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Original paper

Pseudo skin flash on VMAT in breast radiotherapy: Optimization of virtual bolus thickness and HU values

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ABSTRACT

Purpose: Optimisation strategies for volumetric modulated arc therapy (VMAT) in most treatment planning systems for breast cancer do not account for patient positioning, breathing, or anatomical changes. To overcome this limitation, a pseudo-skin flash strategy using a virtual bolus has been proposed. Using this strategy, we determined optimal thickness and value of Hounsfield units (HU) assigned to the virtual bolus to ensure adequate CTV irradiation.

Materials and methods: We modified the original computed tomography data (CT_0) by adding combinations of thicknesses and densities of a virtual bolus on PTVs (CT') of seven bilateral breast cancer patients. Using a single optimization objective template, we obtained a VMAT plan on CT' and recalculated this on the CT_0. Optimal CT' parameters were defined as those that minimized dose differences between CT' and CT_0 plans regarding PTV and OAR dose-volume parameters. We studied bolus parameters regarding robustness by shifting the isocenter 5 and 10 mm in the breathing direction for each CT_0 plan.

Results: The minimal dosimetric impact was between −400 and −600 HU depending on bolus thickness. OARs doses were not significantly affected. Best robustness was found for −500 HU and 15 mm bolus thickness against shifts of up to 10 mm in the breathing direction.

Conclusion: Our results support a bolus thickness equal to the CTV-PTV margin plus 5 mm and a virtual bolus HU value around −500 and −400 depending on the bolus thickness chosen. These findings could play a useful role in maximising robustness and minimising the need for plan renormalization.

1. Introduction

Volumetric modulated arc therapy (VMAT) is a relatively new radiation technique that has become widely used in locations such as prostate and head and neck [1–5]. It is now also being considered a good solution in the treatment for complex anatomies [6] and bilateral breast cancers [7–9]. Its use in breast cancer, however, is controversial because the low-dose bath exposure can increase the risk of second cancers [10] and give rise to new toxicities [11]. In view of these disadvantages, the protocol at our centre is to use VMAT in breast cancer patients only when strictly necessary. To date we have applied this technique only in highly complex cases that did not fulfil the dose constraints using standard techniques. These complex cases included bilateral breast cancer with or without internal mammary and axillary node involvement.

When using VMAT for breast cancer, beam incidences are tangential to the breast at several angles of the VMAT arc. To guarantee the robustness of treatment delivery, for tangential breast irradiation using intensity-modulated radiation therapy (IMRT), several studies [12–14] and the ICRU Report No. 83 [15] recommend the use of the flash region [12]. This region consists of extending the planning target volume (PTV) outside the skin surface. For every field, fluence is extended radially outside the body to take into account breathing, possible anatomical changes due to oedemas, and any uncertainties in position [16]. In IMRT, these issues can be solved in several ways, such as using the skin flash tool (Eclipse Treatment Planning System, Varian Medical Systems, Palo Alto, CA). In VMAT, nevertheless, intensity modulation is originated by means of a direct field-aperture optimization process [17], and the solution given by IMRT does not apply to VMAT. Several companies have proposed solutions. In the Monaco treatment planning system (Elekta AB, Stockholm, Sweden), a flash region solution is available inside the VMAT plan optimizer [16,18]. In tomotherapy (TomoTherapy Hi-Art system, Madison, USA), as the full dose is calculated for the entire CT data, the dose can be optimized to the skin, but

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to allow for swelling, additional bolus structures are required [16,19]. One of the technical problems that VMAT poses in breast cancer in Eclipse is the lack of an automatic tool to take the aforementioned uncertainties into account. To solve this issue, in 2011, Nicolini et al. [17] proposed a strategy that they named the pseudo skin flash. This method has been routinely incorporated into treatment in many institutes and has proven to be robust [16,17,20]. It consists of modifying the original CT data by adding a 10 mm-thick virtual bolus of soft-tissue-equivalent out of the body contour in the area of PTV, and planning radiotherapy treatment on this modified CT data. This plan is then copied and re-calculated onto the original CT data. The authors, however, did not perform a systematic study to compare different HU or thickness assignments to this virtual bolus. Neither did they study its effect on plan robustness or its dosimetric impact. It currently remains unclear, therefore, whether the parameters they chose were optimal. The aim of this paper was to address these issues in a systematic way. Based on our results, we propose a method to select the optimal set of parameters to clinically implement the pseudo skin flash strategy.

2. Materials and methods

Seven synchronous bilateral breast cancer patients treated with radiotherapy in our institution were retrospectively selected for the study. Treatment for these patients was re-planned considering only the breast and boost PTV volumes. Therefore, if nodes were affected, they were not taken into consideration for this study. Table 1 shows breast volumes and laterality of the boost.

We used the same set of CT images and the remaining contours as in the clinical plan. CT planning images were acquired using a large-bore multislice CT scanner (Brilliance™ CT Big Bore v3.6; Philips Healthcare, Cleveland, OH, USA) in supine position with voxel dimensions $2 \times 2 \times 5\ mm^3$. Clinical target volumes (CTV) and organs at risk (OAR) were delineated by expert radiation oncologists following the RTOG Breast Cancer Atlas [21]. In accordance with the RTOG definitions, the CTVs reached the skin. Following our clinical practice, we prescribed a dose of 50 Gy ($EQD_2 = 50.0\ Gy_{4.6}$) to breast volume PTV and 57.5 Gy ($EQD_2 = 60.1\ Gy_{4.6}$) to tumour bed PTV in 25 fractions. Following our institutional protocol, we used dose constraints to OARs.

RapidArc® (Varian Medical Systems, Palo Alto, CA) VMAT mono-isocentric treatment plans were optimized using the photon optimizer algorithm (PO v13.5.35). Dose was calculated by means of the anisotropic analytical algorithm (AAA v13.5.35) with a 2.5 mm dose grid. We used 6 MV X ray beams from a Clinac 2100CD (Varian Medical Systems, Palo Alto, CA) linac equipped with a Millenium 120™ MLC.

All VMAT plans were generated with 3 partial overlapping arcs from 220° to 140° passing through 0° (two clockwise arcs and one counter-clockwise arc) and optimized to achieve the dose objectives to PTV and dose constraints to OARs. PTVs were defined by adding an anisotropic margin to account for positioning uncertainties. For this study, two outward margins beyond the body contour were considered, 5 mm (PTV_{05}) and 10 mm (PTV_{10}). For optimisation purposes we used a breast PTV defined as the combination of the left and right breast PTVs

Table 1
Patient characteristics. L(Left) and R(Right) refer to location of the tumour bed (boost).

Patient	Boost	Left breast volume (cc)	Right breast volume (cc)
#1	L	676	592
#2	L,R	848	800
#3	L	1511	849*
#4	L,R	954	940
#5	L,R	1255	1213
#6	L,R	1091	1324
#7	L,R	943	1010

*Radical mastectomy.

cropped 5 mm inwards from the skin edge ($PTV_{cropped}$). PTVs were cropped to achieve plan objectives without forcing the optimiser to increase skin dose excessively to compensate for the lack of scatter in this region.

To create a robust radiotherapy planning by reducing positioning uncertainties we used the pseudo skin flash method by Nicolini et al [17]. We proceeded as follows:

(i) For each patient, we created two expanded CT sets from the original CT data (CT_0) by adding virtual boluses of 10 mm (CT_{10}) and 15 mm (CT_{15}) on the skin surface in the area where the PTV was contoured. For each expanded CT sets, we varied the HU assignment of the expanded region (virtual bolus) from 0 to −700 HU in 100 HU steps, generating a pool of 16 independent expanded CT sets.

(ii) In the CT_{10} and CT_{15} sets, we respectively expanded the CTV 5 mm (PTV_{05}) and 10 mm (PTV_{10}) outwards (Fig. 1). The pairs CT_{10}-PTV_{05} and CT_{15}-PTV_{10} represent two clinically representative levels of CTV to PTV margin expansions, each one with a convenient bolus thickness to avoid the optimizer delivering full dose to the build-up region.

(iii) A VMAT plan was created on each expanded CT set (Plans_CT') as well as on the CT_0 (Plan0), resulting in 17 plans. For every patient, the same optimisation template was used for the VMAT optimization phase. The planner did not modify any constraint/objective during the optimisation process as the goal was to quantify dosimetric differences depending on the virtual bolus HU assignments.

(iv) The Plans_CT' were then copied and re-calculated by fixing MU on CT_0 (Plans_CT_0). This was the plan that would be used for the patienťs treatment.

2.1. Study on the dosimetric impact of the pseudo skin flash strategy

As there is no added bolus when recalculating the dose distribution on CT_0 fixing MU, we would expect an increase in the delivered dose to PTV. To solve this problem, Nicolini et al. [17] normalized the plan to PTV D_{mean} = 100% of the prescribed dose once the plan was copied and re-calculated. We did not establish any particular normalization to our plans for three reasons: first, because any change in normalization could result in undesirable differences on PTV dose coverage; second, because once the optimization is done, MLC, gantry motion and dose rate are set, so minimal changes in normalization are desirable; and third, because our intention was to study the impact of the different HU and thickness assignments of the virtual bolus on the dose distribution after copying this to the CT_0.

To assess the dosimetric impact of the pseudo skin flash strategy, we used the $PTV_{cropped}$ (defined in CT_0) as the reference volume for comparisons. We performed a two-fold comparison. First, as $PTV_{cropped}$ is present in both CT_0 and expanded CT sets, we compared the $PTV_{cropped}$ dose distribution for Plans_CT' and Plans_CT_0. And second, we compared the dose distribution in the volumes used for optimization, PTV_{05} and PTV_{10}, in Plans_CT' vs the dose distribution in $PTV_{cropped}$ in Plans_CT_0. The former volumes are used to drive the optimization (in expanded CT sets), while the latter volume is used to evaluate the plan clinically (in CT_0). Any significant difference between these two volumes would therefore force a re-optimization.

The dosimetric impact was evaluated as differences between Plans_CT' and Plans_CT_0 in some DVH parameters. In particular, for target volumes we evaluated the mean dose (D_{mean}), the dose received by 98% of the volume (D_{98}), and the dose received by 2% of the volume (D_2). For organs at risk (OAR), we evaluated: D_{mean} and the volume receiving 30 Gy (V_{30}) for the heart structure, the volume receiving 5 Gy (V_5) for the lungs, and the D_{mean} for the liver.

For target volumes, we calculated relative differences as $\frac{X - X_0}{X_0} \cdot 100\%$ (Eq. (1)), where X and X_0 stand for the dosimetric indices of Plans_CT'

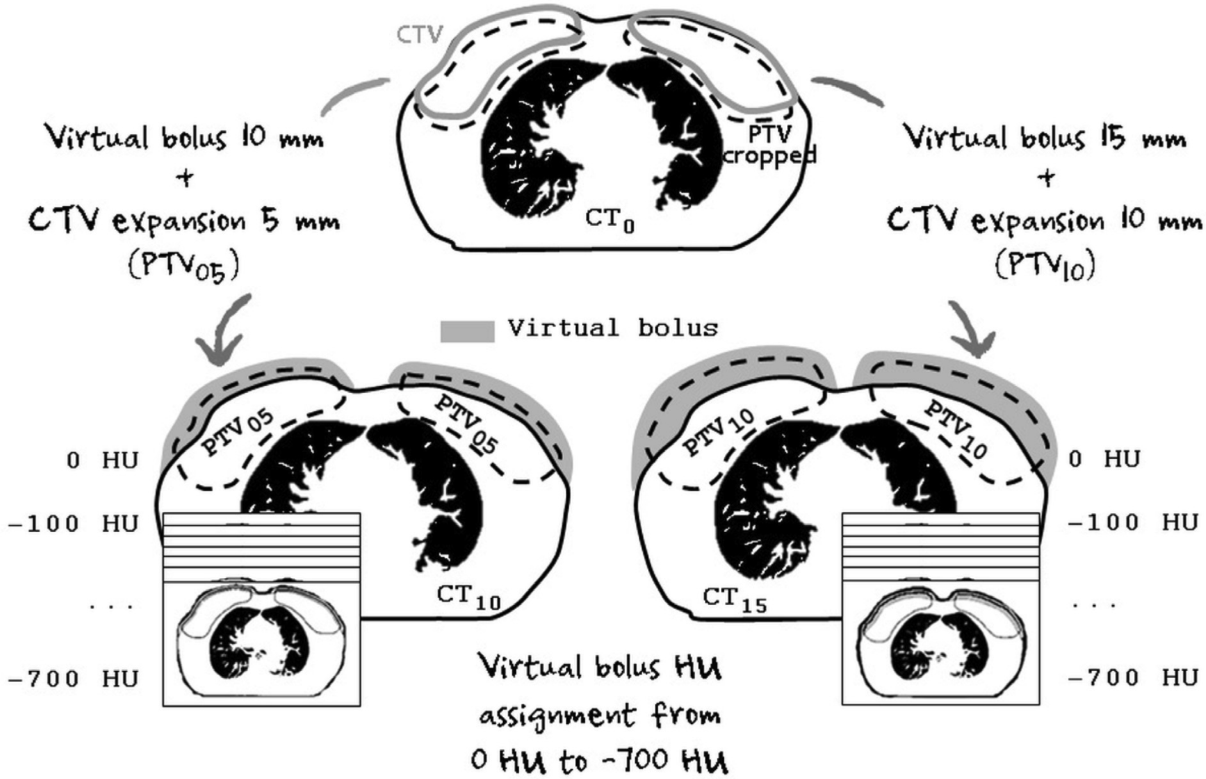

Fig. 1. Schematic representation of the CT data created for our study: CT_0, CT_{10} and CT_{15}. PTVcropped and PTV_{05}/PTV_{10} are the PTVs used in the optimisation phase of Plan0 and Plans_CT, respectively.

and Plans_CT_0, respectively. For OAR, we calculated absolute differences as $X - X_0$ (Eq. (2)). The reference plans are those recalculated in CT_0, that is, Plans_CT_0.

We determined the assignment of HU to the virtual bolus that minimized the dosimetric differences between Plans_CT' and Plans_CT_0.

2.2. Robustness analysis

To quantify plan robustness, the plan uncertainty tool that is inbuilt in Eclipse was used on the Plans_CT_0 and on the Plan0. Using this tool, we generated dose-volume histograms (DVH) by shifting the isocenter 5 mm and 10 mm in the breathing direction (from here on, Plans_CT_0shifted). In contrast with the study on the dosimetric impact, for the robustness analysis we evaluated the two breasts separately. We applied four isocenter shifts: (x,y) equal to (3.5, 3.5) mm and (7.0, 7.0) mm to the right breast (isocenter shifts of 5 mm and 10 mm in absolute values, respectively), and (x,y) equal to (−3.5, 3.5) mm and (−7.0, 7.0) mm to the left breast. "x" refers to left–right shifts and "y" refers to anterior-posterior shifts. These isocenter shifts were chosen to mimic the average (5 mm) and the largest (10 mm) pectoral excursion in free breathing and/or residual positioning of inter- and intra-fraction errors in our series of patients. Two scenarios were studied: one with a CTV-PTV margin of 5 mm and a bolus thickness of 10 mm (CT_{10}-PTV_{05}) and another with a CTV-PTV margin of 10 mm bolus thickness of 15 mm (CT_{15}-PTV_{10}). We created two structures that we called "SkinPTV_" and "L" or "R" (left or right, respectively) (Fig. 2) to enhance differences in the target coverage due to position uncertainties with different bolus thicknesses and HU assignments. These volumes were defined as the region of the CTV extending from the skin surface to 10 mm inwards. We thought that this thin structure at the surface could be more prone to detect differences.

We generated 4 Plans_CT_0shifted for each Plans_CT' and for Plan0. Therefore, a total of 68 Plans_CT_0shifted were obtained for each patient. For all these plans, DVH of "SkinPTV_L" and "SkinPTV_R" were exported from Eclipse and analysed by home-grown software. This software, built in MATLAB (MATLAB and Statistics Toolbox Release 2015b, Massachusetts, United States), automatically reads the dose volume histograms of each isocenter shift and calculates the dose indexes for both PTVs and OARs. DVHs were used to analyse the dose received by 98% of the volume (D_{98}) and the dose received by 2% of the volume (D_2). We compared these dosimetric parameters between Plans_CT_0 and Plans_CT_0shifted, and between Plan0 and its corresponding Plans_CT_0shifted. We calculated the relative differences between these two comparisons by Eq.1 using Plans_CT_0 and Plan0, respectively, as a reference plan.

Statistical significance of the dose differences was assessed using the two-sided, one-sample *t*-test (true mean equal to zero, significance level of 0.05, RStudio v1.0.136 [22]).

Finally, we determined the optimal assignment of HU and virtual bolus thickness that minimized the dosimetric differences between plans and the impact of intra- and inter-fraction motion for the two scenarios of position uncertainty.

3. Results

3.1. Study on the dosimetric impact of the pseudo skin flash strategy

Fig. 3 shows relative differences (Eq.1) in D_{mean}, D_{98} and D_2 for the $PTV_{cropped}$ (defined in CT_0) between Plans_CT' and Plans_CT_0. For all plans, an increase in all dose indexes was obtained once the plan was recalculated on CT_0. D_{mean} differences were up to 5% for 0 HU and a bolus thickness of 15 mm, and up to 3% for 0 HU and a bolus thickness of 10 mm. As expected, these differences decreased for lower HU values.

Fig. 4 shows relative differences (Eq. (1)) in D_{mean}, D_{98} and D_2 for the PTVs used in optimisation between Plans_CT' (PTV_{05} or PTV_{10}) and Plans_CT_0 ($PTV_{cropped}$). Note that the PTV volumes and densities used for this comparison were different from those used for Plans_CT' to

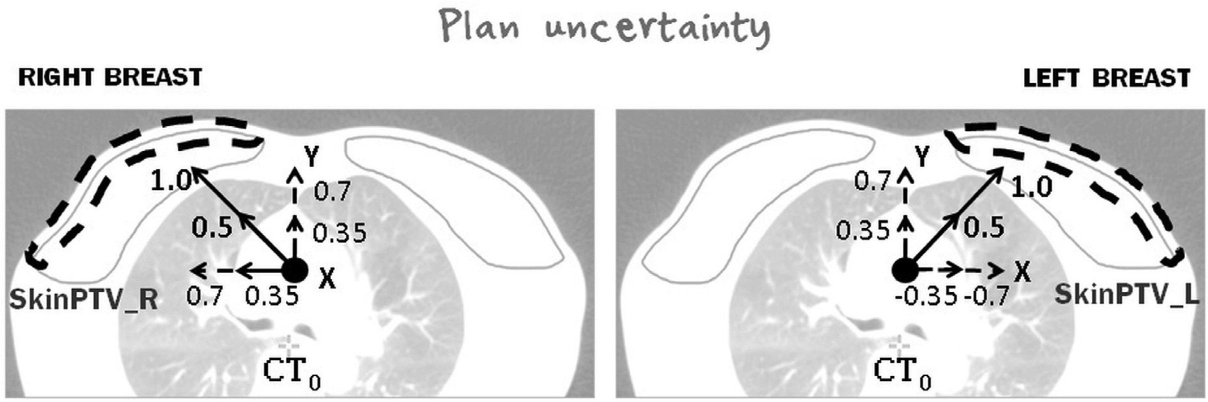

Fig. 2. Schematic representation of the shifts applied to evaluate robustness. The broken lines show the structure where robustness was evaluated.

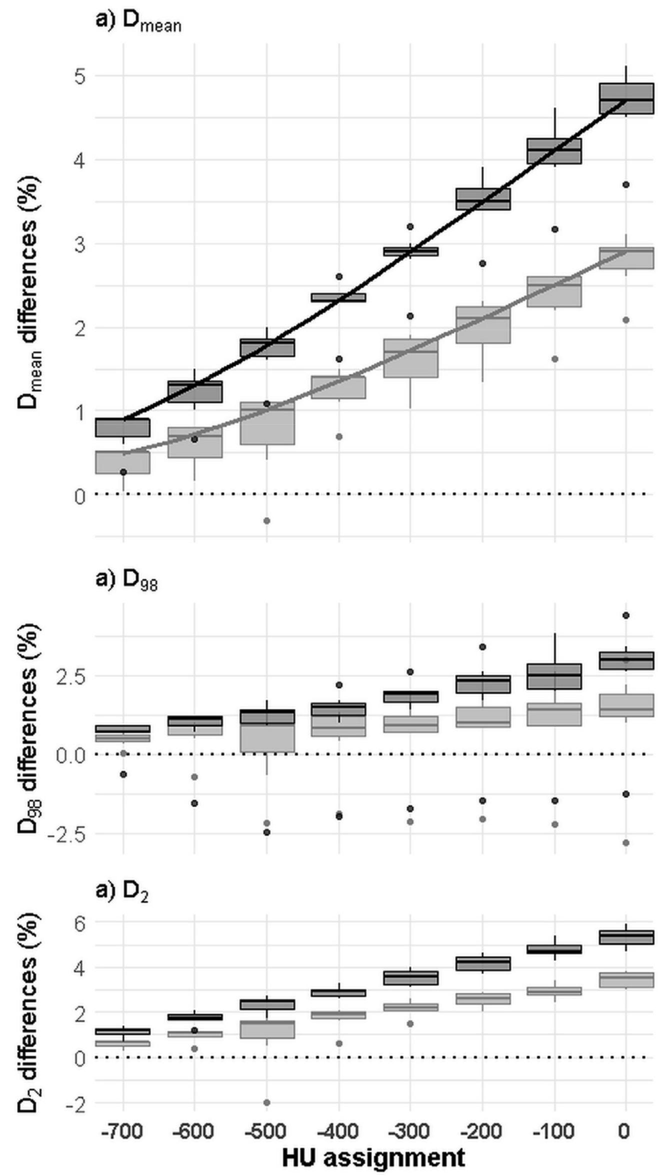

Fig. 3. Boxplots representing relative differences in D_{mean}(a), D_{98}(b) and D_2 (c) between Plans_CT' and Plans_CT_0 for PTVcropped. Grey and black dots represent the corresponding boxplot outliers.

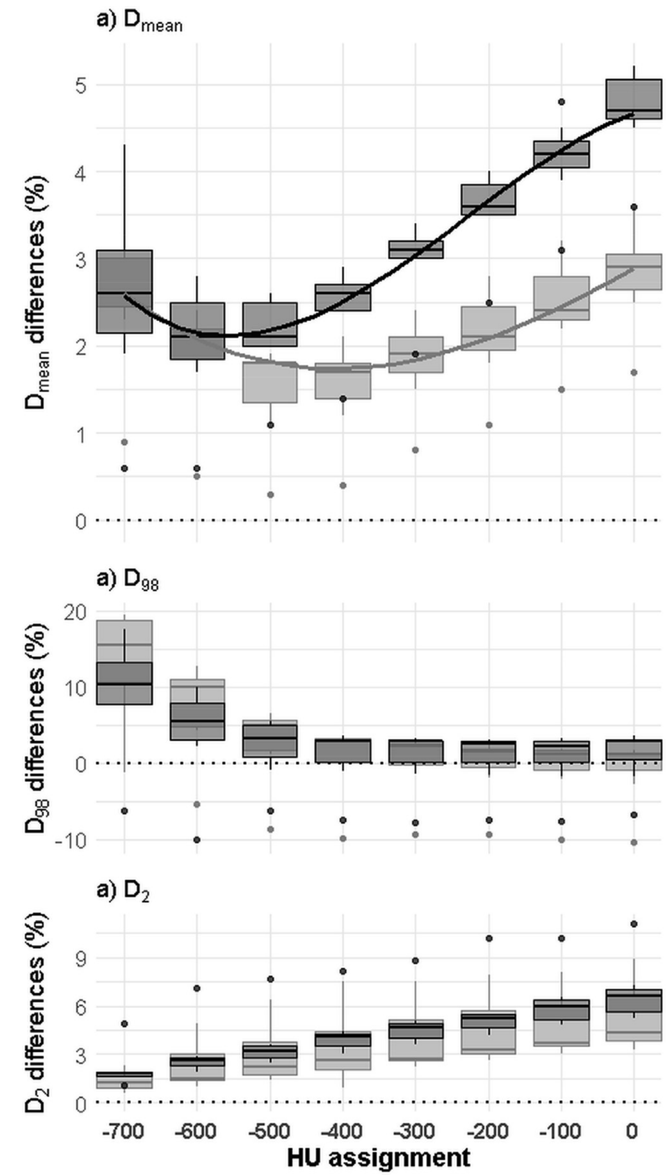

Fig. 4. Boxplots representing relative differences in D_{mean}(a), D_{98}(b) and D_2 (c) between Plans_CT' and Plans_CT_0 for the PTV used in the optimization phase (PTV_{05}/PTV_{10} and $PTV_{cropped}$ respectively). Grey and black dots represent the corresponding boxplot outliers.

Table 2
Summary of absolute differences between Plans_CT' and Plans_CT_0 for dose-volume indexes for heart, lungs and liver.

	HU value assigned to virtual bolus							
	−700	−600	−500	−400	−300	−200	−100	0
Heart V_{30} (%)								
mean (sd)	0.06 ± 0.04	0.09 ± 0.05	0.10 ± 0.07	0.11 ± 0.08	0.14 ± 0.12	0.16 ± 0.12	0.17 ± 0.13	0.19 ± 0.14
min	0.01	0.01	0.02	0.02	0.03	0.03	0.02	0.04
max	0.15	0.16	0.23	0.29	0.41	0.42	0.41	0.44
Heart D_{mean} (Gy)								
mean (sd)	0.02 ± 0.03	0.03 ± 0.04	0.03 ± 0.05	0.02 ± 0.07	0.05 ± 0.10	0.05 ± 0.11	0.04 ± 0.13	0.04 ± 0.13
min	−0.02	−0.03	−0.05	−0.07	−0.08	−0.10	−0.10	−0.13
max	0.09	0.10	0.14	0.18	0.26	0.24	0.32	0.33
Lungs V_5 (%)								
mean (sd)	0.01 ± 0.02	0.02 ± 0.03	0.02 ± 0.05	0.01 ± 0.03	0.03 ± 0.05	0.04 ± 0.08	−0.00 ± 0.04	0.01 ± 0.03
min	−0.01	−0.01	−0.01	−0.04	−0.01	−0.01	−0.11	−0.06
max	0.06	0.10	0.17	0.08	0.16	0.27	0.04	0.03
Liver D_{mean} (Gy)								
mean (sd)	0.06 ± 0.05	0.09 ± 0.07	0.11 ± 0.09	0.13 ± 0.10	0.15 ± 0.12	0.17 ± 0.14	0.18 ± 0.15	0.20 ± 0.16
min	−0.01	−0.03	−0.03	−0.03	−0.04	−0.05	−0.07	−0.07
max	0.15	0.20	0.26	0.29	0.34	0.39	0.42	0.48

Plans_CT_0. Fig. 4a shows a clear tendency for relative D_{mean} differences to be minimal for a HU value equal to −410/−560 for a bolus thickness of 10 mm/15 mm respectively. Furthermore, D_{mean} differences between different bolus thicknesses converged for lower UH values and diverged for larger HU (soft tissue), with these differences being larger for the 15 mm bolus thickness.

As shown in Fig. 4b and c, relative differences in D_{98} were greater for lower HU-values. On the contrary, relative differences in D_2 were greater for higher HU-values.

Table 2 shows the absolute dose and volume differences (Eq. 2) between Plans_CT' and Plans_CT_0 for heart, lungs and liver. The ranges of the absolute differences for all indexes were wider for higher HU values. The differences between bolus thicknesses of 10 mm and 15 mm were not significant.

3.2. Robustness analysis

Fig. 5 shows the relative variation in D_{98} and D_2 (Eq. (1)) between Plans_CT_0 and Plans_CT_0shifted for each virtual bolus HU assignment, for each bolus thickness, and for each isocenter shift. The non-action category refers to the relative difference in dose index between Plan0 and its corresponding Plans_CT_0shifted. As there was no anatomical difference between SkinPTV_R and SkinPTV_L or between the dosimetric indexes obtained for the two structures (p-value > 0.2, two-sided *t*-test with significance level of 0.05), we did not consider laterality as a variable. There were therefore two variables (bolus thickness and HU assignment) and two categories (isocenter shift of 5 mm and isocenter shift 10 mm). Asterisks at the top (for the 10 mm bolus thickness results) and at the bottom of Fig. 5 (for the 15 mm bolus thickness results) indicate when the corresponding boxplot was significantly different from zero.

Fig. 5a and b show that the non-action category led to D_{98} differences of up to 10% and 20% for isocenter shifts of 5 mm and 10 mm, respectively.

For isocenter shifts of 10 mm, differences for the strategy of a bolus thickness of 10 mm were significant. This trend was not observed for isocenter shifts of 5 mm, where the two populations (10 mm and 15 mm bolus thickness) could not be distinguished.

There was a slight dependence between the virtual bolus HU value and D_{98} results. As a trend in data was observed in D_{98} results (Fig. 5a and b), data were fitted to a polynomial curve (grade 3, $r^2 = 0.99$ at least in all the fits). This fit was used as a visual guide and as a rough estimate of the optimal values. For fitting purposes, as non-action (Plan0) had no virtual bolus, the HU value of the non-action (Plan0) category was fixed to −1000 HU (air value).

Table 3 summarizes the optimal assignment of HU and virtual bolus thickness that minimized the dosimetric differences between plans (dosimetric impact) and the impact of intra- and inter-fraction motion (robustness) for the two position uncertainty scenarios studied. Isocenter shifts of 10 mm for 10 mm bolus thickness were not included in Table 3 because Fig. 5b shows that this combination leads to a non-robust plan. Fig. 5b shows significant D_{98} differences for all HU-values of virtual bolus thickness equal to 10 mm.

4. Discussion

4.1. Study on the dosimetric impact of the pseudo skin flash strategy

Fig. 3a shows that the lower the HU assignment of the virtual bolus, the lower the change in normalization needed to compensate for the absence of this bolus in CT_0. However, Fig. 4a shows that density assignments lower than −600 HU led to large differences between Plans_CT' and Plans_CT_0 irrespectively of the bolus thickness. Very low HU assignments may force the optimizer to put extra weight on tangential beamlets to compensate for the bolus low density, leading to an undesirable increase of dose observed in Plans_CT_0. The choice of a HU value lower than −600 or higher than −300 could imply an undesirable change in the dose normalization of the clinical treatment of up to 5%. Therefore, the choice of the HU value assigned to the virtual bolus is critical to ensure a minimal change in the dose normalization in the radiotherapy planning. For example, in the case of virtual bolus thickness of 15 mm, normalization should be changed about 4.5% in the case of equivalent tissue, as Nicolini et al suggested [17]), instead of only 2% in the best scenario (-500 HU). Thus, the choice of a HU value around −400/550 for 10/15 mm bolus thickness would be optimal.

Regarding OAR, in the range of −400 to −600 HU, dose and volume differences were lower than 0.3 Gy or 0.3% in 100% of the patients. For virtual bolus HU assignment values larger than −400 HU, higher differences were observed, although they were always less than 0.5 Gy (absolute dose difference values) and 0.5% (absolute volume difference values), which is not an issue in most clinical cases. The pseudo skin flash strategy did not therefore significantly modify the OAR dosimetric indexes.

4.2. Robustness analysis

Fig. 5 shows that no skin flash strategy led to poor robustness. Relative differences of up to 20% in D_{98} were observed for isocenter shifts

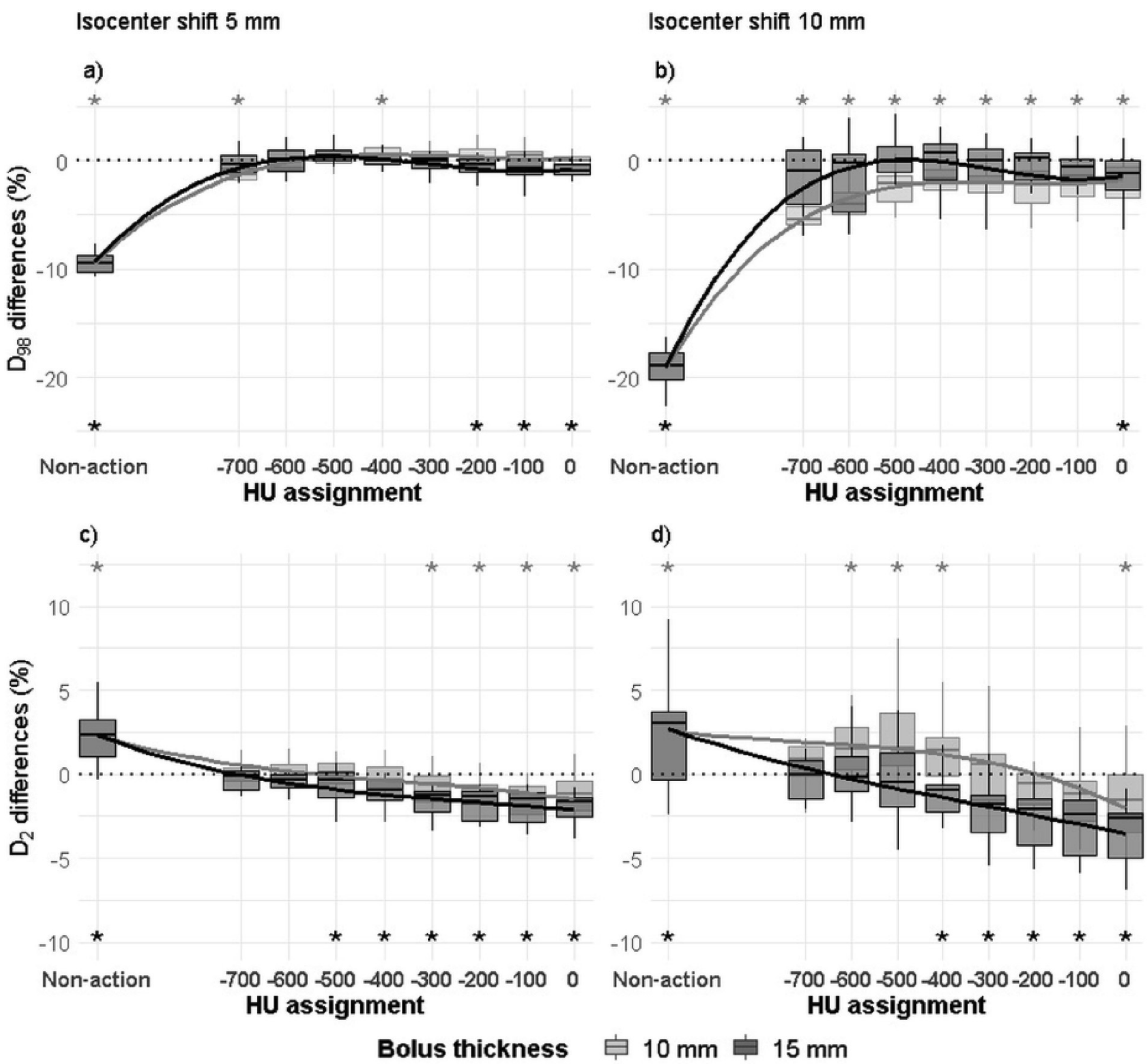

Fig. 5. Boxplots representing relative differences in D_{98} and D_2 between Plans_CT$_0$ and Plans_CT$_0$shifted for each virtual bolus HU assignment, and evaluated on SkinPTV_L and SkinPTV_R. Asterisks at the top (related to 1.0 bolus thickness results) and at the bottom (related to 1.5 bolus thickness results) indicate when the corresponding boxplot is significantly different from zero. Outliers were removed from the figure for simplicity and clarity.

Table 3
Summary of the corresponding HU assignments and dose indexes for the minimum dosimetric impact and the maximum robustness. Bolus thickness of 10 mm would not be robust for shifts up to 10 mm.

	Minimum dosimetric impact		Maximum robustness		
Bolus thickness (mm)	Dmean difference (%)	HU	Isocenter shift (mm)	D_{98} difference (%)	HU
10	1.7	−410	5	0.6	−390
15	2.1	−560	5	0.4	−510
			10	0.1	−470

of 10 mm. A strategy to avoid this undesirable effect is therefore needed, as suggested by Nicolini et al. [17].

In our study, a virtual bolus thickness equal to 15 mm did not seem to be sensitive to the isocenter shift applied (at least to shifts up to 10 mm). Similarly, a virtual bolus thickness equal to 10 mm did not seem to be sensitive to an isocenter shift of 5 mm. However, this 10 mm thickness was sensitive to an isocenter shift of 10 mm. As virtual bolus thickness was defined as CTV-PTV margin plus 5 mm (to take into account the build-up region), the CTV-PTV margin sets the minimum virtual bolus thickness. We therefore postulate that if a margin of x mm is applied, a bolus thickness of x + 5 mm will be necessary to make the plan robust to isocenter shifts up to x mm.

Regarding HU value assignments, shown in Fig. 5a and b, a virtual bolus HU around −400/−500 for 10 mm/15 mm bolus thickness would be the preferred value (Table 3). According to our data, virtual bolus HU value of −500 HU would correspond to mean relative D_{98} (D_2) differences in the peripheral PTV volume equal to −0.2% (0.2%) in the worst scenario studied (isocenter shift of 10 mm). In contrast, using a tissue equivalent HU value would correspond to mean relative D_{98} (D_2) differences in the peripheral PTV volume equal to 1.7% (−3.4%) for a bolus thickness of 15 mm in the worst scenario studied (isocenter shift of 10 mm).

These virtual bolus HU values were similar to the best HU values found by minimizing the dosimetric impact of the pseudo skin flash strategy. Due to this similarity, we chose the HU values found maximum robustness. The choice of these values implies a change in normalisation of less than 2.5%.

The main limitation of this study is that the data were extracted from a group of 7 patients at a single centre. Further studies that include a larger cohort and multi-centre validation are needed to verify our findings.

5. Conclusions

We present a comprehensive study about the pseudo skin flash strategy applied to breast cancer for volumetric radiotherapy planning. Dosimetric impact and robustness were studied by varying the HU value of the virtual bolus, virtual bolus thickness, and isocenter shifts in order to identify the best parameters to implement this strategy.

According to our results, not applying any planning strategy in the optimisation phase to make the VMAT plan robust to any possible displacement would seriously compromise the irradiation of the CTV. In case of a CTV-PTV margin of 10 mm, a bolus thickness of 15 mm would be sufficient to take into account isocenter shifts of up to 10 mm in the breathing direction. For this thickness, a virtual bolus HU-value of approximately −500 HU would be appropriate to implement the planning strategy.

This virtual bolus HU-value of −500 HU is similar to the best HU value found by minimizing the dosimetric impact of the pseudo skin flash strategy (on both PTV and OAR). Therefore, if this virtual bolus HU value was used, for most patients it would not be necessary to re-normalize the clinical dose distribution, and if it was necessary, it would be a minor change among all the other possible virtual bolus HU values.

To sum up, based on our results, we recommend a bolus thickness equal to the CTV-PTV margin plus 5 mm, and a virtual bolus HU value around −500 and −400 depending on the chosen bolus thickness (15 and 10 mm respectively). These values would maximize plan robustness and minimize the need for re-normalization when the plan optimized with the virtual bolus is recalculated on the original CT data.

Although the present study focused on breast radiotherapy, this same methodology could be applied to other locations.

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