optimization. By contrast, D_{mean} was significantly lower with 3D-CRT compared to the TomoHelical approaches (2.5 Gy versus 4.5 Gy, respectively, $p = 0.001$). To improve heart sparing, the combination with breath-hold technique has proven beneficial (Osman et al. 2014; Mast et al. 2016) and is worth being implemented even with advanced RT techniques. Although the 3D-CRT plans were performed according to our clinical practice, it must be highlighted that the PTV coverage can be improved by the addition of multiple subfields to the main tangential fields, exploiting the advantages of the forward-planned IMRT. This simple and easily accessible form of IMRT is proven to improve target volume coverage, dose homogeneity and OARs sparing as well as compared to conventional 3D-CRT (Cavey et al. 2005).

To avoid that the difference in ribcage shape related to aging (Gayzik et al. 2008) may influence dosimetry to OARs, a comparison between patients of the same age was performed (Fig. 1), confirming the results of the study. The CTV described in the HALFMOON technique is in between the ASTRO/AIRO (White et al. 2019; AIRO 2013) and ESTRO (Offersen et al. 2015) target volume delineation. A recent review on anatomic locations of CW recurrences showed that the most common site of recurrence was within the skin and subcutaneous tissues anterior to the pectoralis muscular, followed by muscular recurrence within pectoralis, while none of the analyzed series reported significant isolated recurrences in the intercostal muscles or ribs (Vargo and Beriwal 2015). This pattern of recurrence might lead to reconsider the current ASTRO/AIRO recommendations of including

rib plane, at least in the intermediate-risk tumors. Deep CW recurrences are more likely to occur in the setting of locally advanced tumors (i.e., T4 stage, prior recurrences, or re-irradiation), supporting the contouring of the rib plane in the CTV (Vargo and Beriwal 2015). Our decision of including the major pectoral muscle in the HALFMOON CTV was taken as a precautionary measure and was based on a number of considerations. First, according to the above-mentioned review (Vargo and Beriwal 2015), the major pectoral muscle is the second site of relapse. Second, it is not uncommon that the skin and the subcutaneous tissues covering an implant are so thin that the CTV shrinks down to few millimeters, arising concerns of under-dosage. The application of a tissue-equivalent material to increase the radiation dose on the skin has always been challenging in the presence of implants (Aristei et al. 2018) due to the firm mound of the reconstructed breast, which causes poor adherence and, therefore, dosimetric uncertainties. Third, in some cases, the major pectoralis muscle can also be so thin, completely compressed by the implant that it is difficult to be identified and separated from the overlying soft tissues.

The HALFMOON approach can also be applied in case of adjuvant RT to the breast parenchyma after breast conserving surgery in patients carrying augmentation mammoplasty.

The study limitation is represented by the small number of patients. However, this pilot study served as a basis to implement the HALFMOON technique in our institute, since there were no previous dosimetric reports to be used as a reference. In the effort to set up the dose constraints for IMRT, we have had to consider the implant as a virtual OAR, although it has been known for a long time that the presence of implant does not interfere with dose distribution, as linear absorption coefficient for silicone gel and water is comparable (Shedbalkar et al. 1980; Kuske et al. 1991) and that conventional post-operative dose does not change or damage the mechanical/chemical properties of an implant (McGinley et al. 1980). In addition, it must be pointed out that in the treatment planning, the implant sparing has never been given priority over CTV coverage and normal tissues sparing. Therefore, the plan optimization was not affected by the implant-sparing technique. Given the total dose of 40.05 Gy, we established the following implant minus PTV (Implant-PTV) constraints: $D_{30\%} < 33$ Gy (acceptable 35 Gy); $D_{50\%} < 28$ Gy (acceptable 32 Gy); $D_{70\%} < 24$ Gy (acceptable 28 Gy); and $D_{\text{mean}} < 28.5$ Gy (acceptable 31.5 Gy). These original Implant-PTV constraints are likely to become more restrictive as a result of improved treatment planning skills and setup procedures. The 3D expansion of CTV to PTV, leading to a partial involvement of the implant, ensures that the prescribed isodose covers the target volume, even

if the respiratory motion of the chest was less than 2 mm, on average, along with all anatomical directions in a study conducted in our institute (Ricotti et al. 2017).

In this study, the HALFMOON technique was implemented using helical TomoTherapy, but other techniques, such as conformal field-3D-CRT using multiple subfields and volumetric-modulated arc therapy, can also be applied to match the prescribed dose to the complex geometry of CTV in the reconstructed breast (Nissen et al. 2018; Ashenafi et al. 2010). Critical to the use of HALFMOON technique is the understanding of the extension of CTV in the presence of IBR. Current guidelines are not fully adequate to guide radiation oncologists in contouring IBR patients, with either implant or autologous tissue, and in the light of the growing number of patients undergoing immediate reconstructive procedures, there is a pressing need to expand contouring guidelines to include the reconstructive scenario.

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Compliance with ethical standards

Conflict of interest Leonardi MC, Dell’Acqua V, Cattani F, and Jerezek-Fossa BA received a speaker honorarium from Accuracy International. All other authors declare that they have no conflict of interest.

Ethical approval All procedures performed in the present study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. This article does not contain any studies with animals performed by any of the authors.

The dosimetric study has been approved by the institutional Ethical Committee as part of the research project entitled “Adjuvant radiation treatments with intensity-modulated radiotherapy and/or hypofractionated schedules for breast cancer” (26 May 2016, Milan, Italy).

Informed consent Informed consent was obtained from all individual participants included in the study.

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