

ABC versus C-Rad Technology for Intrafraction Displacement and Dosimetric Impact in Breast Cancer Radiotherapy with Breath-Hold

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Research Article

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Abstract

Purpose

To compare treatment time, intrafraction errors, and dosimetric effects between active breathing control (ABC) and C-Rad optical surface monitoring in postoperative breast cancer radiotherapy.

Methods

Thirty patients with postoperative breast cancer were enrolled, including 15 patients in the ABC group and 15 in the C-Rad group. All patients were immobilized using a KoalaRedi arm support combined with a negative-pressure vacuum cushion and received breath-hold radiotherapy. Treatment time was recorded for each fraction. Intrafraction errors in the X, Y, and Z directions were determined from cone-beam computed tomography (CBCT) scans acquired immediately after treatment. The Mann–Whitney U test was used for intergroup comparisons. Spearman’s rank correlation analysis was performed to assess the relationship between treatment time and intrafraction errors. Receiver operating characteristic (ROC) curve analysis was used to determine the optimal treatment-time threshold for predicting a Z-direction error > 2 mm. Dosimetric simulations were performed using the maximum registration error for each patient to compare the planned dose distribution with the dose distribution after introduction of the corresponding error, with particular attention to doses to the heart, lungs, and target doses.

Results

Median treatment time was significantly shorter in the C-Rad group than in the ABC group (7.44 [6.50–8.07] min vs. 7.99 [7.23–8.51] min, $P < 0.001$). No significant intergroup differences were observed in X- or Y-direction errors; however, Z-direction errors were significantly larger in the C-Rad group (0.146 [0.06–0.21] cm vs. 0.113 [0.05–0.15] cm, $P < 0.001$). In the C-Rad group, Z-direction error was positively correlated with treatment time ($r = 0.167$, $P = 0.006$). A treatment time > 10.93 min predicted a Z-direction error > 2 mm (area under the curve [AUC] = 0.605; sensitivity, 86.3%; and specificity, 31.9%). Dosimetric simulation based on each patient’s maximum intrafraction error showed that, in the ABC group, the maximum error resulted in a mean reduction of 2.32% in planning target volume (PTV) D95 relative to the planned value (median, – 1.13%; $P = 0.002$), whereas changes in heart Dmean, ipsilateral lung V20, and mean lung dose were not statistically significant (all $P > 0.05$). In the C-Rad group, PTV D95 decreased by a mean of 3.80% (median, – 2.90%; $P = 0.006$), with no significant changes in the other dosimetric parameters.

Conclusion

The C-Rad technique resulted in significantly shorter single-fraction treatment times than ABC (7.44 vs. 7.99 min). However, although no significant intergroup differences were observed in lateral (X) or longitudinal (Y) errors, the vertical (Z) error was significantly larger in the C-Rad group (median, 0.13 [0.06–0.21] cm vs. 0.09 [0.05–0.15] cm, $P < 0.001$) and increased with longer treatment times. The threshold for predicting a Z-direction error > 2 mm was 10.93 min. Under maximum intrafraction error conditions, both techniques resulted in small reductions in target coverage (PTV D95: -2.32% for ABC and -3.80% for C-Rad), without significant changes in doses to organs at risk.

1 Introduction

Breast cancer is the most common malignancy among women worldwide^[1, 2]. Postoperative adjuvant radiotherapy significantly reduces locoregional recurrence and improves overall survival^[1, 2]. The precision of radiotherapy directly affects treatment efficacy and safety. Geometric errors can lead to underdosing of the target or excessive irradiation of organs at risk, thereby compromising tumor control and increasing the risk of normal tissue toxicity^[3, 4].

Respiratory motion poses a major challenge in breast cancer radiotherapy, particularly in patients with left-sided breast cancer, for whom cardiac exposure is a particular concern^[5–7]. Various respiratory management techniques have been developed to mitigate the effects of respiratory motion on target position. Active breathing control (ABC) is a breath-hold technique based on airflow monitoring. The patient breathes through a mouthpiece while wearing a nose clip, and treatment is delivered during a deep-inspiration breath-hold. The ABC system detects respiratory status in real time and triggers beam-on when the breath-hold reaches a preset threshold, thereby stabilizing target position and reducing cardiac dose^[8]. However, ABC requires good patient cooperation. Repeated breath-holds may prolong treatment time, and its use may be limited in patients with poor pulmonary function or those who cannot tolerate the mouthpiece^[9].

In recent years, optical surface monitoring systems such as C-Rad have been increasingly adopted in clinical practice. This technology projects structured light onto the patient's surface and captures the reflected patterns to reconstruct the three-dimensional surface contour in real time. By monitoring chest-wall motion, the system derives respiratory information and can trigger treatment during a stable breath-hold^[10, 11]. C-Rad offers the advantages of being noninvasive, radiation-free, and capable of continuous intrafraction monitoring, making it particularly suitable for patients who cannot tolerate the ABC mouthpiece. However, optical systems may have slightly lower accuracy in detecting vertical (Z-axis) displacement than cone-beam computed tomography (CBCT) or other radiographic imaging techniques^[12].

Although both ABC and C-Rad are widely used, direct comparisons of treatment time, intrafraction errors, and their relationships remain limited. More importantly, the dosimetric impact of maximum intrafraction errors has not been systematically quantified for these two techniques. Translating geometric errors into

clinically meaningful dose deviations is essential for guiding technique selection and optimizing treatment workflows.

Therefore, this study aimed to: (1) compare treatment time between ABC and C-Rad; (2) evaluate intrafraction errors and their correlation with treatment time; and (3) analyze, using dosimetric simulation, changes in target and organ-at-risk (OAR) doses under maximum intrafraction error conditions.

2 Materials and Methods

2.1 Study Population

We consecutively enrolled patients with breast cancer who received postoperative adjuvant radiotherapy at Gansu Provincial Maternity and Child-Care Hospital/Gansu Provincial Central Hospital between January 2025 and June 2025.

Inclusion criteria:

- (1) Age ≥ 18 years;
- (2) Eastern Cooperative Oncology Group performance status of 0–2;
- (3) Pathologically confirmed breast cancer requiring adjuvant radiotherapy after total mastectomy or breast-conserving surgery.

Exclusion criteria:

- (1) Previous thoracic radiotherapy;
- (2) Inability to tolerate vacuum-cushion immobilization or breath-hold;
- (3) Bilateral primary breast cancer;
- (4) Distant metastases at initial diagnosis.

2.2 Group Assignment and Radiotherapy Workflow

Patients were assigned to two groups according to their surgical approach and institutional clinical practice.

ABC group

Patients who underwent total mastectomy received deep-inspiration breath-hold radiotherapy assisted by the ABC system. Patients breathed through a mouthpiece while wearing a nose clip. The system monitored airflow during breath-hold and triggered beam-on when the preset threshold was reached.

C-Rad group

Patients who underwent breast-conserving surgery received breath-hold radiotherapy using the C-Rad optical surface monitoring system. The system reconstructed the three-dimensional surface contour in real time using structured light, monitored chest-wall motion to identify the breath-hold plateau, and triggered beam-on after a stable breath-hold had been achieved.

2.3 Immobilization and Simulation

All patients were positioned supine with both arms raised and supported on an armrest and were immobilized using a negative-pressure vacuum cushion. After vacuum molding, the body-surface contours were marked. Computed tomography (CT) simulation was performed with a slice thickness of 3 mm, with scanning extending from the mandible to the inferior margin of the costophrenic angle. Both free-breathing and breath-hold images were acquired and transferred to the treatment planning system.

2.4 Breath-Hold Techniques

ABC group

Patients breathed through a mouthpiece while wearing a nose clip, with the system connected to the ABC airflow-monitoring device. They were trained to take a deep inspiration and hold their breath. The breath-hold threshold was set at 80% of vital capacity. Once a stable breath-hold plateau lasting ≥ 5 s was achieved, CBCT scanning or treatment delivery was initiated.

C-Rad group

The patient's body-surface projection area was continuously monitored by the C-Rad system. Patients were trained to hold their breath after deep inspiration. The system identified the breath-hold plateau by monitoring chest and abdominal surface motion. When displacement changes remained below a preset threshold (typically 3 mm) for ≥ 3 s, CBCT scanning or treatment delivery was initiated.

2.5 Treatment and Data Collection

All patients were treated with volumetric modulated arc therapy. Daily pretreatment CBCT was performed for setup registration relative to the planning CT. Immediately after treatment, a second CBCT scan was acquired to determine the intrafraction error, defined as the residual positional error at the end of treatment. Total treatment time, from beam-on to beam-off, was recorded in min (e.g., 7 min 32 s = 7.53 min). Errors in the left–right (X), longitudinal (Y), and vertical (Z) directions were recorded from the CBCT images.

2.6 Statistical Analysis

Statistical analyses were performed using Statistical Package for Social Sciences version 26.0 (IBM Corp., Armonk, NY, USA). Continuous variables were expressed as medians with interquartile ranges

(IQRs). Data normality was assessed using the Shapiro–Wilk test. Because the data were not normally distributed, intergroup comparisons were performed using the Mann–Whitney U test. The correlation between treatment time and intrafraction errors was evaluated using Spearman’s rank correlation coefficient. Receiver operating characteristic (ROC) curve analysis was performed to identify the optimal treatment-time threshold for predicting a Z-direction error > 2 mm, with the threshold selected by maximizing the Youden index. All tests were two-sided, and $P < 0.05$ was considered statistically significant.

2.7 Dosimetric Deviation Simulation

To evaluate the clinical significance of intrafraction errors, dosimetric simulations were performed based on each patient’s maximum observed three-dimensional displacement during treatment. The intrafraction error for each fraction was expressed as the magnitude of the displacement vector ($D = \sqrt{X^2 + Y^2 + Z^2}$). For each patient, the fraction with the largest D value was selected to represent the maximum systematic displacement error. The magnitude and direction of this error were entered into the treatment planning system, and the isocenter was shifted accordingly to recalculate the dose distribution. The following dosimetric parameters were compared: mean heart dose (heart Dmean), mean ipsilateral lung dose (ipsilateral lung Dmean), and planning target volume D95% (PTV D95%). Differences between the planned and simulated values were expressed as absolute and relative percentage changes. Within-group comparisons were performed using paired t-tests or Wilcoxon signed-rank tests, as appropriate.

3 Results

3.1 Patient and Treatment Characteristics

A total of 30 patients were enrolled, with 15 patients in each group. Baseline characteristics, including age, body mass index, tumor laterality, and T stage, were well balanced between the groups ($P > 0.05$). Radiotherapy regimens and the number of fractions differed between the groups according to the respective clinical protocols ($P < 0.001$). Detailed characteristics are presented in Table 1.

Table 1
Baseline characteristics of patients in the two groups.

Characteristic	ABC group (n = 15)	C-Rad group (n = 15)	Statistic	P value
Age (years, mean $\pm$ SD)	49.1 $\pm$ 8.7	46.1 $\pm$ 10.3	t = 0.873	0.390
BMI (kg/m ² , mean $\pm$ SD)	24.6 $\pm$ 3.4	24.0 $\pm$ 4.0	t = 0.476	0.637
Tumor laterality [n (%)]			χ^2 = 0.536	0.464
Left	7 (46.7)	6 (40.0)		
Right	8 (53.3)	9 (60.0)		
T stage [n (%)]			χ^2 = 4.250a	0.236
Tis	1 (6.7)	6 (40.0)		
T1	8 (53.3)	7 (46.7)		
T2	5 (33.3)	2 (13.3)		
T3	1 (6.7)	0 (0)		
Radiotherapy regimen [n (%)]			χ^2 = 13.333a	< 0.001
Simultaneous boost (50 Gy/25 fx + boost to 60 Gy)	13 (86.7)	2 (13.3)		
Sequential boost (40.5 Gy/15 fx + boost 8.7 Gy/3 fx)	2 (13.3)	13 (86.7)		
Number of fractions, median [IQR]	25 [25–25]	18 [18–18]	Z = 4.792	< 0.001

3.2 Treatment Time and Intrafraction Errors

A significant difference in single-fraction treatment time was observed between the two groups (Table 2). The median treatment time was 7.44 min (IQR, 6.50–8.07) in the C-Rad group, which was significantly shorter than the 7.99 min (IQR, 7.23–8.51) observed in the ABC group (Mann–Whitney U test: Z = 6.712, P < 0.001). These findings indicate a clear time-efficiency advantage of C-Rad over ABC.

Table 2
Comparison of treatment time and intrafraction errors between the two groups.

Variable	M (Q1, Q3)		Z value	P value
	ABC group (N = 355)	C-Rad group (N = 283)		
Time (min)	7.989 (7.23, 8.51)	7.441 (6.50, 8.07)	-6.712	0.000
X (cm)	0.090 (0.03, 0.13)	0.092 (0.04, 0.14)	-0.455	0.649
Y (cm)	0.167 (0.06, 0.25)	0.148 (0.05, 0.23)	-1.434	0.152
Z (cm)	0.113 (0.05, 0.15)	0.146 (0.06, 0.21)	-4.135	0.000

Regarding intrafraction errors (Table 2; Fig. 1), no significant differences were observed between the two techniques in the X (left–right) or Y (longitudinal) directions (> 0.05). However, the error in the vertical (Z) direction was significantly greater in the C-Rad group than in the ABC group (median, 0.13 cm [IQR, 0.06–0.21] vs. 0.09 cm [IQR, 0.05–0.15], $P < 0.001$), indicating that the vertical direction represented the primary dimension in which the two techniques differed. Correlation analyses (Figs. 2 and 3) showed that none of the X-, Y-, or Z-direction errors were significantly correlated with treatment time in the ABC group (all $P > 0.05$). In contrast, in the C-Rad group, the vertical (Z) error was positively correlated with treatment time ($r = 0.167$, $P = 0.006$), whereas the X- and Y-direction errors were not significantly correlated with treatment time. These findings suggest that vertical errors with C-Rad tend to increase as treatment time is prolonged. To identify a clinically relevant time threshold, a ROC curve was constructed using a Z-direction error > 2 mm as the clinical alert threshold (Fig. 4). The optimal treatment-time cutoff was 10.93 min, with an area under the curve (AUC) of 0.605 (95% confidence interval [CI], 0.561–0.649; $P < 0.001$), a sensitivity of 86.3%, and a specificity of 31.9%. Thus, when single-fraction treatment time exceeds 10.93 min, the risk of a Z-direction error > 2 mm may increase, providing a reference for monitoring and controlling vertical intrafraction displacement in clinical practice.

3.3 Dosimetric Simulation Results

To assess the clinical dosimetric impact of maximum intrafraction errors, the isocenter was shifted in the treatment planning system according to each patient’s maximum three-dimensional vector displacement, and the dose distribution was recalculated. The relative percentage changes between the simulated and original planned values for heart Dmean, ipsilateral lung V20, ipsilateral lung Dmean, and PTV D95 are presented in Table 3.

Table 3
Paired comparison of dosimetric indices (relative percentage changes).

Group	Parameter	Mean $\pm$ SD (%)	Median (Q1, Q3) (%)	P value*
ABC (n = 15)	Heart Dmean	2.45 $\pm$ 12.77	3.16 (–7.65, 9.93)	0.470
	Ipsilateral lung V20	0.77 $\pm$ 18.14	1.06 (–16.74, 20.64)	0.871
	Ipsilateral lung Dmean	0.35 $\pm$ 13.05	0.919	0.919
	PTV D95	–2.32 $\pm$ 2.31	–1.13 (–2.83, –0.65)	0.002
C-Rad (n = 15)	Heart Dmean	0.62 $\pm$ 14.44	1.93 (–11.85, 15.86)	0.870
	Ipsilateral lung V20	–2.32 $\pm$ 27.07	–2.32 (–26.26, 14.78)	0.745
	Ipsilateral lung Dmean	–2.63 $\pm$ 16.62	–2.63 (–16.09, 8.81)	0.550
	PTV D95	–3.80 $\pm$ 4.49	–2.90 (–5.78, –0.58)	0.006

* Wilcoxon signed-rank test for a median change of zero (i.e., to determine whether the intrafraction error resulted in a significant dose change).

In the ABC group, the maximum intrafraction error resulted in a significant reduction in PTV D95 relative to the planned value, with a median change of – 1.13% (IQR, – 2.83% to – 0.65%; $P = 0.002$). In contrast, changes in heart Dmean, ipsilateral lung V20, and ipsilateral lung Dmean were not statistically significant (all $P > 0.05$). These findings indicate that, in the ABC group, the maximum intrafraction error primarily resulted in a mild reduction in target coverage, with no significant effect on doses to organs at risk.

In the C-Rad group, PTV D95 also decreased significantly, with a median change of – 2.90% (IQR, – 5.78% to – 0.58%; $P = 0.006$), whereas changes in heart and lung dose parameters were not statistically significant. Notably, the mean reduction in PTV D95 was – 2.32% $\pm$ 2.31% in the ABC group and – 3.80% $\pm$ 4.49% in the C-Rad group. Although the median reduction in the C-Rad group (– 2.90%) was numerically greater than that in the ABC group (– 1.13%), the intergroup difference did not reach statistical significance (Mann–Whitney $U = 78.0$, $Z = -1.477$, $P = 0.140$). Therefore, although C-Rad was associated with a numerically greater reduction in target coverage, the present data do not demonstrate a statistically significant difference between the two techniques in their effects on PTV D95. This finding may be attributable, at least in part, to the small sample size (15 patients per group) and substantial interpatient variability. Larger studies are warranted to confirm these findings and better characterize the dosimetric implications of intrafraction displacement.

4 Discussion

Our study found that the C-Rad group had significantly shorter treatment times than the ABC group, with a median difference of approximately 0.55 min, which was both statistically significant and potentially clinically relevant. Similar findings have been reported in the literature ^[13]. This difference may be

attributable to differences in the treatment workflow. ABC requires patients to use a mouthpiece and nose clip, and each breath-hold requires preparation and respiratory adjustment. In addition, beam-on is dependent on airflow detection, which may introduce additional waiting time. In contrast, C-Rad requires patients to perform a natural breath-hold, while the optical surface monitoring system rapidly identifies the breath-hold plateau through real-time surface monitoring, potentially reducing the need for repeated breath-holds. These features suggest that C-Rad may offer an advantage in treatment-time efficiency, particularly in busy clinical settings or among patients with poor tolerance of the ABC mouthpiece.

No significant intergroup differences were observed in horizontal (X) or longitudinal (Y) errors, indicating that both techniques provided comparable positional accuracy in the left–right and craniocaudal directions after CBCT-based correction. However, vertical (Z-direction) errors were significantly larger in the C-Rad group than in the ABC group. Several factors may account for this difference. Optical surface monitoring may be less sensitive to vertical displacement than to horizontal displacement. ABC directly monitors respiratory status through airflow measurements, potentially providing greater breath-hold stability. In contrast, C-Rad relies on changes in the external body surface and may be influenced by abdominal breathing, surface deformation, and other factors. This finding is consistent with previous reports indicating that optical surface monitoring systems may have slightly lower accuracy for detecting vertical displacement than radiographic imaging techniques.

A positive correlation between Z-direction error and treatment time was observed only in the C-Rad group, suggesting that prolonged treatment may be associated with unconscious postural relaxation or respiratory drift, resulting in greater accumulated vertical displacement. The absence of a similar correlation in the ABC group may be attributable to the more stringent breath-hold triggering and monitoring provided by the ABC system. ROC analysis identified 10.93 min as the treatment-time threshold for predicting a Z-direction error > 2 mm in the C-Rad group. This finding suggests that when a single treatment fraction exceeds this duration, clinicians should be particularly vigilant for increased vertical displacement and consider mid-treatment repositioning or a repeated breath-hold, when clinically appropriate.

The two breath-hold techniques demonstrated distinct patterns of dosimetric deviation, reflecting their respective technical characteristics and potential clinical applications. Based on each patient's maximum intrafraction error, we systematically evaluated its impact on target and OAR doses. Regardless of the technique used, the maximum intrafraction error resulted in a statistically significant decrease in PTV D95% (ABC: median, – 1.13%; $P = 0.002$; C-Rad: median, – 2.90%; $P = 0.006$), whereas changes in mean heart and lung doses were not statistically significant. This finding has important clinical implications, suggesting that the primary dosimetric consequence of intrafraction errors may be a reduction in target coverage rather than substantial changes in OAR doses. This pattern may be related to the predominance of vertical (Z-axis) displacement in both groups. Vertical displacement may shift part of the target outside the intended irradiation field, thereby directly reducing target dose. Meanwhile, the heart and lungs are adjacent to the target, and their dose changes depend on the direction and magnitude of displacement. Depending on the direction of the error, portions of these OARs may move

out of or into the high-dose region, resulting in small dose increases or decreases and substantial interindividual variability. Consequently, the mean changes in OAR doses did not reach statistical significance.

From a clinical acceptability perspective, the reductions in PTV D95% did not exceed the commonly cited 5% threshold. In the ABC group, the median reduction was only 1.13%, with the largest individual reduction being approximately 2.8%. In the C-Rad group, the median reduction was 2.90%, and the largest individual reduction approached 5.8%. Although the intergroup difference was not statistically significant ($P = 0.140$), a greater proportion of patients in the C-Rad group experienced target-coverage reductions approaching 5%. This finding suggests that inadequate control of vertical displacement with C-Rad may potentially increase the risk of target undercoverage. Therefore, for patients treated using C-Rad, particular attention should be given to real-time monitoring and prompt correction of vertical intrafraction displacement, especially when treatment time exceeds 10.93 min, as indicated by the ROC analysis. Furthermore, mean heart and lung doses did not differ significantly from the planned values in either group, indicating that, under the simulated maximum-error conditions, neither technique was associated with a systematic increase or decrease in OAR doses.

5 Limitations

This study has several limitations. First, group allocation was nonrandomized, and the two groups differed in surgical type. Therefore, the results reflect the performance of each technique under current clinical practice and do not directly establish the superiority of either technique in the same patient population. Second, patients with left- and right-sided breast cancer were not analyzed separately, precluding subgroup analysis of cardiac protection in patients with left-sided breast cancer. Third, dosimetric deviations were based on treatment-planning system simulations rather than actual *in vivo* measurements, which may have introduced systematic errors. Future prospective randomized studies involving homogeneous patient populations and stratification by breast laterality are needed to directly compare error control, time efficiency, and dosimetric effects and to define the optimal indications for each technique. Fourth, the dosimetric simulations were based on each patient's "maximum single-fraction error," representing a worst-case potential risk rather than the average effect. In routine clinical practice, errors in most fractions are substantially smaller than the maximum observed error; therefore, our findings may overestimate the typical dosimetric impact. In addition, the simulations did not account for cumulative interfraction errors or the duration of intrafraction errors. Future studies could incorporate cumulative dose reconstruction or stochastic error models to provide a more refined assessment.

In conclusion, in patients receiving postoperative breast cancer radiotherapy, the ABC technique provides better control of vertical displacement, albeit with a slightly longer treatment time. For patients requiring high positional precision, this accuracy advantage may be clinically important. The C-Rad technique significantly shortens treatment time but is associated with larger vertical errors and their potential dosimetric consequences. Therefore, the choice of technique should be individualized according to the patient's need for positional precision and tolerance of the treatment procedure.

Declarations

Ethics approval and consent to participate

This study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board/Ethics Committee of Gansu Provincial Maternity and Child-Care Hospital/Gansu Provincial Central Hospital (approval number:GSFY-2024-011). All patients provided written informed consent before participating in any study-related procedure.

Consent for publication

Not applicable. This manuscript does not contain any individual person's data in any form (including individual details, images, or videos).

Competing interests

The authors declare that they have no competing interests.

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Author Contribution

H.L.J., Z.K.H., G.L.Y., M.G.Y., W.Y.T., Z.Z.C., and L.X.D. made substantial contributions to the conception and design of the study. H.L.J., Z.K.H., G.L.Y., M.G.Y., and W.Y.T. were responsible for data acquisition. H.L.J., Z.K.H., and G.L.Y. performed data analysis and interpretation. H.L.J. drafted the manuscript. Z.Z.C. and L.X.D. critically revised the manuscript for important intellectual content. All authors reviewed and approved the final version of the manuscript.

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Not applicable.

Availability of data and materials

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Figures

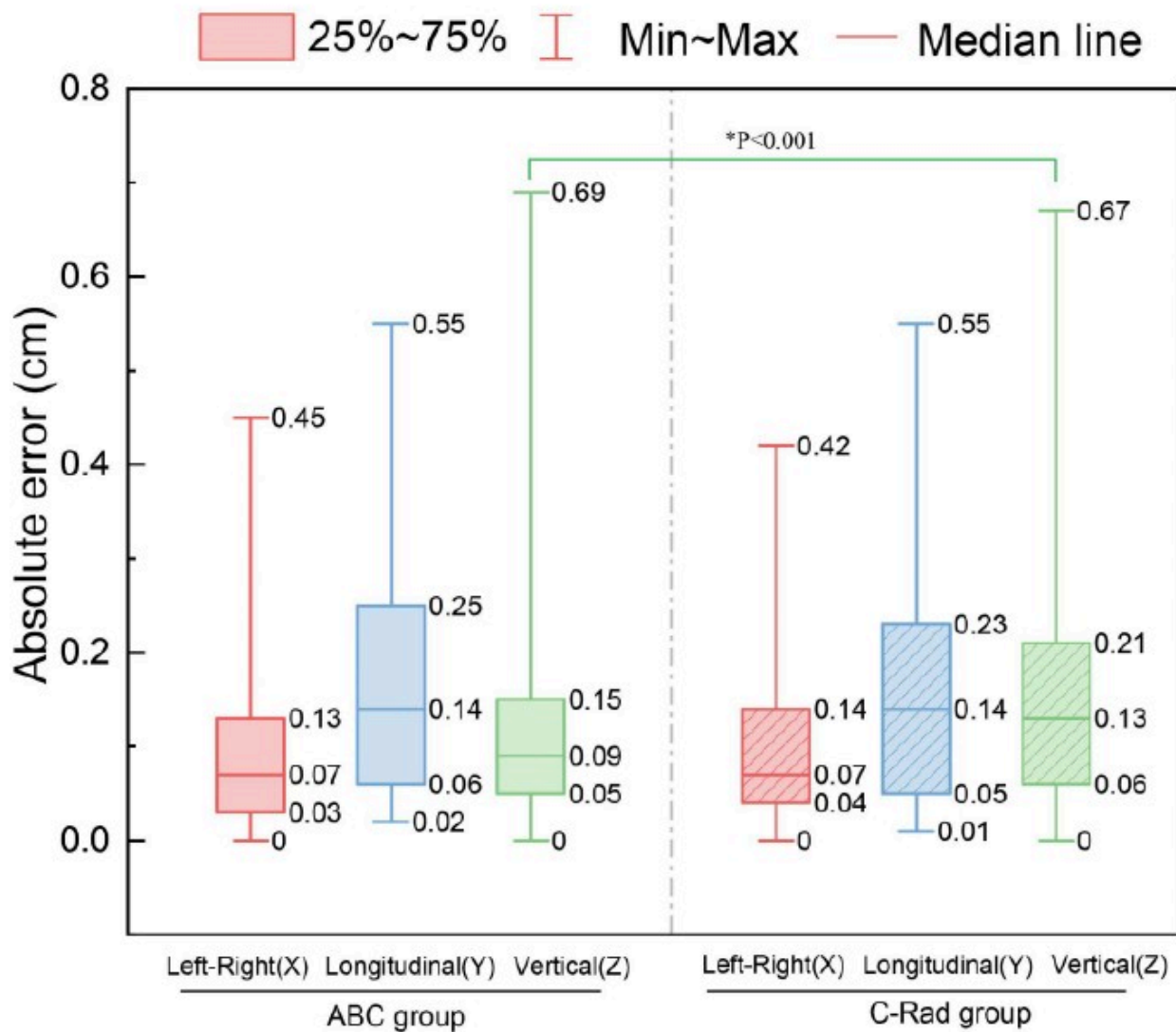


Figure 1

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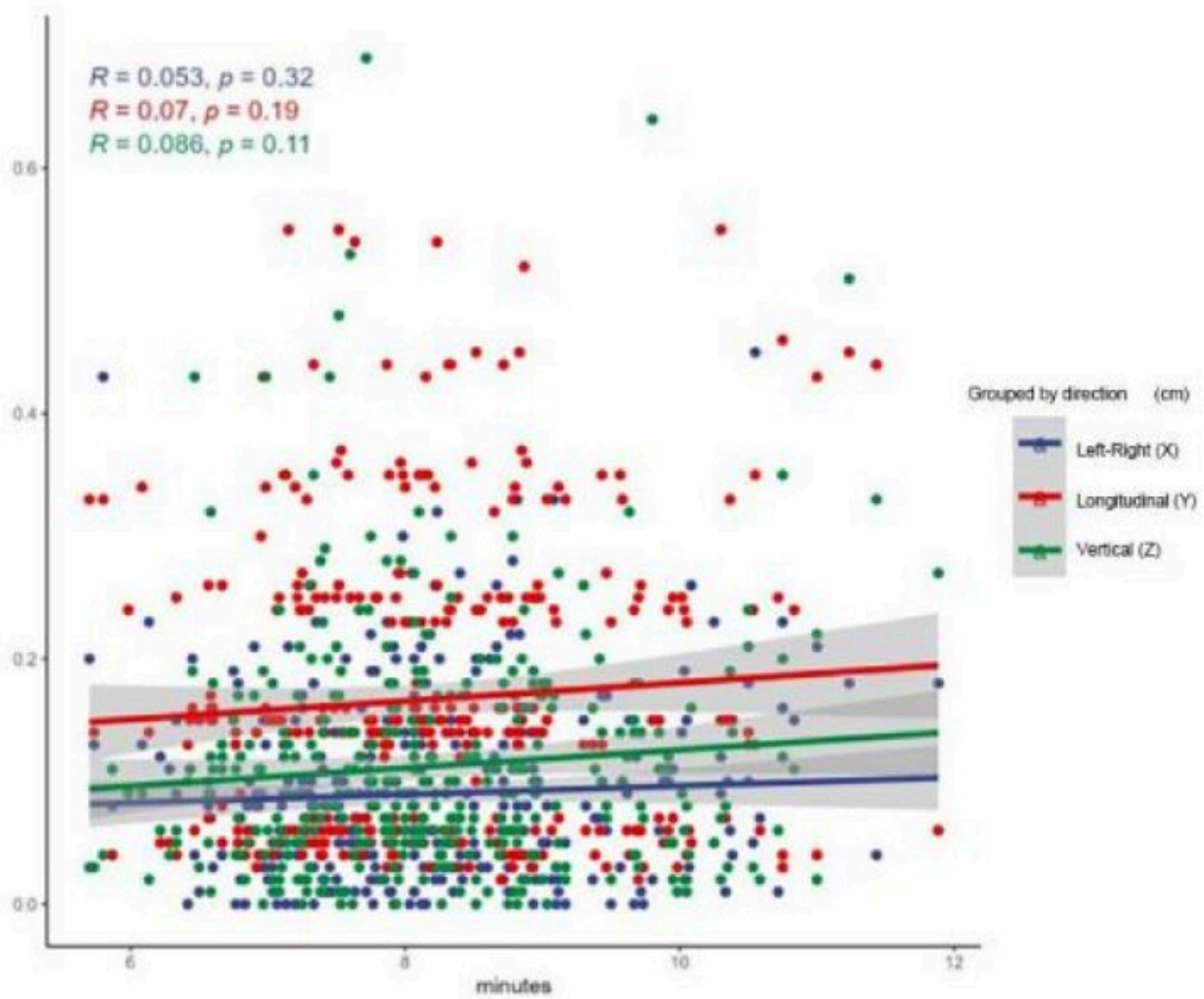


Figure 2

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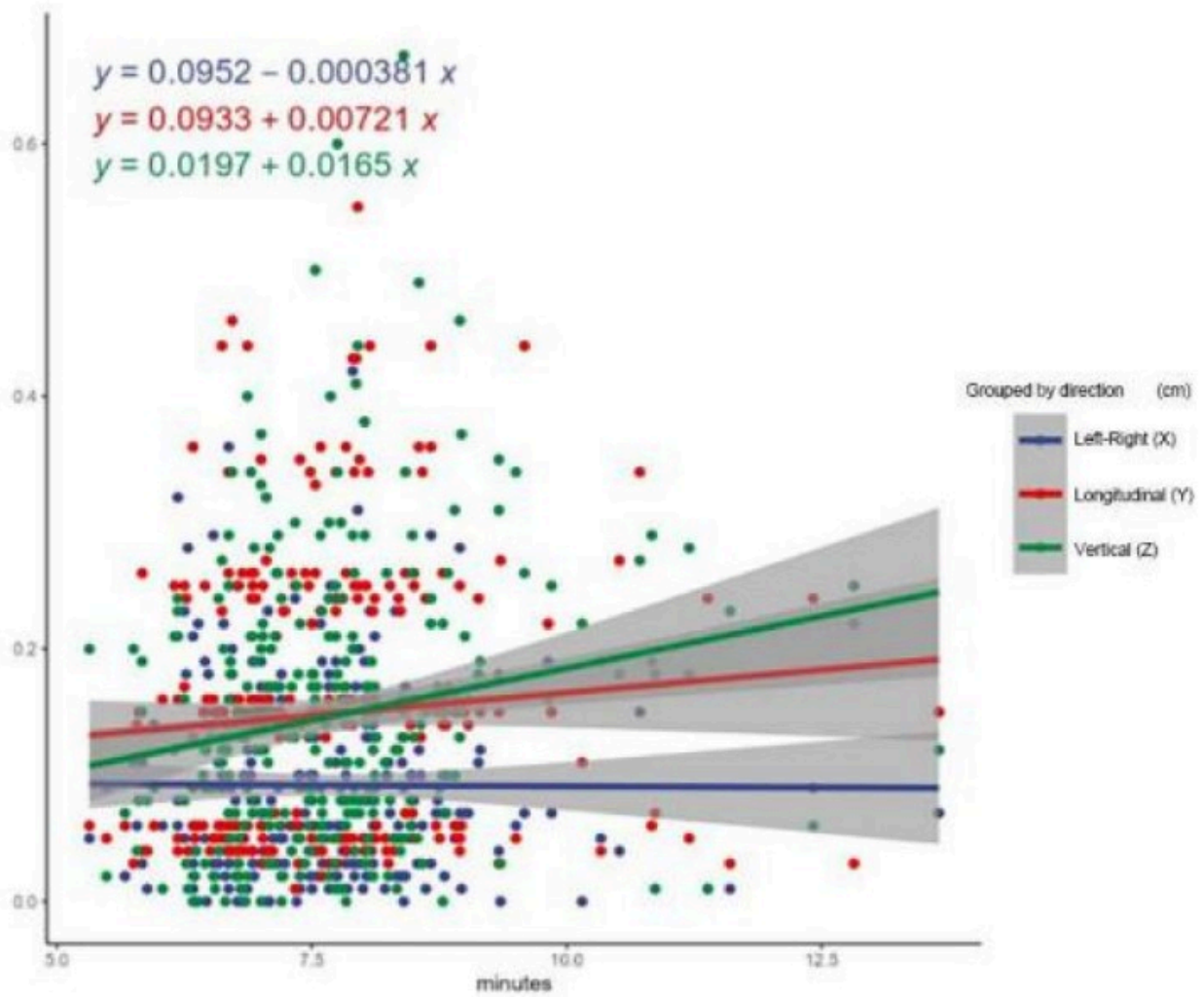


Figure 3

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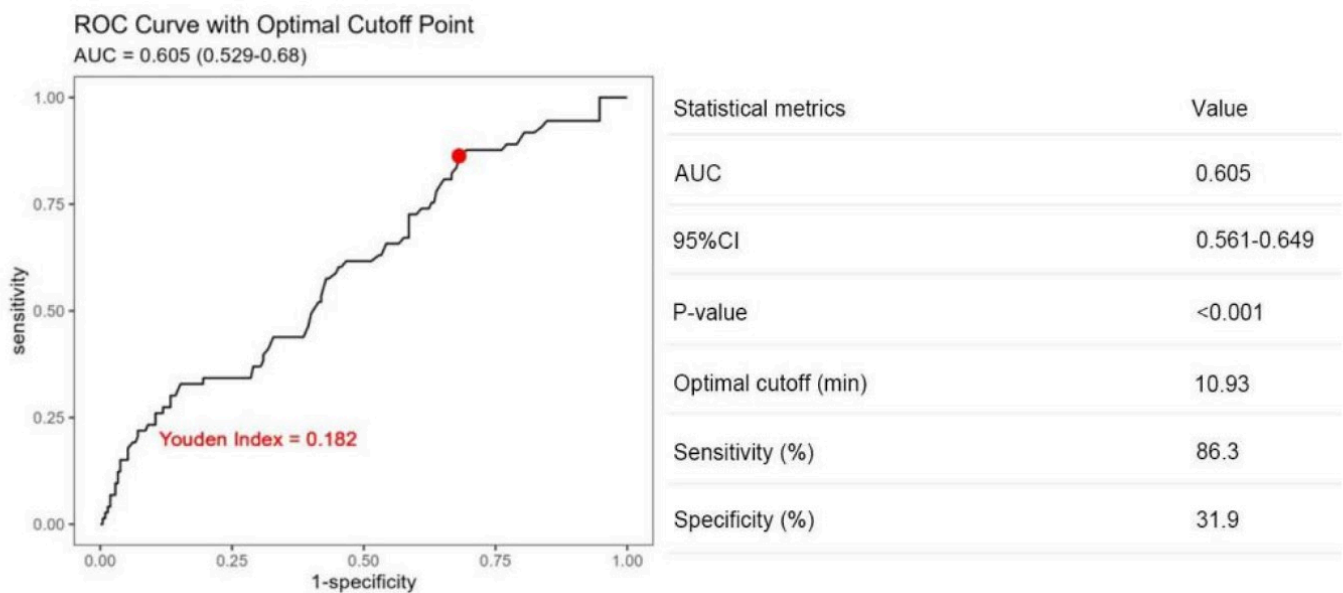


Figure 4

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