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Original Article

A Dosimetric Comparison of Breast Radiotherapy Techniques to Treat Locoregional Lymph Nodes Including the Internal Mammary Chain

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Abstract

Aims: Radiotherapy target volumes in early breast cancer treatment increasingly include the internal mammary chain (IMC). In order to maximise survival benefits of IMC radiotherapy, doses to the heart and lung should be minimised. This dosimetry study compared the ability of three-dimensional conformal radiotherapy, arc therapy and proton beam therapy (PBT) techniques with and without breath-hold to achieve target volume constraints while minimising dose to organs at risk (OARs).

Materials and methods: In 14 patients' datasets, seven IMC radiotherapy techniques were compared: wide tangent (WT) three-dimensional conformal radiotherapy, volumetric-modulated arc therapy (VMAT) and PBT, each in voluntary deep inspiratory breath-hold (vDIBH) and free breathing (FB), and tomotherapy in FB only. Target volume coverage and OAR doses were measured for each technique. These were compared using a one-way ANOVA with all pairwise comparisons tested using Bonferroni's multiple comparisons test, with adjusted *P*-values ≤ 0.05 indicating statistical significance.

Results: One hundred per cent of WT(vDIBH), 43% of WT(FB), 100% of VMAT(vDIBH), 86% of VMAT(FB), 100% of tomotherapy FB and 100% of PBT plans in vDIBH and FB passed all mandatory constraints. However, coverage of the IMC with 90% of the prescribed dose was significantly better than all other techniques using VMAT(vDIBH), PBT(vDIBH) and PBT(FB) (mean IMC coverage $\pm$ 1 standard deviation = 96.0% $\pm$ 4.3, 99.8% $\pm$ 0.3 and 99.0% $\pm$ 0.2, respectively). The mean heart dose was significantly reduced in vDIBH compared with FB for both the WT ($P < 0.0001$) and VMAT ($P < 0.0001$) techniques. There was no advantage in target volume coverage or OAR doses for PBT(vDIBH) compared with PBT(FB).

Conclusions: Simple WT radiotherapy delivered in vDIBH achieves satisfactory coverage of the IMC while meeting heart and lung dose constraints. However, where higher isodose coverage is required, VMAT(vDIBH) is the optimal photon technique. The lowest OAR doses are achieved by PBT, in which the use of vDIBH does not improve dose statistics.

Key words: Heart-sparing radiotherapy; internal mammary chain radiotherapy; proton beam therapy for breast cancer

Introduction

The 2014 Early Breast Cancer Trialists' Collaborative Group systematic overview reported a significant reduction in breast cancer mortality associated with post-mastectomy locoregional breast radiotherapy irrespective of the number of lymph nodes involved and systemic therapies used [1].

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Two recently reported randomised trials of breast/chest wall ± locoregional lymph node radiotherapy (including the internal mammary chain [IMC]) reported disease-free survival benefits in the locoregional lymph node radiotherapy group [2,3]. Subsequently, the Danish Breast Cancer Group IMC study, which compared outcomes in right breast-affected patients (who had the IMC irradiated) versus left breast-affected patients (who did not have the IMC irradiated), showed an overall survival benefit for IMC irradiation of 4.4% in all node-positive patients and 7.4% in those patients with a medial or central tumour and/or a minimum of four positive lymph nodes [4]. Following publication of these data, the UK Royal College of Radiologists issued guidance that IMC irradiation should be considered in patients at higher risk of locoregional recurrence [5].

In long-term breast cancer survivors treated with radiotherapy, fatal radiation-induced heart disease is the main competing cause of mortality. Standard radiotherapy techniques to treat the IMC (using wide tangents [WT] with matched photon-electron fields in free breathing [FB]) have previously been shown to deliver mean heart doses (MHD) of around 9 Gy [6]. A case–control study suggested that the rate of radiation-induced major coronary events increases linearly with dose (7.4%/Gy) and that there is no apparent threshold below which patients are safe [7–9]. Therefore, reducing the heart dose in patients undergoing IMC radiotherapy is of vital importance.

Technical solutions exist for reducing the heart dose associated with breast cancer radiotherapy. The UK HeartSpare IA trial showed that a simple and cost-effective voluntary breath-hold technique (voluntary deep inspiratory breath-hold; vDIBH) could at least halve MHD from 2 Gy to <1 Gy in the context of breast/chest wall radiotherapy alone [10]. Intensity-modulated radiotherapy, volumetric-modulated arc therapy (VMAT) and proton beam therapy (PBT) can also reduce heart doses, but limiting heart doses cannot be achieved in isolation [11–15]. For locoregional pan-lymph node treatments, where the target volume envelops the thorax, multi-field photon beam arrangements can increase low doses to the organs at risk (OAR), potentially increasing the risk of radiation-induced heart disease and secondary cancers [16–18]. PBT has been shown in dosimetry studies to deliver lower cardiac doses compared with photon-based techniques [11,12,14], but the additional benefit of breath-hold to PBT has been less well studied.

The aim of this study was to compare target volume coverage and OAR doses using seven radiotherapy techniques in order to establish optimal solutions for implementation in UK IMC radiotherapy practice.

Materials and Methods

Patient Selection and Volume Delineation

Fourteen patients from a single centre with left-sided breast cancer who had been previously treated within the HeartSpare II trial [19] (by virtue of having any heart within the 50% isodose on the FB computed tomography planning scan) were selected. The patients' median age was 57 years (range 31–68 years). Ten patients had undergone wide local excision, one mastectomy and three mastectomies with deep inferior epigastric perforators flap reconstruction. All patients had undergone two radiotherapy planning computed tomography scans, one in FB and one in vDIBH. Left-sided clinical target volumes ([CTVs] breast, axillary levels 1–4 and IMC) were delineated by a panel of four clinical oncologists based on ESTRO guidelines [20]. The planning target volumes (PTVs) were constructed by adding a 5 mm margin to the CTVs for all photon plans [21]. All PTVs were clipped 5 mm from the skin surface. The PTV IMC excluded lung for all photon techniques except tomotherapy, which was optimised and reported for the whole PTV IMC, reflective of local practice. CTVs were used for proton plan optimisation and evaluation. The following normal structures were contoured: heart, left anterior descending coronary artery (LAD), left lung, right lung, right breast, thyroid gland, oesophagus and brachial plexus.

Treatment Planning

For each patient, seven plans were generated: wide tangents in voluntary deep inspiratory breath-hold (WT(vDIBH)), wide tangents in free breathing (WT(FB)), volumetric-modulated arc therapy in voluntary deep inspiratory breath-hold (VMAT(vDIBH)), volumetric-modulated arc therapy in free breathing (VMAT(FB)), tomotherapy in free breathing (Tomotherapy(FB)), proton beam therapy in voluntary deep inspiratory breath-hold (PBT(vDIBH)) and proton beam therapy in free breathing (PBT(FB)). Planning was carried out across two centres. The Royal Marsden NHS Foundation Trust carried out WT, VMAT and PBT planning and Cambridge University Trust carried out the tomotherapy planning. Optimisation priorities were defined before planning to achieve consistency between inverse planned semi-automated intensity-modulated radiotherapy techniques. All plans were for a fractionation schedule of 40 Gy in 15 fractions. The mandatory target volume constraints for the PTVs and OAR dose objectives are summarised in Table 1.

WT plans were created manually in the Pinnacle^3 v9.10 (Philips, Fitchburg, WI, USA) treatment planning system (TPS) using opposing wide tangential step-and-shoot photon beams with a non-divergent posterior field edge modified to cover the breast or chest wall, IMC and the inferior part of lymph node levels 1–3. A matched anterior field was used to cover the PTVs of lymph node level 4 and the superior part of levels 1–3. Heart and lung shielding was achieved using multileaf collimation. 6 MV photon beams were used for most patients. 10 MV beams were used for the anterior field to achieve coverage of nodal volumes at depth.

VMAT plans were generated using the Pinnacle^3 TPS using Pinnacle's SmartArc optimisation algorithm with 2° control point spacing. A 'bowtie' technique consisting of two partial arcs, as described by Viren *et al.* [22], was used. The two anticlockwise partial arcs each consisted of about 40° (30–50° range) of rotation about the angles used for

Table 1
Target volume and organ at risk dose constraints and objectives

Volume	Constraint	Objective
PTV WB	$V_{38\ Gy} \geq 90\%$	
PTV nodes (level 1–4 axilla)	$V_{32\ Gy} \geq 90\%$	$V_{36\ Gy} \geq 90\%$
PTV IMC	$V_{32\ Gy} \geq 90\%$	$V_{36\ Gy} \geq 90\%$
All PTVs	$D_{max} = 110\%$	
Heart	$V_{17\ Gy} \leq 10\%$	Mean heart dose $\leq$ 6 Gy
Left lung	$V_{17\ Gy} \leq 35\%$	
Right lung	Mean lung dose $\leq$ 4 Gy	
Right breast	Mean breast dose $\leq$ 3.5 Gy	

PTV, planning target volume; WB, whole breast; IMC, internal mammary chain.

tangential beams. Suitable gantry start and stop angles were chosen depending on the individual patient anatomy. Optimisation methods were used to ensure that the fields were shaped to the entire PTV. Robustness studies were used to ensure the VMAT plans exhibited similar robustness compared with the WT plans (see supplementary material in Appendix).

Tomotherapy plans were created in the tomotherapy Hi-ART System v4.2.2, planned using a 5 cm field width and a 0.287 pitch. An initial modulation factor of 1.6 was set, which was increased throughout optimisation with an end planning modulation of ~2.6. Ipsilateral lung, contralateral lung, heart and the lateral part of the contralateral breast were all directionally blocked for planning. An additional flash volume was created to ensure adequate coverage of the whole breast PTV as it moved with the patient's breathing cycle.

PBT plans were generated using the RayStation v6 TPS (RaySearch Laboratories, Stockholm, Sweden) using intensity-modulated pencil beam scanning. A two beam approach with one anterior/posterior and one en face beam (45/315°) was used to maximise robustness and improve plan quality [11]. Proton plans were created using the TPS's robustness optimisation algorithm. A range uncertainty correction of 3.5% and isotropic 5 mm uncertainty for set up errors was incorporated. These metrics were derived from a separate planning study, where eight patients previously treated at our centre who had regular cone beam computed tomography scans were re-planned with tangents, VMAT and PBT with five different combinations of range and set-up uncertainty parameters. Estimates of the delivered dose were compared with the planned dose in order to evaluate the robustness optimisation parameters that resulted in PBT plans as robust as photon plans (see supplementary data in Appendix).

Dosimetric Evaluation and Statistical Analysis

In total, 98 plans were created and evaluated. The whole breast (PTV WB), level 1–4 axilla (PTV nodes) and PTV IMC were analysed separately to avoid compensation for poor coverage of the IMC by other PTVs.

Statistical analysis was carried out in Graph Pad Prism™ (San Diego, CA, USA) using a one-way ANOVA with all pairwise comparisons tested using Bonferroni's multiple comparisons test, with adjusted *P*-values $\leq$ 0.05 indicating statistical significance. Target volume coverage and OAR doses were compared between each of the seven techniques. The percentage of plans meeting all target volume and OAR mandatory constraints was assessed as a measure of the success of the technique.

Results

Figure 1 illustrates dose distributions on the same axial computed tomography slice in the same patient for the seven techniques.

The proportion of plans meeting all mandatory constraints (pass rate) and the mean target and OAR volume doses for the 14 patients and seven techniques are presented in Table 2. All techniques met the mandatory target volume dose constraints in all patients.

Dose Comparisons for Planning Target Volumes

For coverage of the nodal PTVs with 36 Gy (90% prescribed dose), PBT was significantly superior to all photon treatments with the exception of VMAT(vDIBH) for IMC coverage (Figure 2a). VMAT(vDIBH) achieved significantly greater coverage of the IMC with 36 Gy in comparison to all other photon therapies. All arc therapy techniques achieved greater coverage of the nodal PTVs with 36 Gy when compared with the WT techniques (Figure 2b) but there was no statistically significant difference between the arc therapy technique used.

Dose Comparisons for Organs at Risk

OAR doses varied considerably between techniques. The MHD was significantly reduced using breath-hold as compared with FB for both WT and VMAT photon techniques (Figure 2c). There was no significant difference in MHD between WT and VMAT in vDIBH or WT and VMAT in FB. Tomotherapy and WT(FB) resulted in a significant increase in MHD when compared with all other photon techniques. PBT significantly reduced MHD compared with each of the photon techniques. However, there was no statistically significant improvement in MHD when PBT was planned in vDIBH as compared with FB. Both heart V_{17Gy} and maximum LAD dose were statistically

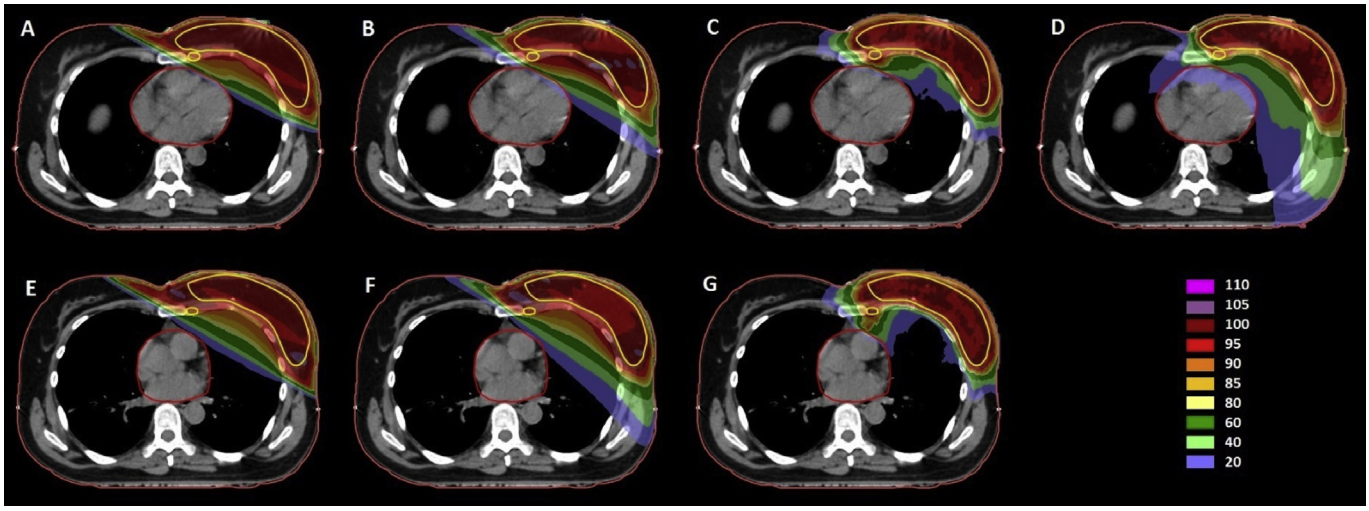

Fig 1. Images of the same computed tomography slice in the same patient showing the dose distribution achieved by each of the seven radiotherapy planning techniques. The top row displays free breathing plans: (A) wide tangents in free breathing (WT(FB)), (B) volumetric-modulated arc therapy in free breathing (VMAT(FB)), (C) proton beam therapy in free breathing (PBT(FB)), (D) tomotherapy in free breathing (tomotherapy(FB)). The bottom row displays breath-hold scans: (E) wide tangents in voluntary deep inspiratory breath-hold (WT(vDIBH)), (F) volumetric-modulated arc therapy in voluntary deep inspiratory breath-hold (VMAT(vDIBH)), (G) proton beam therapy in voluntary deep inspiratory breath-hold (PBT (vDIBH)). The structures outlined in yellow are the whole breast and internal mammary chain clinical target volumes.

significantly lower for photon techniques in breath-hold and tomotherapy.

Ipsilateral lung dose (lung $V_{17\ Gy}$) was significantly reduced using breath-hold as compared with FB for the WT technique and VMAT technique (Figure 2d). There was also no significant reduction in ipsilateral lung dose for PBT in vDIBH compared with FB. However, PBT resulted in significantly lower ipsilateral lung doses when compared with all photon therapies.

The contralateral lung dose was within constraints for all patients using all techniques (Table 2). However, tomotherapy resulted in a statistically higher mean contralateral lung dose when compared with other photon techniques (Figure 2e). Contralateral breast doses were also within the constraint set for all patients using all modalities (Table 2). However, PBT (in vDIBH and FB) resulted in a significant reduction in contralateral breast dose when compared with all photon techniques (Figure 2f).

Discussion

This study, comparing seven techniques for locoregional breast cancer radiotherapy, including irradiation of the IMC, shows that it is possible to achieve adequate target volume coverage using all techniques tested, albeit with varying doses to OARs.

The simple WT technique with vDIBH met mandatory target volume constraints with low doses to the OARs for all 14 patients studied. Coverage of the nodal target volumes with 80% of the prescribed dose (32 Gy) is consistent with the target volume coverage achieved in the randomised controlled trials demonstrating the benefits of pan-regional lymph node radiotherapy. For example, in the MA20 study, which showed a disease-free survival benefit with regional lymph node radiotherapy (including the IMC), Whelan *et al.* [3] specified that the IMC should be covered with the 80% isodose, whereas in the Danish Breast Cancer Group (DBCG) IMN study, which showed an overall survival benefit from inclusion of the IMC in the target volume, it was specified that 90% of the IMC CTV should be covered by the 90% isodose [4]. The WT technique achieves lower MHDs than those previously published for three-dimensional conformal radiotherapy to the IMC [12–15] by eliminating the use of an anterior field, in contrast to the matched photon-electron field technique, for example.

Our results are consistent with previous data showing that arc therapies and PBT offer improved coverage of target volumes compared with field-based treatments. However, arc therapies in FB struggle to achieve coverage of the IMC with 90% of the prescribed dose while maintaining a low MHD [12,13,15,23]. VMAT(FB) and tomotherapy techniques met all planning constraints and both techniques performed relatively well on heart V_{17Gy} and left lung V_{17Gy}, but less well on MHD. The nature of tomotherapy's delivery resulted in the largest mean heart and contralateral lung doses of the techniques tested. This, combined with the inability to deliver tomotherapy in breath-hold, poses an ongoing limitation of the technique. Nonetheless, for patients who are unable to tolerate breath-hold it is useful to note that both tomotherapy and VMAT(FB) reduced heart $V_{17\ Gy}$ and LAD doses when compared with WT(FB) due to their ability to shape higher isodoses away from the anterior aspect of the heart. Although the MHD is the only parameter on which a dose-effect relationship has been reported [7], it is conceivable that this is a surrogate for doses to the anterior part of the heart (which are more specifically reflected in the heart $V_{17\ Gy}$ and LAD doses), in

Table 2
Comparison target volume and organ at risk mean dose parameters (± 1 standard deviation) and pass rates for the 14 patients for wide tangents (WT), volumetric-modulated arc therapy (VMAT), tomotherapy and proton beam therapy (PBT) plans in voluntary deep inspiratory breath-hold (vDIBH) and free breathing

Structure	Dose objective/ constraint	WT (vDIBH)	WT (FB)	VMAT (vDIBH)	VMAT (FB)	Tomotherapy (FB)	PBT (vDIBH)	PBT (FB)
PTV WB V_{38Gy} (%)	Constraint ≥90	95.4 ± 1.7	95.4 ± 1.7	95.3 ± 1.6	95.2 ± 1.8	91.7 ± 1.4	99.1 ± 0.4	99.4 ± 0.8
PTV nodes V_{32Gy} (%)	Constraint ≥90	95.3 ± 1.3	95.9 ± 2.0	99.7 ± 0.4	99.1 ± 0.5	97.9 ± 1.9	100 ± 0	100 ± 0
PTV IMC V_{32Gy} (%)	Constraint ≥90	95.3 ± 2.5	93.1 ± 2.8	99.5 ± 0.6	94.7 ± 3.5	92.5 ± 3.0	100 ± 0	100 ± 0
PTV nodes V_{36Gy} (%)	Objective ≥90	74.6 ± 7.1	81.5 ± 6.2	96.7 ± 2.1	95.1 ± 2.7	92.0 ± 5.9	100 ± 0	100 ± 0
PTV IMC V_{36Gy} (%)	Objective ≥90	77.8 ± 7.1	79.1 ± 4.8	96.0 ± 4.3	80.7 ± 13.2	81.0 ± 6.0	99.8 ± 0.3	99.9 ± 0.2
MHD (Gy)	Objective ≤6	2.5 ± 1.2	5.3 ± 1.0	2.6 ± 1.0	4.5 ± 1.3	6.4 ± 1.4	0.5 ± 0.1	1.0 ± 0.1
Heart V_{17Gy} (%)	Constraint ≤10	2.0 ± 2.5	9.4 ± 5.1	1.8 ± 2.1	6.9 ± 3.4	3.7 ± 2.4	0.3 ± 0.2	1.3 ± 0.2
Maximum LAD dose (Gy)	Objective ≤17	26.2 ± 12.6	38.6 ± 1.5	23.3 ± 11.9	36.2 ± 3.3	23.8 ± 5.0	12.0 ± 9.0	17.4 ± 9.2
Left lung V_{17Gy} (%)	Constraint ≤35	27.9 ± 5.5	34.2 ± 4.5	28.2 ± 4.5	32.1 ± 2.9	33.2 ± 1.6	16.3 ± 2.0	19.3 ± 1.1
Mean right lung dose (Gy)	Constraint ≤4	0.8 ± 0.7	0.7 ± 0.2	0.7 ± 0.2	0.9 ± 0.3	3.5 ± 0.3	1.1 ± 0.5	0.7 ± 0.4
Mean right breast dose (Gy)	Constraint ≤3.5	1.4 ± 0.7	1.2 ± 0.6	1.5 ± 0.9	1.7 ± 1.0	2.3 ± 0.6	0.2 ± 0.1	0.2 ± 0.2
Pass rate		14/14	6/14	14/14	12/14	14/14	14/14	14/14

PTV, planning target volume; WB, whole breast; IMC, internal mammary chain; MHD, mean heart dose; LAD, left anterior descending coronary artery.

which case the risk of late cardiac events associated with a plan that meets the heart $V_{17\ Gy}$ constraint but not the MHD constraint may not be as high as predicted on existing data [7]. The decision over how to balance target volume coverage versus MHD will ultimately come down to the balance of clinical risks as well as the feasibility of delivering a particular technique in each case.

For VMAT and vDIBH, Osman *et al.* [14] have previously shown a reduction in MHD with the combination of partial arc VMAT and vDIBH as compared with three-dimensional conformal radiotherapy in vDIBH (4.1 Gy versus 5.0 Gy). Our data show that even lower MHDs can be achieved (VMAT(vDIBH) = 2.6 Gy ± 1.0 standard deviation; WT(vDIBH) = 2.5 Gy ± 1.2 standard deviation) but this difference is likely to be explained by the combination of the higher target volume coverage dose constraint (V95% ≥ 95%) together with the increased dose prescription (42.56 Gy in 16 fractions) used in the previous study.

PBT is superior to photon therapies, both for target volume coverage and OAR dose, as previously shown [12,15,24]. There seems to be no significant benefit in attempting to treat patients with PBT in vDIBH, consistent with findings from recent studies investigating this combination [25,26]. PBT is the only therapy capable of delivering a mean contralateral breast dose <1 Gy. This is probably important for young patients (<40 years) in whom any dose >1 Gy increases the risk of secondary malignancy [27,28]. We have attempted to address the issue of the robustness of PBT plans in this study but it may be necessary to further increase this level of robustness optimisation, which would have a corresponding effect on OAR dose. The effect of even minor discrepancies in tissue density along the path of the proton and the potential effect of these on dose deposition remain of concern. For example, the position of a proton beam directly adjacent to the LAD raises the possibility that, if the end of the Bragg peak were to be underestimated by a matter of millimetres, the full dose could be deposited in this critical structure [29,30]. This risk could be reduced by carrying out daily cone beam computed tomography scanning with online correction to decrease inter-fraction positional uncertainty. Additionally, although this planning study shows no dosimetric advantage of using breath-hold in the context of protons, the use of breath-hold could help to reduce intra-fraction motion.

By using a seven-way comparison of techniques we have shown that, for photon techniques, moving the heart out of the way (using breath-hold) is a more effective strategy for reducing heart dose than purely shaping the dose (using arc therapy). Recent modelling data published by the Early Breast Cancer Collaborative Group [31] suggest that the absolute increase in cardiac mortality associated with a MHD of 4 Gy is extremely low (0.3% for a non-smoker before the age of 80 years). In this study, MHDs <4 Gy were achieved by both WT(vDIBH) and VMAT(vDIBH), establishing these techniques as acceptable options for heart-sparing IMC radiotherapy. It is possible to reduce MHDs to below 4 Gy with arc therapies in FB, but this may be at the cost of reduced nodal target volume coverage. The additional dosimetric benefits offered by PBT are small and would be

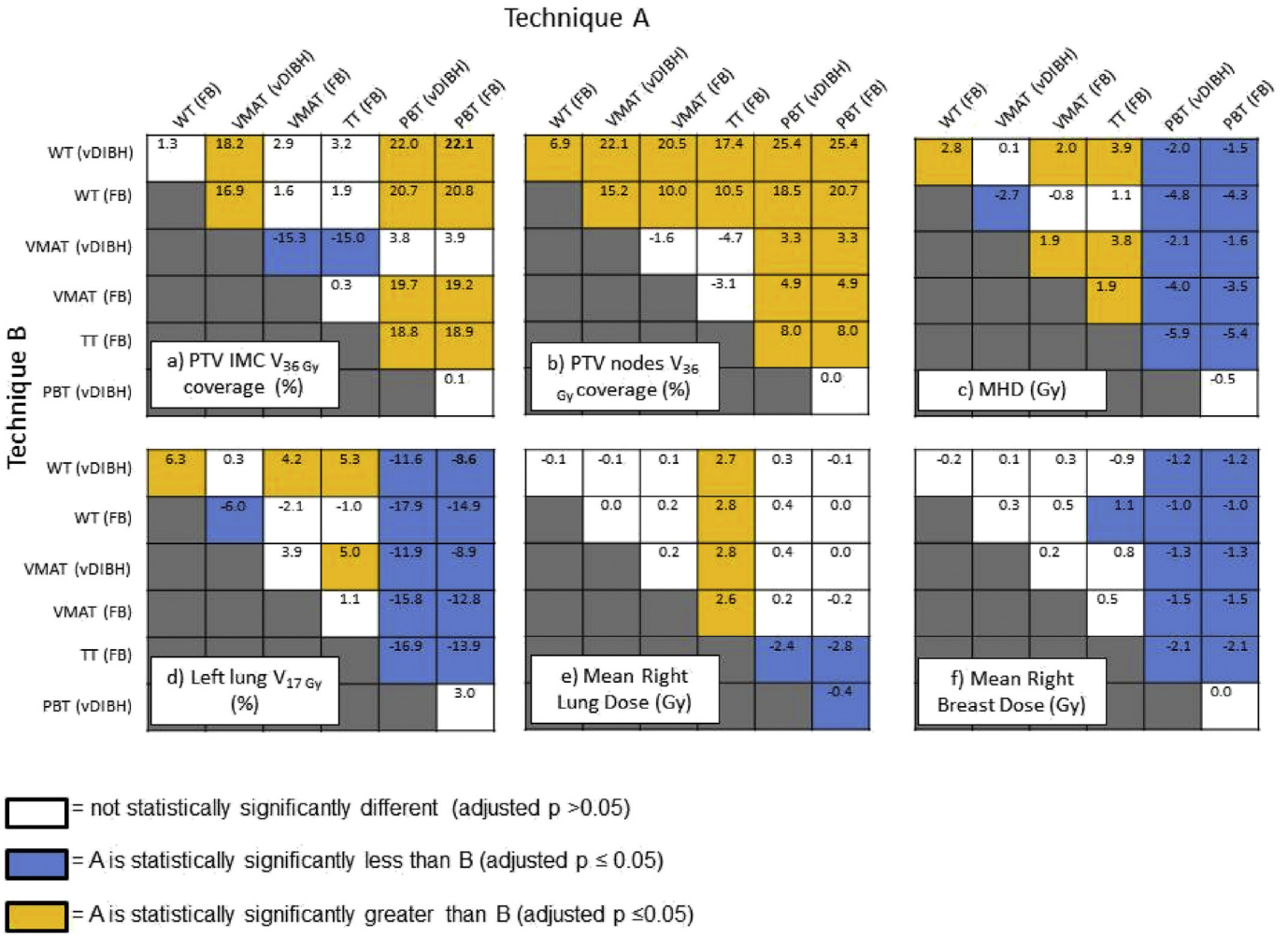

Fig 2. Differences in mean target volume coverage and organ at risk doses between techniques (Technique A, Technique B). WT(vDIBH), wide tangents in voluntary deep inspiratory breath-hold; WT(FB), wide tangents in free breathing; VMAT(vDIBH), volumetric-modulated arc therapy in voluntary deep inspiratory breath-hold; VMAT(FB), volumetric-modulated arc therapy in free breathing; TT(FB), tomotherapy in free breathing; PBT(vDIBH), proton beam therapy in voluntary deep inspiratory breath-hold; PBT(FB), proton beam therapy in free breathing.

unlikely to result in significant differences in cardiac toxicity. For example, for a non-smoker with no additional cardiac risk factors, the delivery of pan-regional lymph node radiotherapy using WT or VMAT in vDIBH would deliver on average 2 Gy greater MHD than using PBT, which would result in an absolute increase in cardiac mortality of less than 0.15% [31]. However, there will be individual patients with anatomical variations (e.g. those with pectus excavatum) in whom PBT will achieve a clinically significantly greater reduction in MHD compared with the optimal photon technique (VMAT in vDIBH).

This study was limited by differences in radiotherapy planning between individuals and across two sites. Although optimisation parameters were defined before planning and mandatory dose constraint coverage of target volumes was prioritised for all techniques, inter-planner variation between the three dosimetrists and individual interpretation of the dose objectives resulted in variations in target volume coverage with higher dose, MHD and LAD dose. The generalisability of the results was further limited by the small sample size used in this study. The study also provided no data regarding the feasibility of implementing the techniques tested. It is possible that the resource implications associated with implementing VMAT(vDIBH) for all patients requiring IMC radiotherapy could slow or prevent the implementation of IMC radiotherapy in resource-limited healthcare settings. By comparison, the WT(vDIBH) technique could be implemented in many radiotherapy centres with relatively little need for additional equipment or training (provided a dose of 32 Gy to the locoregional nodes is deemed acceptable). The HeartSpare Plus clinical phase II study is currently testing the feasibility, resource impact and acute toxicities of WT(vDIBH) versus VMAT techniques.

Ultimately, one technique will not be appropriate for all patients. This study presented a range of possible techniques for treating the IMC that can be tailored to the

individual based on factors such as risk of recurrence, anatomy and ability to tolerate breath-hold.

Conclusion

In this dosimetry study, simple WT radiotherapy delivered in vDIBH achieved satisfactory coverage of the IMC while meeting heart and lung dose constraints. However, where higher isodose coverage is required, VMAT(vDIBH) is the optimal photon technique. The lowest OAR doses are achieved by PBT, in which the use of vDIBH does not improve dose statistics. Ideally centres will have access to more than one technique in order to select the optimal solution for individual patients.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.clon.2018.01.017.

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