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ORIGINAL RESEARCH

The Impact of Different Grid Size Values and Dose Calculation Algorithms on Plan Accuracy in Vmat-Based Radiotherapy for Breast Cancer

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ABSTRACT

This study evaluated the impact of dose calculation algorithms (Monte Carlo and Pencil Beam) and grid size values (1.5 mm, 3 mm, and 5 mm) on the accuracy of VMAT-based radiotherapy plans for breast cancer. Six different treatment plans were generated for each patient using combinations of algorithm and grid size values. The plan created with the Monte Carlo algorithm and a 1.5 mm grid size was designated as the reference plan, and all other plans were compared dosimetrically to this baseline. Results showed that both the choice of algorithm and grid size significantly influenced dose distribution in target volumes (PTVs) and organs at risk (OARs). For example, the D%98 value of the PTVmeme in the reference plan was 47.2 ± 1.0 Gy, which decreased to 44.4 ± 1.4 Gy in the Pencil Beam plan with a 5 mm grid size. For OARs, algorithm selection had a more pronounced impact. The V20 of the ipsilateral lung was 24.2 ± 0.9% in the reference plan but dropped to 20.3 ± 1.2% in the Pencil Beam plan with a 1.5 mm grid size ($p<0.05$). In conclusion, the Monte Carlo algorithm combined with a 1.5 mm grid size provides more accurate and reliable dose calculations for both PTVs and OARs. The Pencil Beam algorithm and larger grid sizes may underestimate dose, potentially resulting in underdosing of target volumes or unexpected overdose to critical organs. Therefore, using the Monte Carlo algorithm with a 1.5 mm grid size is considered the most appropriate choice for accurate radiotherapy planning.

Key Words: VMAT. Breast Cancer. Radiotherapy. Monte Carlo. Pencil Beam. Grid Size.

Meme Kanseri Radyoterapisinde Vmat (Volumetric Modulated Arc Therapy) Tekniği ile Farkli Grid Size Değerleri ve Doz Hesaplama Algoritmalarinin Plan Doğruluğuna Etkisi

ÖZET

Bu çalışmada, meme kanseri radyoterapisinde VMAT tekniğiyle oluşturulan planlarda, doz hesaplama algoritmaları (Monte Carlo ve Pencil Beam) ve grid size (1,5 mm, 3 mm, 5 mm) değerlerinin plan doğruluğu üzerindeki etkileri karşılaştırmalı olarak değerlendirilmiştir. Planlama sürecinde, her hasta için algoritma ve grid size kombinasyonlarıyla toplam 6 farklı plan oluşturulmuştur. Monte Carlo algoritması ve 1,5 mm grid size kullanılarak oluşturulan plan, referans plan olarak kabul edilmiş; diğer planlar bu referans plan ile dozimetrik olarak karşılaştırılmıştır. Elde edilen bulgular, hem hedef hacimlerde hem de riskli organlardaki doz dağılımının, kullanılan algoritma ve grid size değerlerinden etkilendiğini göstermektedir. PTVmeme D%98 değeri referans planda (Monte Carlo 1,5 mm grid size) 47,2±1,0 Gy olarak hesaplanırken, Pencil Beam algoritması ile 5 mm grid size hesaplatılan planda 44,4±1,4 Gy'ye düştüğü gözlemlenmiştir. Riskli organlar açısından ise, özellikle algoritma değişiminin doz dağılımı üzerinde belirgin etkiler oluşturduğu görülmüştür. İpsilateral akciğerin V20 değeri referans planda %24,2±0,9 iken, Pencil Beam algoritması ile 1,5 mm grid size hesaplatılan planda %20,3 ±1,2 olarak hesaplanmış; bu azalma istatistiksel olarak anlamlı bulunmuştur ($p<0,05$). Sonuç olarak, Monte Carlo algoritması ve 1,5 mm grid size kullanımı, hedef hacimlerde ve riskli organlarda güvenilir ve doğru doz hesaplamaları sunmuştur. Pencil Beam algoritması ve 5 mm grid size ile oluşturulan planlarda ise, dozlar referans plana kıyasla daha düşük hesaplanmış; bu durum, tedavi sırasında hedef hacimlerin yeterince ışınlanmaması ve riskli organların beklenenden daha fazla doz almasına yol açabilir. Bu nedenle, tedavi planlarının doğruluğunu artırmak amacıyla Monte Carlo algoritması ile 1,5 mm grid size kombinasyonunun kullanılması en uygun seçenektir.

Anahtar Kelimeler: Radyoterapi. Tedavi planlama sistemi. Algoritma. Grid size. Vmat.

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Breast cancer is the most common type of cancer among women worldwide, and early diagnosis combined with appropriate treatment approaches has significantly increased survival rates. According to 2022 data, breast cancer, which occurs in both sexes, ranks second in global cancer incidence with about 2.3 million new cases, representing 11.6% of all cancers.

This high incidence rate necessitates an effective and multidisciplinary treatment approach. In this context, surgery, radiotherapy, chemotherapy, hormonotherapy, and immunotherapy are among the primary treatment modalities for breast cancer[1].

Studies have shown that radiotherapy increases survival rates and reduces cancer recurrence[2]. The primary aim of radiotherapy is to deliver an adequate dose to the tumor site while maximizing the protection of healthy tissues[3]. Therefore, advanced treatment techniques are required. In recent years, technological advancements in radiotherapy have enabled the development of more precise and effective treatment methods. As a result of these developments, Volumetric Modulated Arc Therapy (VMAT) has emerged as an effective technique in modern radiotherapy[4–5]. VMAT is characterized by the ability to continuously irradiate the patient as the gantry rotates around them; during this process, the multileaf collimator (MLC) moves dynamically, and both the dose rate and gantry rotation speed can be modulated simultaneously. VMAT modulates dose intensity within the target volume, enabling the delivery of high doses to the tumor from multiple angles while achieving a steep dose gradient in surrounding tissues[6]. Particularly in treatments requiring precise dose distribution, VMAT has become a frequently preferred technique for malignancies in various anatomical regions. However, due to its high precision and complexity, VMAT increases the complexity of radiation dose calculation[7].

Reynaert et al. (2007) reported that dose calculation algorithms have a direct impact on calculation accuracy and the protection of healthy tissues. These algorithms model the physical interactions of radiation within tissues, thereby enabling more reliable dose estimation for both the target volume and organs at risk. The study emphasized that different algorithms can produce significant calculation differences at tissue interfaces (e.g., air–tissue or bone–soft tissue). Thus, the choice of algorithm is a critical factor affecting plan accuracy, especially in anatomically heterogeneous regions[8]. The Monte Carlo algorithm models the transport and interactions of photons and electrons within tissue with the highest level of realism. It simulates processes such as scattering, absorption, and energy loss of radiation in the human body using probability distributions based on physical laws, and calculates the resulting dose distribution. Monte Carlo performs with high accuracy even in heterogeneous tissues with varying densities, such as air–bone interfaces, where dose calculation is more challenging[9].

The Pencil Beam algorithm, on the other hand, divides a broad radiation beam into multiple narrow "pencil" beams, calculating the contribution of each to the overall dose distribution separately. However, these calculations consider only the forward motion of the beams, while lateral scattering and secondary radiation effects are either ignored or represented by simplified models. Therefore, while the Pencil Beam algorithm provides sufficient accuracy for homogeneous tissues and large-field irradiations, it may exhibit deviations in heterogeneous tissues with varying densities, such as air–bone transitions, and in small-field irradiations[10].

Another planning parameter that directly affects treatment accuracy is the grid size. In treatment planning systems (TPS), dose calculation algorithms use tissue density information obtained from computed tomography (CT) images to calculate the radiation dose. In this process, imaging data are converted into Hounsfield Unit (HU) values, and the interactions of photons and/or particles within the patient's anatomy are simulated using physical models. Grid size refers to the dimensions of the three-dimensional calculation unit (voxel) used during dose computation on each CT image voxel by the TPS software, and determines the intervals at which the dose is calculated[11–12].

Alzahraa Ali et al. (2024) reported that grid size is a crucial parameter directly affecting both dose distribution accuracy and calculation time. Smaller grid sizes provide higher calculation accuracy but increase computation time. Conversely, larger grid sizes reduce computation time but may decrease dose distribution precision in heterogeneous regions, leading to uncertainties in target volumes and organs at risk. Therefore, grid size is considered a critical parameter influencing the dosimetric accuracy of a treatment plan[13].

This study is one of the limited number of works in the literature evaluating Monte Carlo and Pencil Beam algorithms with different grid size values in VMAT plans for breast cancer. In this context, the dosimetric effects of different algorithms and grid size values on plan accuracy were comparatively analyzed in treatment plans generated using the VMAT technique, and the dose distribution in the planning target volume (PTV) as well as the doses to organs at risk were examined.

Material and Method

In this retrospective study, treatment plans were generated using computed tomography (CT) images

previously acquired from 10 patients with left-sided breast cancer who had undergone breast-conserving surgery (BCS) and received radiotherapy at the Department of Radiation Oncology, Bursa Uludag University Faculty of Medicine.

All plans were created in the Monaco treatment planning system (TPS), compatible with the Elekta Synergy linear accelerator, using the VMAT technique. For each patient, 6 MV photon energy and a 230° arc were employed. Two separate target volumes PTVbreast and PTVsupraclavicular were planned to receive a total dose of 50 Gy, delivered in 25 fractions of 2 Gy per day. All planning target volume (PTV) and organ at risk (OAR) contours were delineated by an experienced radiation oncologist. To compensate for potential patient movement and positioning errors during treatment, an isotropic margin of 5 mm was added to the clinical target volume (CTV) to generate the PTV[14]. The PTV was limited to 5 mm beneath the skin surface. Normal Tissue is healthy tissues and organs that are not intended to receive radiation during treatment but may absorb a certain amount of dose due to their anatomical proximity to the irradiation field or their presence within it. During planning, the objectives were to ensure that at least 95% of the target volume received at least 95% of the prescribed dose and that the maximum dose did not exceed 110% of the prescription.

During the treatment planning process, two different dose calculation algorithms (Monte Carlo and Pencil Beam) and three different grid size values (1.5 mm, 3 mm, and 5 mm) were applied for each patient. This resulted in six different treatment plans per patient, and a total of 60 treatment plans for all 10 patients. In these plans, all parameters other than algorithm and grid size were kept constant, allowing for a comparative dosimetric evaluation of the effects of only these two variables on plan accuracy.

For each patient, the reference plan was generated using the Monte Carlo algorithm with a 1.5 mm grid size. The other plans were derived from the reference plan by altering only the algorithm and grid size parameters, followed by recalculation without re-optimization.

The Monte Carlo algorithm was selected as the reference due to its high dose calculation accuracy[15]. Liu et al. (2020) compared 3D-CRT (Three-Dimensional Conformal Radiotherapy), IMRT (Intensity-Modulated Radiation Therapy), and VMAT techniques in the treatment of left-sided breast cancer, reporting that VMAT achieved superior target conformity and reduced doses to organs at risk such as the heart and lungs. The study emphasized the clinical advantage of VMAT in minimizing heart dose during left breast irradiation[16]. Based on these findings, the VMAT technique was chosen for the present study. In the reference plan, a grid size of 1.5 mm was used to enhance dose calculation precision, in line with literature reports that smaller grid sizes increase calculation accuracy[17].

The abbreviations for the algorithm and grid size combinations used in this study were as follows:

- **MC1.5**: Monte Carlo, 1.5 mm grid size (reference plan)
- **MC3**: Monte Carlo, 3 mm grid size
- **MC5**: Monte Carlo, 5 mm grid size
- **PB1.5**: Pencil Beam, 1.5 mm grid size
- **PB3**: Pencil Beam, 3 mm grid size
- **PB5**: Pencil Beam, 5 mm grid size

Ethical Approval

This study received ethical approval from the Bursa Uludağ University Health Research Non-Interventional Ethics Committee, with decision number 2025/4/22, dated 19.02.2025.

Statistical Analysis

Statistical analysis was performed using SPSS (Statistical Package for the Social Sciences) software, version 27.0. The normality of data distribution was assessed using the Shapiro–Wilk test. For data showing a normal distribution ($p>0.05$), the paired t-test was used. The Wilcoxon Signed-Rank Test was applied with data not showing a normal distribution ($p<0.05$).

Results

Target Volumes (PTV):

Changes in algorithm and grid size were found to affect the calculated dose distribution in target volumes. Plans generated using the Monte Carlo algorithm with a 1.5 mm grid size produced higher dose values for both target volumes compared to those generated using the Pencil Beam algorithm with a 5 mm grid size. For PTVbreast, the Dmean was 50.1 ± 0.6 Gy in the MC1.5 plan, whereas it was 47.5 ± 0.9 Gy in the PB5 plan. Similarly, D98, D95, and D50 values were consistently higher in MC-based plans. For PTVsupraclavicular, the Dmean was 50.3 ± 0.5 Gy in the MC1.5 plan compared to 49.5 ± 0.7 Gy in the PB5 plan. Regarding Dmax, the highest value (55.2 ± 0.4 Gy) was obtained in the MC1.5 plan, whereas the lowest value (53.6 ± 0.7 Gy) was recorded in the PB5 plan (Table I).

Organs at Risk (OAR):

Algorithm and grid size variations also had a marked impact on OAR doses. Plans generated with the

Monte Carlo algorithm and a 1.5 mm grid size calculated higher doses to critical organs compared to plans using the Pencil Beam algorithm with a 5 mm grid size. For example, the Dmean to the heart was 6.3 ± 0.5 Gy in the MC1.5 plan and 3.8 ± 0.4 Gy in the PB5 plan. The heart V5 was 44.8% in MC1.5 and 23.6% in PB5. For the left anterior descending artery (LAD), the D_mean was 13.2 ± 4.7 Gy in the MC3 plan and 11.5 ± 2.5 Gy in the PB5 plan. The ipsilateral lung Dmean was 13.6 ± 0.4 Gy in the MC1.5 plan and 10.4 ± 0.6 Gy in the PB5 plan, while the V20 was 24.3 ± 1.0% in MC3 and 20.3% in PB5. The contralateral breast Dmean was 5.0 ± 1.0 Gy in MC3 and 3.6 ± 0.9 Gy in PB5 (Table III).

Table I. Values for target volumes (PTV) normalized to MC1.5

PTV		MC1.5	MC3	MC5	PB1.5	PB3	PB5
PTV_{breast}	D_{mean}(Gy)	50.1±0.6	49.8±0.8	49.8±6.0	48.0±0.9	47.9±0.9	47.5±0.9
	$D_{\%98}$(Gy)	47.2±1.0	46.9±1.1	46.1±1.2	45.1±1.4	45.0±1.4	44.4±1.4
	$D_{\%95}$(Gy)	48.4±0.7	48.2±0.7	47.5±0.9	46.2±1.0	46.4±1.6	45.7±1.0
	$D_{\%50}$(Gy)	50.3±0.6	50.1±0.6	50.0±0.6	48.1±0.8	47.9±0.8	47.6±0.8
	$D_{\%2}$(Gy)	52.1±0.9	51.6±0.6	51.9±0.2	50.1±1.0	49.8±1.0	49.4±0.9
PTV_{SCV}	D_{mean}(Gy)	50.3±0.5	50.3±0.4	50.1±0.4	49.7±0.7	49.5±0.7	49.1±0.7
	$D_{\%98}$(Gy)	47.0±1.0	46.7±1.0	45.8±1.1	46.1±1.1	45.8±1.0	44.9±1.0
	$D_{\%95}$(Gy)	48.5±0.7	48.3±0.7	47.6±0.8	47.6±0.9	47.3±0.9	46.8±1.1
	$D_{\%50}$(Gy)	50.5±0.4	50.4±0.5	50.4±0.4	49.8±0.6	49.5±0.6	49.2±0.6
	$D_{\%2}$(Gy)	52.2±0.4	52.1±0.4	51.9±0.4	52.2±0.9	51.9±0.9	51.4±0.9
D_{max} (Gy)		55.2±0.4	54.4±0.5	54.0±0.7	54.9±0.7	54.2±08.	53.6±0.7

MC1.5: Monte Carlo algorithm with 1.5 mm grid size; MC3: Monte Carlo with 3 mm grid size; MC5: Monte Carlo with 5 mm grid size; PB1.5: Pencil Beam algorithm with 1.5 mm grid size; PB3: Pencil Beam with 3 mm grid size; PB5: Pencil Beam with 5 mm grid size; PTVbreast: Planning Target Volume – Breast; PTVSCV: Planning Target Volume – Supraclavicular; D_mean: mean dose value; D_{98}%: dose received by 98% of the volume; D_{95}%: dose received by 95% of the volume; D_{50}%: dose received by 50% of the volume; D_2%: dose received by 2% of the volume. All values are presented as mean ± standard deviation.

Discussion and Conclusion

In this study, the effects of Monte Carlo and Pencil Beam algorithms and three grid size values (1.5 mm, 3 mm, and 5 mm) on plan accuracy were comparatively evaluated in treatment plans generated using the VMAT technique for left-sided breast cancer. The findings demonstrated that dose distributions for both target volumes and organs at risk (OARs) were influenced by algorithm and grid size parameters. In particular, plans generated with the Pencil Beam algorithm and larger grid sizes exhibited greater discrepancies in dose calculations. Therefore, both the algorithm and grid size should be considered critical parameters directly affecting the accuracy of treatment plans.

Table II. Values for target volumes (PTV) normalized to MC1.5

PTV		MC1.5	MC3	MC5	PB1.5	PB3	PB5
PTV_{brast}	D_{mean}	1.000	0.995	0.994	0.959	0.956	0.949
	$D_{\%98}$	1.000	0.992	0.975	0.955	0.952	0.939
	$D_{\%95}$	1.000	0.944	0.981	0.955	0.958	0.944
	$D_{\%50}$	1.000	0.995	0.994	0.956	0.953	0.947
	$D_{\%2}$	1.000	0.991	0.997	0.962	0.957	0.948
PTV_{SCV}	D_{mean}	1.000	1.000	0.995	0.987	0.983	0.975
	$D_{\%98}$	1.000	0.995	0.975	0.982	0.975	0.956
	$D_{\%95}$	1.000	0.996	0.982	0.981	0.977	0.966
	$D_{\%50}$	1.000	0.999	0.998	0.986	0.981	0.975
	$D_{\%2}$	1.000	0.998	0.993	1.000	0.994	0.984
D_{max} (Gy)		1,000	0.984	0.978	0.993	0.981	0.971

MC1.5: Monte Carlo algorithm with 1.5 mm grid size; MC3: Monte Carlo with 3 mm grid size; MC5: Monte Carlo with 5 mm grid size; PB1.5: Pencil Beam algorithm with 1.5 mm grid size; PB3: Pencil Beam with 3 mm grid size; PB5: Pencil Beam with 5 mm grid size; PTVbreast: Planning Target Volume – Breast; PTVSCV: Planning Target Volume – Supraclavicular; D_mean: mean dose value; D_{98}%: dose received by 98% of the volume; D_{95}%: dose received by 95% of the volume; D_{50}%: dose received by 50% of the volume; D_2%: dose received by 2% of the volume.

Since the plans were generated by recalculation without re-optimization, monitor unit (MU) values remained unchanged. Normalization to the reference plan enabled clearer and more comparable evaluation of dose differences among plans with varying algorithm and grid size combinations. This approach allowed deviations in target volumes and OARs to be quantified in percentage terms, facilitating an accurate assessment of their impact on plan accuracy (Tables II and IV).

Chung et al. (2006) investigated the effects of different grid sizes (1.5 mm–4 mm) on dose distribution in head-and-neck IMRT plans. Their comparisons revealed that plans created with smaller grid sizes (1.5 mm) showed notable dose differences compared to those with larger grid sizes (4 mm), particularly in surface regions and areas with steep dose gradients, with discrepancies reaching up to 5.6%. This supports the conclusion that grid size directly influences dose calculation accuracy[17]. Consistent with the literature, our results confirmed that grid size directly affects dose calculation accuracy. For instance, when the grid size in the Monte Carlo algorithm increased from 1.5 mm to 5 mm, the PTVbreast D98 dose decreased from 47.2 Gy to 46.1 Gy, a statistically significant reduction ($p < 0.05$). Similarly, within the Pencil Beam algorithm, the PTVsupraclavicular D98 decreased from 46.1 ± 1.1 Gy with a 1.5 mm grid size to 44.9 ± 1.0 Gy with a 5 mm grid size, representing a 2.6% reduction (Tables I and II).

Table III. Dose values for organs at risk (OAR) according to changes in algorithm and grid size.

Riskli Organlar		MC1.5	MC3	MC5	PB1.5	PB3	PB5
Heart	D_{mean}(Gy)	6.3±0.5	6.4±0.3	6.5±0.3	3.7±0.4	3.9±0.6	3.8±0.4
	V_{25} (%)	1.4±0.7	1.4±0.7	1.4±0.8	1.0±0.6	1.0±0.6	1.0±0.6
	V_{10} (%)	14.5±2.3	14.7±2.3	15.1±0.2	9.1±2.6	9.1±2.6	8.8±3.0
	V_5 (%)	44.8 ±5.7	45.1±5.6	45.6±5.6	22.3±5.3	23.6±4.1	23.6±3.9
LAD	D_{mean}(Gy)	14.3±2.5	13.2±4.7	15.0±2.3	11.2±2.6	11.3±2.6	11.5±2.5
	D_{maks}(Gy)	28.5±5.1	28.8±4.9	29.1±4.3	25.5±5.3	25.9±5.2	26.0±4.7
Ipsalateral lung	D_{mean}(Gy)	13.6±0.4	13.5 ±0.5	13.6±0.4	10.4 ±0.6	10.5±0.5	10.4±0.6
	V_{30} (%)	13.9±1.49	13.9±1.5	13.9 ±1.5	12.0±1.6	12.2±1.5	12.2±1.4
	V_{20} (%)	24.2±0.9	24.3±1.0	24.3±0.9	20.2±1.3	20.3±1.2	20.3 ±1.2
	V_{10} (%)	43.7±3.0	43.6±2.4	43.5±2.8	32.5±1.1	32.6±1.1	32.4±1.1
	V_5 (%)	68.1±4.4	68.0±4.5	67.9±4.5	44.6±7.9	46.3±4.7	45.9±4.7
Contralateral lung	D_{mean}(Gy)	5.8±2.0	5.8±1.9	5.7±1.9	3.6±1.7	3.7±1.8	3.9±1.8
	V_{10} (%)	11.9±13.1	11.8±13.1	11.8±13.1	5.6±8.0	6.2±9.1	6.0±9.0
	V_5 (%)	42.6±14.9	42.6±14.9	42.6±14.9	26.2±16.8	26.4±26.4	26.2±16.9
Contraleteral breast	D_{mean}(Gy)	4.9±1.0	5.0±1.0	4.7±1.2	3.6±0.9	3.6±0.9	3.6±0.9
	V_5 (%)	42.9±15.3	42.9±15.3	42.9±15.2	23.6±10.2	23.5±10.1	23.1±9.9
	V_2 (%)	86.5±16.0	86.5±16.0	86.6±15.9	71.9±20.3	71.9±20.3	71.8±20.5
Normal tissue	V_{10} (%)	15.4±4.1	15.3±4.1	15.4±4.1	13.1±3.8	13.0±3.8	13.1±3.9
	V_5 (%)	26.8±5.6	27.1±6.2	26.9±5.6	21.4±4.9	21.4±4.9	21.3±5.0

MC1.5: Monte Carlo algorithm with 1.5 mm grid size; MC3: Monte Carlo with 3 mm grid size; MC5: Monte Carlo with 5 mm grid size; PB1.5: Pencil Beam algorithm with 1.5 mm grid size; PB3: Pencil Beam with 3 mm grid size; PB5: Pencil Beam with 5 mm grid size; D_mean: mean dose value; D_max: maximum dose value; V_{30}: percentage of the volume receiving 30 Gy or more; V_{25}: percentage of the volume receiving 25 Gy or more; V_{20}: percentage of the volume receiving 20 Gy or more; V_{10}: percentage of the volume receiving 10 Gy or more; V_5: percentage of the volume receiving 5 Gy or more; V_2: percentage of the volume receiving 2 Gy or more. All values are presented as mean ± standard deviation.

Table IV. Values for organs at risk (OAR) normalized to MC1.5

Riskli Organlar		MC1.5	MC3	MC5	PB1.5	PB3	PB5
Heart	D_{mean}	1.000	1.021	1.030	0.597	0.629	0.599
	V_{25}	1.000	1.007	1.000	0.745	0.737	0.730
	V_{10}	1.000	1.012	1.037	0.627	0.630	0.609
	V_5	1.000	1.007	1.019	0.498	0.527	0.527
LAD	D_{mean}	1.000	1.084	1.139	0.848	0.858	0.872
	D_{maks}	1.000	1.013	1.023	0.897	0.909	0.912
Ipsilateral lung	D_{mean}	1.000	0.993	1.001	0.764	0.770	0.767
	V_{30}	1.000	1.000	1.004	0.865	0.881	0.880
	V_{20}	1.000	1.004	1.006	0.836	0.839	0.838
	V_{10}	1.000	0.999	0.996	0.744	0.745	0.742
	V_5	1.000	0.999	0.997	0.656	0.678	0.675
Contralateral lung	D_{mean}	1.000	0.988	0.970	0.621	0.628	0.666
	V_{10}	1.000	0.999	0.994	0.470	0.519	0.508
	V_5	1.000	1.000	1.001	0.615	0.620	0.615
Contralateral breast	D_{mean}	1.000	1.006	0.947	0.730	0.729	0.725
	V_5	1.000	0.999	0.997	0.550	0.546	0.538
	V_2	1.000	1.000	1.001	0.831	0.831	0.830
Normal tissue	V_{10}	1.000	0.999	1.005	0.850	0.844	0.850
	V_5	1.000	1.014	1.006	0.798	0.799	0.797

MC1.5: Monte Carlo algorithm with 1.5 mm grid size; MC3: Monte Carlo with 3 mm grid size; MC5: Monte Carlo with 5 mm grid size; PB1.5: Pencil Beam algorithm with 1.5 mm grid size; PB3: Pencil Beam with 3 mm grid size; PB5: Pencil Beam with 5 mm grid size; D_mean: mean dose value; D_max: maximum dose value; V_{30}: percentage of the volume receiving 30 Gy or more; V_{20}: percentage of the volume receiving 20 Gy or more; V_{10}: percentage of the volume receiving 10 Gy or more; V_5: percentage of the volume receiving 5 Gy or more; V_2: percentage of the volume receiving 2 Gy or more.

Similar trends were observed in OARs. For example, in the Monte Carlo algorithm, the LAD Dmean increased from 13.2 ± 4.7 Gy with a 3 mm grid size to 15.0 ± 2.3 Gy with a 5 mm grid size, representing a 13.9% increase. For the contralateral lung in the Pencil Beam algorithm, the Dmean increased from 3.6 ± 1.7 Gy to 3.9 ± 1.8 Gy when grid size increased from 1.5 mm to 5 mm, corresponding to a 6.8% increase. The most notable changes with grid size variation were observed in the Dmean of the LAD and contralateral lung, indicating that smaller grid sizes enhance calculation accuracy, particularly for small-volume structures and high dose-gradient regions, while larger grid sizes reduce this accuracy (Tables III and IV).

In clinical practice, selecting an appropriate grid size requires balancing calculation time and dose accuracy. Snyder et al. (2017) investigated different grid sizes (1 mm, 1.5 mm, and 2.5 mm) in vertebral stereotactic radiosurgery (SRS) plans. They reported that a 1 mm grid size provided the highest accuracy for spinal cord dose estimation but increased computation time by 84% compared to 2.5 mm, making it impractical for routine clinical use. Conversely, a 1.5 mm grid size offered an optima l balance between speed and accuracy[18]. Although rapid computation is essential in clinical settings, high dose-gradient treatments such as SRS and SBRT, which require millimeter-level precision, necessitate smaller grid sizes and advanced algorithms for optimal dose accuracy[19]. In our study, the proximity of critical structures such as the heart and lungs to the target volume in left-sided breast cancer also required higher dose calculation precision.

Our results showed that Monte Carlo with a 3 mm grid size produced dose results comparable to those with a 1.5 mm grid size. For example, for PTVbreast, the D95 was 48.4 ± 0.7 Gy in MC1.5 and 48.2 ± 0.7 Gy in MC3, representing only a 0.4% decrease in MC3 compared to the reference plan (Tables I and II). Similarly, the heart Dmean increased from 6.3 ± 0.5 Gy in MC1.5 to 6.4 ± 0.3 Gy in MC3, a 1.6% increase. These results indicate that the dosimetric differences between MC1.5 and MC3 plans were minimal. Considering both dose accuracy and computation time, the Monte Carlo algorithm with a 3 mm grid size appears to offer an optimal and clinically feasible compromise (Tables III and IV).

Table V. Statistical analysis of target volumes

PTV		MC1.5 vs MC3	MC1.5 vs MC5	MC1.5 vs PB1.5
PTV_{breat}	D_{mean}	0.007 α	0.005 α	0.001 α
	$D_{\%98}$	0.005 α	0.005 α	0.001 α
	$D_{\%95}$	0.141 β	0.001 α	0.001 α
	$D_{\%50}$	0.007 α	0.005 α	0.001 α
	$D_{\%2}$	0.005 α	0.074 β	0.001 α
PTV_{SCV}	D_{mean}	0.074 β	0.014 α	0.005 α
	$D_{\%98}$	0.047 α	0.005 α	0.005 α
	$D_{\%95}$	0.099 β	0.001 α	0.001 α
	$D_{\%50}$	0.059 β	0.093 β	0.005 α
	$D_{\%2}$	0.074 β	0.001 α	0.203 β
D_{max} (Gy)		0.001 α	0.001 α	0.183 β

α: Significant difference between groups ($p < 0.05$); β: No significant difference between groups ($p > 0.05$); MC1.5: Monte Carlo algorithm with 1.5 mm grid size; MC3: Monte Carlo with 3 mm grid size; MC5: Monte Carlo with 5 mm grid size; PB1.5: Pencil Beam algorithm with 1.5 mm grid size; PB3: Pencil Beam with 3 mm grid size; PB5: Pencil Beam with 5 mm grid size; vs: comparison; PTVbreast: Planning Target Volume – Breast; PTVSCV: Planning Target Volume – Supraclavicular; D_mean: mean dose value; D_{98}%: dose received by 98% of the volume; D_{95}%: dose received by 95% of the volume; D_{50}%: dose received by 50% of the volume; D_2%: dose received by 2% of the volume.

Cilla et al. (2014) compared Pencil Beam and Collapsed Cone Convolution algorithms in left breast cancer radiotherapy and demonstrated that the Pencil Beam algorithm overestimated lung doses and target volume doses by approximately 14%, reducing plan accuracy[20]. Our findings support the literature, showing that Pencil Beam caused significant dose deviations in heterogeneous regions such as the breast. In contrast, the Monte Carlo algorithm yielded more reliable dose estimations, improving plan accuracy. This underscores the critical importance of algorithm selection for dosimetric accuracy. Monte Carlo provides high accuracy in heterogeneous anatomical regions such as the breast and head-and-neck, while Pencil Beam, despite faster computation, shows notable discrepancies in dose calculation compared to Monte Carlo[21]. These differences were particularly pronounced in low-dose regions and tissues distant from the treatment field. For example, the heart V5 decreased from 44.8 ± 5.7% in the reference plan to 22.3 ± 5.3% in PB1.5. The contralateral breast V5 also showed a substantial reduction from 42.9 ± 15.3% in the reference plan to 23.1 ± 9.9% in PB5 (Tables I and III). Sardari et al. (2023) similarly reported that the Monaco TPS underestimated out-of-field doses by approximately 60% compared to phantom measurements in IMRT plans for nasopharyngeal cancer[22].

Table VI. Statistical analysis of organs at risk

Riskli Organlar		MC1.5 vs MC3	MC1.5 vs MC5	MC1.5 vs PB1.5
Heart	D_{mean}	0.005 α	0.005 α	0.001 α
	V_{25}	0.039 α	0.214 β	0.001 α
	V_{10}	0.001 α	0.001 α	0.001 α
	V_5	0.001 α	0.001 α	0.001 α
LAD	D_{mean}	0.001 α	0.001 α	0.001 α
	D_{maks}	0.002 α	0.085 β	0.001 α
Ipsilateral lung	D_{mean}	0.575 β	0.172 β	0.001 α
	V_{30}	0.943 β	0.192 β	0.001 α
	V_{20}	0.609 β	0.246 β	0.005 α
	V_{10}	0.294 β	0.164 β	0.001 α
	V_5	0.096 β	0.177 β	0.001 α
Contralateral Lung	D_{mean}	0.878 β	0.333 β	0.005 α
	V_{10}	0.688 β	0.035 α	0.002 α
	V_5	0.7 β	0.652 β	0.001 α
Contralateral Breast	D_{mean}	0.838 β	0.093 β	0.001 α
	V_5	0.704 β	0.206 β	0.001 α
	V_2	0.4 β	0.335 β	0.001 α
Normal tissue	V_{10}	0.329 β	0.001 α	0.001 α
	V_5	0.332 β	0.012 α	0.005 α

α: Significant difference between groups ($p < 0.05$); β: No significant difference between groups ($p > 0.05$); MC1.5: Monte Carlo algorithm with 1.5 mm grid size; MC3: Monte Carlo with 3 mm grid size; MC5: Monte Carlo with 5 mm grid size; PB1.5: Pencil Beam algorithm with 1.5 mm grid size; PB3: Pencil Beam with 3 mm grid size; PB5: Pencil Beam with 5 mm grid size; vs: comparison; D_mean: mean dose value; D_{98}%: dose received by 98% of the volume; D_{95}%: dose received by 95% of the volume; D_{50}%: dose received by 50% of the volume; D_2%: dose received by 2% of the volume.

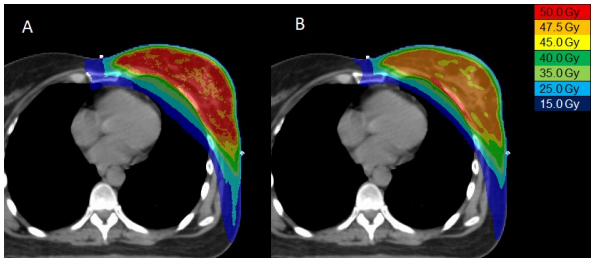


Figure 1:
A: MC1.5 plan; B: PB1.5 plan. Comparison of dose distributions generated using two different calculation algorithms.

Due to the close proximity of PTVbreast and PTV_{SCV} to the chest wall, a small portion of the ipsilateral lung may be exposed to high radiation doses. However, a much larger volume of the lung may receive low-dose radiation as a result of scattered radiation, even if it is not directly located beneath the target volume. Therefore, in breast radiotherapy, while the majority of the lung does not receive high doses, a considerable volume is exposed to low doses. The V5 parameter, which indicates the volume of the ipsilateral lung exposed to low doses, is a clinically important metric. If underestimated, it may lead to an inaccurate assessment of lung toxicity. This underestimation could increase the risk of radiation pneumonitis and, in the long term, result in serious complications such as pulmonary fibrosis[23]. In this context, evaluating the V5 value when assessing the low-dose exposure of the ipsilateral lung carries clinical importance. In our study, the V5 value was found to be 68.1% in the MC1.5 plan, while it was 44.6% in the PB1.5 plan, representing an underestimation of 34.5%. Similarly, in the literature, it has been reported that the Pencil Beam algorithm tends to estimate lower low-dose values compared to the Monte Carlo algorithm. Borges et al. (2013), in a study involving seven breast cancer patients treated with the IMRT technique, compared the Monte Carlo and Pencil Beam Convolution (PBC) algorithms and found that the PBC algorithm estimated the ipsilateral lung V5 value 10.2% lower than the Monte Carlo algorithm[24]. These results reveal that the Pencil Beam algorithm models low-dose regions inadequately, particularly in heterogeneous tissues such as the lung.

In our study, the largest differences were observed between the reference plan and PB5. For instance, the PTVbreast D98 was 47.2 ± 1.0 Gy in the reference plan and 44.4 ± 1.4 Gy in PB5, a 4.35% decrease. For the heart, the Dmean was 6.3 ± 0.5 Gy in the reference plan and 3.7 Gy in PB5, a 41.3% difference. These findings indicate that the Pencil Beam algorithm with a 5 mm grid size leads to significant deviations in dose estimation for both target volumes and OARs compared to the reference plan, thereby reducing plan accuracy (Tables I and III). Consistent with our results, Kim et al. (2018) compared Acuros XB (AXB) and Anisotropic Analytical Algorithm (AAA) in prostate VMAT plans with different grid sizes, finding that AAA yielded higher PTV V95% and lower OAR doses compared to AXB, and that increasing grid size from 1 mm to 5 mm produced differences in both target volume and OAR doses[25].

In left breast radiotherapy, doses to the LAD and heart are critical due to the risk of late cardiac toxicity. Maintaining the heart V25 below 10% is important to reduce cardiovascular complication risk. Beaton et al. (2019) reported that keeping heart V25 < 10% and LAD Dmax < 45 Gy was associated with low cardiovascular mortality[26]. In our study, these tolerance limits were maintained, consistent with the literature. However, due to its inability to accurately model dose in heterogeneous media, the Pencil Beam algorithm underestimated OAR doses, potentially increasing toxicity risk[27].

This study is among the few that compare different grid sizes and dose calculation algorithms in left breast cancer radiotherapy. The findings indicate that in heterogeneous anatomical regions such as the breast, both algorithm and grid size are decisive factors for plan accuracy. The combination of the Monte Carlo algorithm with a small grid size improves dose calculation accuracy and plan reliability, while the Pencil Beam algorithm with larger grid sizes increases calculation discrepancies. Therefore, in anatomical regions with varying tissue densities, the use of Monte Carlo with the smallest feasible grid size is recommended to ensure treatment accuracy.

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Idea and design: K.G., S.K.C., A.K
Data collection and processing: K.G., A.K,O. , Ö.A.
Analysis and interpretation of data: K.G., S.K.C., A.K,O., Ö.A.,S.G.T.
Writing of significant parts of the article: K.G., S.K.C., A.K.,S.G.T.

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