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Original Research Article

Selection criteria and method for deep inspiration breath-hold in patients with left breast cancer undergoing PMRT/IMRT

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ABSTRACT

Purpose: This study explored whether a free-breathing mean heart dose (FB-MHD) of 4 Gy is a reliable dose threshold for selecting left breast cancer patients after modified radical mastectomy suitable for deep inspiration breath-hold (DIBH) and developed anatomical indicators to predict FB-MHD for rapid selection.
Materials and methods: Twenty-three patients with left breast cancer treated with DIBH were included to compare FB and DIBH plans. The patients were divided into the high-risk (FB-MHD $\geq$ 4 Gy) and low-risk (FB-MHD $<$ 4 Gy) groups to compare dose difference, normal tissue complication probability (NTCP) and the DIBH benefits. Another 30 patients with FB only were included to analyze the capacity of distinguishing high-risk heart doses patients according to anatomical metrics, such as cardiac-to-chest Euclidean distance (CCED), cardiac-to-chest gap (CCG), and cardiac-to-chest combination (CCC).
Results: All heart doses were significantly lower in patients with DIBH plans than in those with FB plans. Based on FB-MHD of 4 Gy cutoff, the heart dose, NTCP for cardiac death, and benefits from DIBH were significantly higher in the high-risk group than in the low-risk group. The CCED was a valid anatomical indicator with the largest area under the curve (AUC) of 0.83 and maintained 95 % sensitivity and 70 % specificity at the optimal cutoff value of 2.5 mm.
Conclusions: An FB-MHD of 4 Gy could be used as an efficient dose threshold for selecting patients suitable for DIBH. The CCED may allow a reliable prediction of FB-MHD in left breast cancer patients at CT simulation.

Introduction

Radiation-induced adverse cardiovascular events have become a major threat to the long-term survival of breast cancer patients [1]. Previous studies have revealed a clear dose-effect relationship between the heart irradiation dose and disease risk, with no safe dose threshold [2]. Currently, the deep inspiration breath-hold (DIBH) is the most widely utilized heart dose reduction technique for breast cancer patients during post-mastectomy radiotherapy (PMRT) [3,4]. From a dosimetric perspective, the DIBH technique should be recommended for all patients. However, implementing DIBH requires additional medical resources and greater demands on the patient's respiratory function and cooperation [5,6]. Moreover, the degree of benefit from DIBH varies widely among individuals, resulting in a mean heart dose (MHD) reduction of 26.2–75.0 % [7]. Radiotherapy practitioners have tried different methods to select candidates for DIBH. However, the ideal selecting heart dose or dose benefit is uncertain, complicating patient selection.

To address this issue, it is necessary to set a suitable dose threshold for the cost-effective selection of patients for DIBH [8]. The DBCG Proton Trial has used an MHD of 4 Gy as a criterion for selecting left breast cancer patients for proton therapy, considering the patient's heart

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dose distribution and the resulting health system burden [9]. It is worthwhile to explore whether a free-breathing MHD (FB-MHD) equal to 4 Gy could serve as a dose threshold for selecting patients for DIBH. In addition, several studies have investigated anatomical metrics using simulation CT images to predict heart dose or DIBH benefit, including maximum heart distance, heart volume in the irradiation field, cardiac contact distance, and heart-to-chest distance. These metrics were predominantly developed for tangential field three-dimensional conformal radiotherapy (3D-CRT) [10,11], and there are no consistent recommendations. Intensity-modulated radiation therapy (IMRT) has been widely favored in PMRT for breast cancer patients currently due to its ability to enhance dose conformity and homogeneity [12]. However, no validated anatomical indicators for IMRT have been reported to date.

It has been reported that patients with left-sided breast cancer who have undergone modified radical mastectomy typically experience higher heart doses than those who undergo breast-conserving surgery [13]. Thus, the primary objective of this study was to investigate whether an FB-MHD of 4 Gy could serve as a reliable threshold for selecting patients suitable for DIBH post-modified radical mastectomy with PMRT/IMRT. The secondary aim was to develop practical and easily measurable anatomical indices to accurately predict FB-MHD, thus helping clinicians select patients suitable for DIBH.

Materials and methods

Patient population

A total of 53 patients with left breast cancer after modified radical mastectomy who underwent PMRT/IMRT at our institution between January 2019 and December 2021 were included. Thirty were treated with FB, and another 23 were treated with DIBH. Institutional Review Board approval was obtained prior to the start of the study (committee approval number: NFEC-2018–038).

Simulation, delineation, and treatment planning

All patients were positioned supine on breast styrofoam for simulation CT scanning. Patients undergoing DIBH were scheduled for CT scanning sequentially with FB and DIBH using consistent setup parameters. Within the Eclipse system, the planning target volume (PTV) and organs at risk (OARs) were delineated based on the Radiation Therapy Oncology Group (RTOG) delineation guidelines [14] and the cardiac atlas established by Feng et al [15]. For patients undergoing DIBH, a senior radiation oncologist delineated the PTV on DIBH and FB localized CT images, respectively. Subsequently, IMRT plans were developed by a senior physicist using the same planning system. The irradiated area was the left chest wall and the regional lymphatic drainage area, excluding the internal mammary lymph node chains (IMNs). The prescribed dose for all patients was 50 Gy/25 fractions/5 weeks.

Dosimetric parameters

Heart dose parameters were collected and recorded, including the MHD and $V_{5\ Gy} - V_{30\ Gy}$. Patients were divided into the high-risk (FB-MHD $\geq$ 4 Gy) and low-risk (FB-MHD $<$ 4 Gy) groups.

Geometric parameters

Anatomical indices were measured according to CT images that delineated the PTV and heart. The measured CT levels ranged from the upper border of the heart outline below the left pulmonary artery that is the left atrium to the lower border, where the heart blends with the diaphragm.

As illustrated in Fig. 1, a line was drawn connecting the medial edge of the PTV to the ventral border of the heart at the same level. This line intersected the PTV at point A_{upper} and the heart at point B_{upper}. Similarly, the lateral edge of the PTV was linked to the dorsal margin of the heart at the same level, forming tangents at points A_{lower} (PTV) and B_{lower} (heart). The region of the PTV between points A_{upper} and A_{lower}, adjacent to the heart, was defined as the PTV heart surface, while the

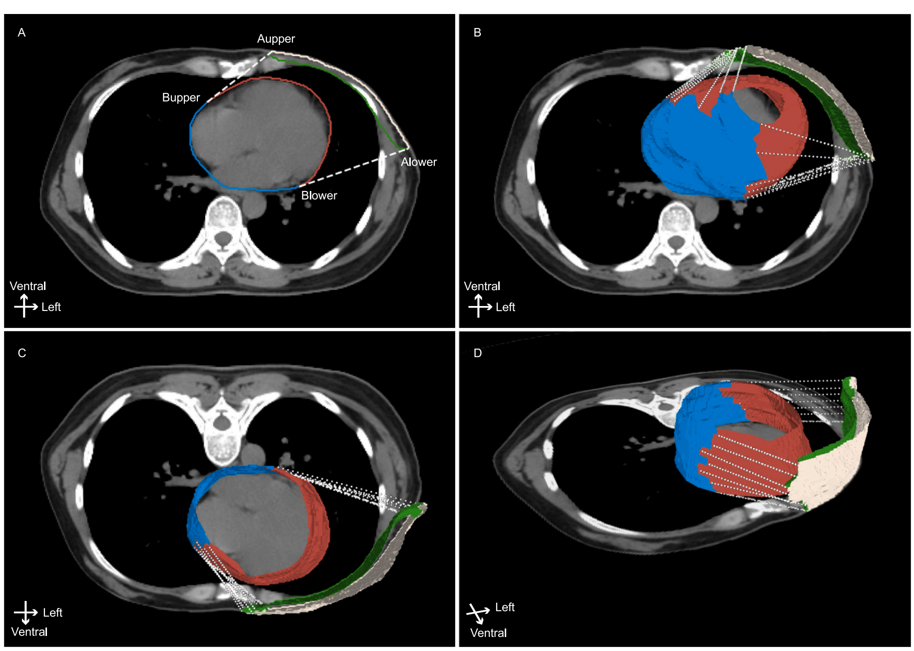

Fig. 1. Demonstration of the measurement of the cardiac-to-chest Euclidean distance (CCED), cardiac-to-chest gap (CCG), and cardiac-to-chest combination (CCC). A, B, C, and D were all at the same CT level; A and B were the foot-head direction view, C was the head-foot direction view, and D was the right anterior view. The red area was the heart PTV surface, the blue area was the heart non-PTV surface, the green area was the PTV heart surface, the beige area was the PTV non-heart surface, and the white dashed line was the tangent line between the heart contour and the PTV. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

remaining area was the PTV non-heart surface. Likewise, the section of the heart outline between points B_{upper} and B_{lower}, near the PTV, was defined as the heart PTV surface, with the remainder being the heart non-PTV surface. The distance between voxel points on the PTV heart surface and the heart PTV surface at the same CT level was the Euclidean distance, and the shortest Euclidean distance was defined as the cardiac-to-chest Euclidean distance (CCED). The corresponding formulas for these measurements were as follows:

$$d(A,B) = \sqrt[2]{(x_{Ai} - x_{Bi})^2 + (y_{Ai} - y_{Bi})^2 + (z_{Ai} - z_{Bi})^2} \quad (1)$$

$$d(\Omega_1, \Omega_2) = \min_{A \in \Omega_1, B \in \Omega_2} d(A,B) \quad (2)$$

where point A was the ith element on the heart ($x_i x_{Ai}$, y_{Ai}, z_{Ai}) and point B was the ith element on the PTV ($x_i x_{Bi}$, y_{Bi}, z_{Bi}). The set consisting of all element points on the heart was $\Omega_{1,}$ and the set consisting of all element points on the PTV was Ω_2.

The three-dimensional region of space enclosed by the PTV heart surface, the heart PTV surface, and the connecting lines was referred to as the cardiac-to-chest gap (CCG) and delineated by the white dotted line in Fig. 1A. The collective entity of the heart, cardiac-to-chest gap, and PTV together was defined as the cardiac-to-chest combination (CCC). The SciPy software package was used to calculate the CCED and generate the CCG, and the Scikit geometry software package was used to calculate the CCG and CCG/CCC.

NTCP

The normal tissue complication probability (NTCP) model estimates the risk of normal tissue toxicity. The cardiotoxicity endpoint of interest in this study was long-term cardiac mortality after radiotherapy, and the formula for NTCP calculation was as follows:

$$NTCP = \left\{ 1 - \prod_{i=1} [1 - P(D_i)^s]^{V_i} \right\}^{1/s} \quad (3)$$

$$P(D) = 2^{-\exp\{e\gamma(1 - D/D50)\}} \quad (4)$$

where V_i was the relative volume of the heart irradiated with a dose of D_i, and the maximum relative slope of the dose-response curve was given by γ. $D50$ was the dose that led to a 50 % complication probability when delivered uniformly to the entire organ. The model parameters were as follows: $s = 1$, $\gamma = 1.28$, and $D50 = 52.4$ Gy [16].

Statistical analysis

A paired t test or paired Wilcoxon signed rank test was performed to test the differences between FB and DIBH plans. Independent sample t test was used to determine whether the difference between the two groups was significant. Spearman's or Pearson correlation analysis was used to assess the relationship between heart dose and anatomical indices. Receiver operating characteristic curve (ROC) was used to examine the overall discriminatory power of anatomical indicators in identifying high-risk patients with FB-MHD using the corresponding area under the curve (AUC). Differences were considered to be statistically significant at a bilateral p value less than 0.05. All statistical analyses were performed with IBM SPSS Statistics Software 27.0 (Armonk, NY, USA).

Results

A total of 23 patients with left-sided breast cancer treated with DIBH were included. Among them, 11 (47.83 %) had an FB-MHD < 4 Gy, and 12 (52.17 %) had an FB-MHD ≥ 4 Gy.

Dosimetric comparison between FB and DIBH

In comparison to FB, DIBH demonstrated a significant decrease in heart volume (481.85 ± 63.91 cm^3 vs. 521.95 ± 79.49 cm^3, $p = 0.001$), accompanied by significantly lower values for all evaluated heart dosimetric parameters, including MHD and $V_{5\ Gy} - V_{30\ Gy}$. The reduction in MHD was notably substantial, amounting to 146.22 cGy (31.36 %). In addition, DIBH did not affect PTV dose coverage or increase the dose of other OARs (Table 1).

Comparison of the low-risk and high-risk groups

There was no significant difference in heart volume with FB between the low-risk and high-risk groups ($p = 0.420$). The heart dose and NTCP were significantly higher in the high-risk group, and this group also demonstrated greater reductions in the MHD, heart $V_{10\ Gy}$–$V_{30\ Gy}$, and NTCP (all $p < 0.05$) (Table 2). Individually, patients in the high-risk group also experienced significantly greater MHD reductions from DIBH than patients in the low-risk group (Fig. 2).

Furthermore, FB-MHD was significantly and positively correlated with MHD reductions induced by DIBH ($r = 0.864/3$, $p < 0.001$), $V_{5\ Gy}$ ($r = 0.659$, $p = 0.001$), $V_{10\ Gy}$ ($r = 0.795$, $p < 0.001$), $V_{20\ Gy}$ ($r = 0.786$, $p < 0.001$), $V_{25\ Gy}$ ($r = 0.871$, $p < 0.001$), and $V_{30\ Gy}$ ($r = 0.879$, $p < 0.001$).

Anatomical indicators for selecting patients with a ≥ 4 Gy FB-MHD

A total of 20 of the 30 patients treated with FB were in the high-risk group, and 10 were in the low-risk group. Consistent with the above results, patients in the high-risk group also had significantly greater MHD and heart $V_{5\ Gy}$–$V_{30\ Gy}$ values. The CCED and CCG/CCC were significantly lower in the high-risk group ($p < 0.05$) (Table 3). The CCED, CCG, and CCG/CCC showed a significant negative linear correlation with the FB-MHD, with r values of − 0.635 ($p < 0.001$), −0.428 ($p = 0.018$), and − 0.503 ($p = 0.04$), respectively. The predictive capability of indicators for the FB-MHD is illustrated in Fig. 3, demonstrating AUC values of 0.83 ($p = 0.0037$), 0.72 ($p = 0.0529$), and 0.74 ($p = 0.0347$). CCED exhibited the largest AUC, with an optimal threshold of 2.50 mm, and predicted an FB-MHD ≥ 4 Gy with a sensitivity of 95 % and a specificity of 70 %.

Discussion

Our results showed that the DIBH technique significantly reduced the heart dose without compromising PTV coverage and increasing the dose to other critical OARs. The overall heart irradiated dose and risk of post-radiotherapy cardiac mortality were significantly higher in patients with an FB-MHD ≥ 4 Gy than those with an FB-MHD < 4 Gy. Furthermore, patients with an FB-MHD ≥ 4 Gy had greater cardiac benefits from DIBH. To facilitate clinical application, we used integers as selection thresholds. Among the 53 patients in this study, 52 (98 %) had an FB-MHD ≥ 3 Gy, 32 (60 %) had an FB-MHD ≥ 4 Gy, and 7 (13 %) had an FB-MHD ≥ 5 Gy. Fig. 1 in the Supplementary Material shows a detailed patient dose distribution overview. Selecting a 3 or 5 Gy threshold would overwhelm medical centers or make DIBH inaccessible for most patients. Thus, an FB-MHD of 4 Gy was the most beneficial selection threshold. Furthermore, we developed a model to measure anatomical indicators by analyzing CT images to identify patients with an FB-MHD of 4 Gy or higher. We found that CCED was the best indicator, with a sensitivity of 95 % and a specificity of 70 % at a 2.5 mm cutoff value. By establishing a dose threshold and indicator, our study addresses key challenges in patient selection, offering a streamlined approach to identifying candidates for DIBH.

No specific studies have explored the dose threshold for identifying appropriate patients with left breast cancer eligible for DIBH. Tanna et al. [17] used an FB-MHD > 3 Gy as the selection threshold for using

Table 1
Dose volume histograms comparison between FB and DIBH.

Parameters	FB	DIBH	Absolute difference	Relative reduction(%)	P-value
Heart					
Volume (cm^3)	521.95 ± 79.49	481.85 ± 63.91	40.10	7.05	0.001
Dmean(cGy)	434.61 ± 118.79	288.39 ± 54.45	146.22	31.36	<0.001
$V_{5\ Gy}$ (%)	19.38 ± 5.58	12.40 ± 3.92	6.97	34.68	<0.001
$V_{10\ Gy}$ (%)	8.46 ± 3.64	3.70 ± 1.70	4.76	53.79	<0.001
$V_{20\ Gy}$ (%)	4.19 ± 2.86	1.36 ± 1.04	2.83	62.39	<0.001
$V_{25\ Gy}$ (%)	3.17 ± 2.62	0.81 ± 0.90	2.36	75.27	<0.001
$V_{30\ Gy}$ (%)	2.29 ± 2.11	0.51 ± 0.72	1.78	78.25	<0.001
Lung (Left)					
Volume (cm^3)	1089.14 ± 215.62	1786.10 ± 305.64	696.97	65.98	<0.001
Dmean (cGy)	1287.60 ± 157.59	1216.34 ± 169.55	71.29	5.47	0.002
$V_{20\ Gy}$ (%)	24.09 ± 3.55	22.57 ± 3.46	1.52	5.97	0.006
Lung (Right)					
Volume (cm^3)	1269.26 ± 206.22	2033.15 ± 302.31	763.89	61.38	<0.001
Dmean (cGy)	95.64 ± 31.80	102.64 ± 45.99	N/A	N/A	0.325
$V_{20\ Gy}$ (%)	0.01 ± 0.05	0.03 ± 0.11	N/A	N/A	0.180
PTV					
Volume (cm^3)	530.01 ± 167.99	523.90 ± 169.02	N/A	N/A	0.410
Dmean (cGy)	5155.83 ± 20.13	5155.66 ± 25.67	N/A	N/A	0.952
$V_{95\%}$ (%)	99.82 ± 0.18	99.82 ± 0.06	N/A	N/A	0.940
Right breast					
Dmean (cGy)	341.84 ± 146.71	342.19 ± 138.45	N/A	N/A	0.984

Abbreviations: FB = free breathing; DIBH = deep inspiration breath-hold; Dmean = mean dose; V_{XGy} (%) = a percentage volume of radiation receiving at least XGy; PTV = planning target volume; N/A = not applicable.

Table 2
Comparison of heart dose volume histograms under FB and dose benefits from DIBH between the high-risk group and low-risk group.

Parameter	low-risk group (n = 11)	high-risk group (n = 12)	Δ	P-value
Heart DVH				
Volume (cm^3)	507.60 ± 80.01	535.11 ± 80.13	27.51	0.420
Dmean (cGy)	338.18 ± 45.12	523.00 ± 92.46	184.82	<0.001
$V_{5\ Gy}$ (%)	15.76 ± 2.52	22.70 ± 5.61	6.95	0.001
$V_{10\ Gy}$ (%)	5.55 ± 2.15	11.13 ± 2.45	5.59	<0.001
$V_{20\ Gy}$ (%)	1.87 ± 1.07	6.31 ± 2.26	4.44	<0.001
$V_{25\ Gy}$ (%)	1.19 ± 0.84	4.98 ± 2.35	3.79	<0.001
$V_{30\ Gy}$ (%)	0.72 ± 0.61	3.73 ± 1.97	3.01	<0.001
NTCP (%)	0.08 ± 0.07	0.66 ± 0.43	0.57	0.001
Heart dose benefit				
Volume (cm^3)	39.05 ± 53.63	41.07 ± 49.21	2.02	0.926
Dmean (cGy)	84.38 ± 34.06	202.91 ± 95.22	119.53	0.001
$V_{5\ Gy}$ (%)	5.43 ± 2.74	8.39 ± 4.85	3.09	0.089
$V_{10\ Gy}$ (%)	2.90 ± 1.77	6.47 ± 2.70	3.59	0.001
$V_{20\ Gy}$ (%)	1.21 ± 1.03	4.31 ± 2.33	3.10	0.001
$V_{25\ Gy}$ (%)	0.94 ± 0.74	3.66 ± 2.25	2.72	0.002
$V_{30\ Gy}$ (%)	0.59 ± 0.54	2.87 ± 1.82	2.28	0.001
NTCP (%)	0.07 ± 0.06	0.57 ± 0.38	0.50	0.001

Abbreviations: FB = free-breathing; DIBH = deep inspiration breath-hold; Δ= difference between high-risk and low-risk groups; DVH = Dose volume histogram; Dmean = mean dose; V_{XGy} (%) = a percentage volume of radiation receiving at least XGy; NTCP = normal tissue complication probability.

DIBH in their study but noted that the choice of this metric was random and lacked a clear rationale. Skytta et al. [18] compared hscTnT levels in 58 left breast cancer patients before and after radiotherapy; those with an over 30 % increase in hscTnT exhibited significantly higher MHD than those with stable hscTnT (4.0 ± 1.8 Gy vs. 2.8 ± 1.4 Gy, $p = 0.02$). Interestingly, the average FB-MHD and DIBH-MHD of the patients in our study were 4.3 and 2.8 Gy, respectively. Using 4 Gy as the threshold, patients chosen for DIBH may also experience stabilization in hscTnT. Furthermore, the expert panel recommended an MHD < 4 Gy when regional lymph nodes are included [19]. Several studies have indicated that the radiation dose to the heart is inhomogeneous and that MHD is insufficient to accurately predict cardiac substructural doses, particularly of the left ventricle (LV) and left anterior descending coronary artery (LAD), which are close to the irradiation field [20,21]. The BACCARAT study [20] and the research by Naimi et al. [22] underscored the inadequacy of MHD in forecasting cardiac substructural doses, with coefficients of determination R^2 values of the linear prediction models for LAD and LV each falling below 0.7. However, correlation analyses in both studies revealed a significant link between the MHD and the LV Dmean and LAD Dmean ($r = 0.78$ and 0.67 in the BACCARAT study, $r = 0.81$ and 0.80 in Naimi et al.'s study). By contrast, Finnegan et al.'s analysis of a large cohort showed that the MHD could effectively predict the cardiac substructure dose (R^2 values ranging from 0.720 to 0.863), specifically achieving R^2 values of 0.863 for the LV and 0.797 for the LAD [23]. Furthermore, MHD stands out as the predominant parameter for evaluating the heart dose in practice, with a multitude of previous studies devising predictive models centered on MHD [2,24,25,26]. In a large case-control study, Darby et al. [2] reported a linear increase in the risk of major coronary events by 7.4 % per Gy with MHD, whereas no significant relationship was observed with LAD Dmean. In addition, the choice of MHD as the dose parameter was justified by the relative simplicity of outlining the entire heart, whereas delineating cardiac substructures is intricate, necessitating a more challenging and time-consuming process with added effort in image interpretation [27,28].

Selecting suitable DIBH patients by predicting the heart dose using anatomical metrics is convenient and fast. However, most published metrics have been developed in the technical context of tangential-field 3D-CRT. The use of IMRT in breast cancer is gradually increasing, especially when regional lymph nodes are involved. Trampetti et al. found a poor correlation between the MHD and the two-dimensional metrics HCD ($r = -0.25$, $p = 0.050$) and CCDps ($r = 0.25$, $p = 0.047$) in patients with left breast cancer treated with VMAT [29]. This finding may be attributable to the differences in radiotherapy techniques since multifield IMRT often does not form a fixed tangent field such as that in 3D-CRT. In addition, factors such as CT slice thickness and observer measurement errors can impact the accurate acquisition of anatomical metrics [30]. Here, we approached anatomical metrics by evaluating the three-dimensional spatial distance between the heart and the PTV for IMRT. We developed a model that automates rapid and precise measurements to reduce the workload of medical staff and minimize measurement errors. This newly created index can quickly and accurately predict left-sided breast cancer patients with an MHD ≥ 4 Gy (AUC = 0.83).

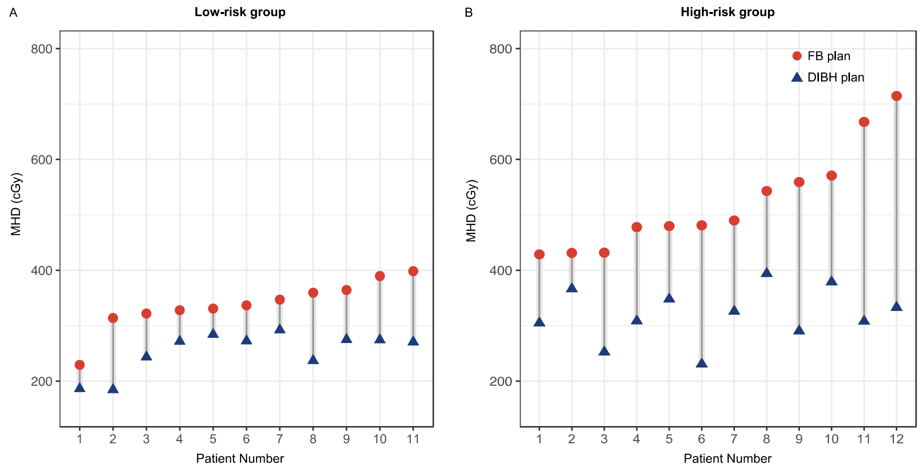

Fig. 2. Demonstration of mean heart dose (MHD) for free-breathing (FB) and deep inspiration breath-hold (DIBH) in patients in the low-risk group (FB-MHD < 4 Gy) versus patients in the high-risk group (FB-MHD ≥ 4 Gy).

Table 3
Comparison of dosimetric and geometric parameters in the high-risk group and low-risk group.

Parameter	Low-risk group (n = 10)	High-risk group (n = 20)	t	P-value
Heart dosimetric parameters				
Volume (cm^3)	529.59 ± 95.35	525.33 ± 70.92	0.138	0.891
Dmean(cGy)	350.61 ± 31.65	467.06 ± 28.58	−10.157	<0.001
$V_{5\ Gy}$ (%)	13.78 ± 2.50	19.50 ± 5.09	−3.333	0.002
$V_{10\ Gy}$ (%)	6.13 ± 0.94	8.35 ± 1.81	−3.627	0.001
$V_{20\ Gy}$ (%)	3.07 ± 1.14	4.71 ± 1.30	−3.39	0.002
$V_{25\ Gy}$ (%)	2.18 ± 1.10	3.40 ± 1.16	−2.757	0.010
$V_{30\ Gy}$ (%)	1.51 ± 0.90	2.35 ± 0.96	−2.294	0.030
Geometric parameters				
CCED (mm)	3.29 ± 1.80	1.30 ± 1.04	3.863	0.001
CCG (cm3)	329.50 ± 38.82	287.73 ± 61.87	1.943	0.062
CCG/CCC	0.34 ± 0.04	0.30 ± 0.04	2.362	0.025

Abbreviations: Dmean = mean dose; V_{XGy} (%) = a percentage volume of radiation receiving at least XGy; CCED = cardiac-to-chest Euclidean distance; CCG = cardiac-to-chest gap; CCC = cardiac-to-chest combination.

This study has several limitations. First, only post-modified radical mastectomy patients who underwent IMRT were included. Therefore, the findings and conclusions drawn from this study may not be directly applicable to patients after breast-conserving surgery or those undergoing other radiotherapy techniques, such as 3D-CRT. Second, variations in radiotherapy techniques, patient characteristics, and ethnic diversity across different medical centers may limit the generalizability of the selection thresholds and anatomical indicators identified in our study to all breast cancer patients. Third, this study primarily approached the issue from the dosimetric and NTCP modeling perspective and lacked data on the actual occurrence of radiation-induced heart disease in clinical practice, which will be explored in subsequent prospective studies. Finally, for the small sample size, future studies with larger and more diverse cohorts to reinforce the findings are warranted.

Conclusions

Our study showed that an FB-MHD of 4 Gy can be used as an efficient dose threshold for selecting patients with left breast cancer undergoing PMRT/IMRT for the DIBH technique in tertiary hospitals in China. The CCED, measured quickly and accurately with the constructed model, enables the accurate prediction of patients' FB-MHD. This approach will help clinicians to promptly assess patients' suitability for DIBH following the completion of FB CT simulation scanning.

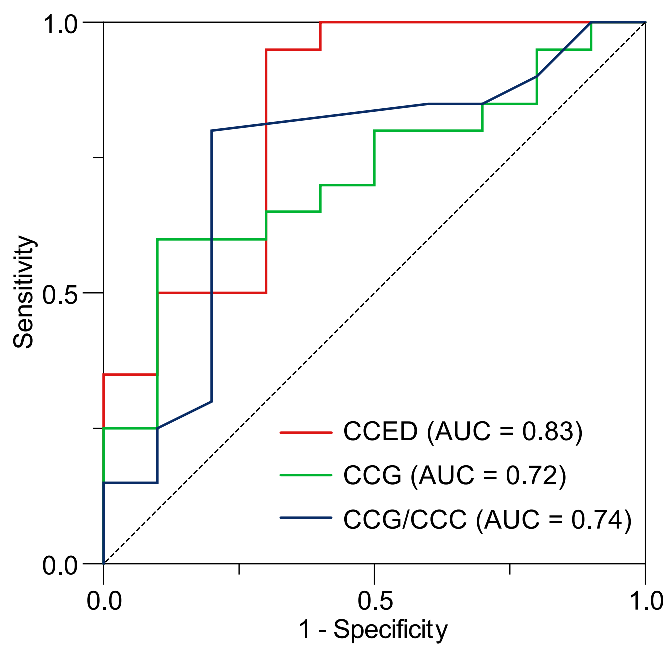

Fig. 3. Receiver operating characteristic (ROC) curve of cardiac-to-chest Euclidean distance (CCED), cardiac-to-chest gap (CCG) and CCG /cardiac-to-chest combination (CCC) for the prediction of mean heart dose (MHD).

Ethics approval

This study was approved by the Ethics Committee of Nangfang Hospital, Southern Medical University (the committee's approval Number: NFEC-2018-038；NFEC-2023-445).

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Declaration of Generative AI and AI-assisted technologies in the writing process

No Artificial Intelligence tool was used during the preparation of this work.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ctro.2024.100812.

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