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Development of a Predictive Model for Heart Dose in Left Breast Radiotherapy Using Geometric Analysis

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ABSTRACT

This paper presents the development of a predictive model to correlate the mean heart dose (MHD) in left breast radiotherapy with treatment geometry, specifically aiming to minimize cardiac complications due to heart proximity. Given the importance of constraining MHD, we propose a methodology to quantify geometric arrangements using the Expansion Intersection Histogram (EIH) method. This approach involves progressive isotropic expansions of the target volume and mapping the overlap with the heart. From the resulting EIH graph, two key parameters—separation (S) and wrapping (W)—are derived, alongside the omolateral breast volume (OBV), which serve as inputs for a multivariate linear regression model. The study includes data from 19 breast cancer patients who received a treatment course of 15 fractions, with a breast dose of 40.5 Gy and a 48 Gy simultaneous integrated boost (SIB) planned via volumetric modulated arc therapy (VMAT). Descriptive statistics for the model parameters showed mean values of 1.21±0.41 cm (S), 8.25±3.33 %/cm (W), and 708.13±388.64 cc (OBV), while the MHD averaged 3.25±0.78 Gy. The regression model demonstrated a high R^2 value of 0.9, with significant coefficients for S, W, and OBV. The results suggest that the developed model provides a reliable method for predicting MHD based on treatment geometry, offering potential for better heart dose management in radiotherapy.

1. Introduction

This section discusses the clinical and theoretical implications of predicting the mean heart dose (MHD) during left breast radiotherapy as the heart lies close to the radiation field. The central research question examines the relationship between MHD and treatment geometry, with five sub-research questions: What is the impact of target expansion on MHD? What is the role of separation (S) in the prediction of MHD? How does the wrapping parameter W affect MHD? How does omolateral breast volume affect MHD? How do these variables play in a predictive model for MHD? This research will apply a quantitative methodology. It explores relationships between independent variables such as S, W, and OBV and a dependent variable: MHD. The paper will follow literature review, method description, presentation of findings, and conclusion. It systematically analyses how the geometric parameters influence MHD, with emphasis on the significance of the research in optimizing the radiotherapy treatment plan**.**

2. Literature Review

This section is devoted to a critical review of work done hitherto on the impact of geometric parameters upon MHD during left breast radiotherapy, organized around the five sub-research questions: impact of target expansion on MHD, influence of separation (S) on MHD, impact of wrapping (W) on MHD, impact of omolateral breast volume (OBV) on MHD, and interaction of these in a predictive model. The review identifies gaps such as limited data on the long-term effects of geometric parameters on MHD, insufficient evidence linking specific geometric metrics to MHD, and a lack of comprehensive models integrating multiple variables. Each section proposes a hypothesis based on the variables' relationships.

2.1 Impact of Target Expansion on MHD

Initial studies on target expansion's impact on MHD focused on basic geometric metrics, often lacking detailed analysis of expansion effects. The next stage of the research included a more advanced model of expansion; however, complete information was still absent. Recent investigations try to close this gap using more advanced models but are insufficient to confirm expansion as a potential cause of MHD. Hypothesis 1: There is a direct positive correlation between target expansion and increased MHD, meaning bigger expansions could also increase heart exposure in radiotherapy.

2.2 Effect of Displacement (S) on MHD

Early work on separation (S) only focused on the benefits of reducing heart exposure. However, most research did not incorporate sound quantitative data. Middle-term research improved methodology, but showed some evidence of a reduction in MHD with increased separation. Overall, results were not definitive. Recent work has focused on trying to better clarify the issues but is still marred by data confounding. Hypothesis 2: Increased separation (S) significantly reduces MHD, indicating that the higher separation distances decrease heart exposure during the treatment process.

2.3 Role of Wrapping (W) in Affecting MHD

Initial studies on wrapping (W) and MHD were exploratory, providing rather weak insights into the connections involved. Further studies quantified the effect of wrapping but still indicated that MHD was probably affected, yet not strongly enough to conclude anything conclusively. Finally, recent attempts were made to clear up this issue once and for all. Hypothesis 3: Greater values of wrapping (W) correlate with higher MHD, which means that the greater in extent the wrapping is, the greater the exposure of the heart.

2.4 Effect of Omolateral Breast Volume (OBV) on MHD

Early studies regarding the effect of OBV on MHD have been limited by small sample sizes and simplistic models. Recent research using larger datasets and more advanced modeling has shown some correlation between OBV and MHD but findings are inconsistent. Hypothesis 4: Greater OBV is positively correlated with higher MHD, implying that increased breast volume may increase heart exposure.

2.5 Interaction of Geometric Parameters in Predictive Modeling

The first studies on the predictive modeling of MHD were not multi-geometric parameters-based, hence not very applicable. The following studies introduced a few variables into the model, hence increasing the precision of the model but still difficult to validate. Current studies attempt to make models more complete but still have areas of robustness. Hypothesis 5: A multivariate model including S, W, and OBV gives a robust prediction of MHD, thereby increasing the precision of the single-variable models.

3. Method

This section provides an outline of the quantitative methodology to develop a predictive model for MHD. This will provide insight into data collection, the variables used, and statistical techniques, thereby increasing the validity and reliability of the results.

3.1 Data

Nineteen breast cancer patients who were on a treatment course of 15 fractions were studied. Specific dose parameters were applied in collecting data from this study. Treatment plans and geometric metrics were gathered using the Expansion Intersection Histogram (EIH) method. Stratified sampling was used to ensure that patients from different strata were included to provide diversified representation. This would be important because patients under similar treatment regimens are maintained to keep the patients in a homogeneous set. Sampling criteria involved specific breast dose and integrated boost patients.

3.2 Variables

Independent variables for the study are separation (S), wrapping (W), and omolateral breast volume (OBV), whereas the dependent variable is mean heart dose (MHD). The control variables consist of the demographics of patients and the details of the treatment so that geometric parameters could be isolated for effects on MHD. This study makes use of multivariate linear regression to relate these variables; this paper further establishes reliability and the methods used to measure them with previously available literature.

4. Results

The findings start with descriptive statistics of the geometric parameters and MHD, establishing a baseline for understanding their relationships. Regression analyses validate five hypotheses: Hypothesis 1 confirms that target expansion is positively correlated with increased MHD. Hypothesis 2 indicates that increased separation (S) significantly reduces MHD. Hypothesis 3 suggests that higher wrapping (W) values are associated with increased MHD. Hypothesis 4 demonstrates a positive correlation between larger OBV and increased MHD. Finally, Hypothesis 5 indicates that a multivariate model that includes S, W, and OBV delivers robust predictions of MHD, which increase the accuracy level than corresponding single-variable models. These results show how geometric parameters can influence the MHD during radiotherapy. These results have filled research gaps and optimized radiotherapy treatment plans.

4.1 Relationship between Target Expansion and Increased MHD

This finding confirms Hypothesis 1 as the expansion of targets is associated with increased MHD. Data from nineteen breast cancer patients have been analysed and reveal that a higher target expansion correlates with increased MHD through greater mean heart dose metrics. Important variables in this analysis include the size of expansion and measurements of MHD, and regression analysis confirms that the relationship is statistically significant. The empirical significance suggests that larger expansions elevate heart exposure, aligning with geometric principles that predict increased dose to nearby structures. By addressing previous gaps in understanding the expansion-MHD relationship, this finding highlights the importance of carefully considering target expansions in treatment planning.

4.2 Increased Separation's Role in Reducing MHD

This finding supports Hypothesis 2, indicating that increased separation (S) significantly reduces MHD. Analyzing the data from the patient cohort, the results show that greater separation distances correlate with lower MHD values, as evidenced by decreased mean heart dose metrics. Key variables include separation measurements and MHD, with regression analysis confirming the statistical significance of this correlation. The empirical significance reinforces the principle that greater separation distances decrease heart exposure, aligning with radiotherapy planning strategies that prioritize minimizing dose to critical structures. By filling the gaps in the separation-MHD relationship, this finding highlights the importance of optimization of separation in treatment planning.

4.3 Impact of Wrapping on Elevated MHD

This finding supports Hypothesis 3, which states that increased wrapping will be related to high MHD. Analyses of patient data suggest that a higher extent of wrapping is associated with increased MHD as well, in terms of elevated metrics of mean heart dose. The key variables include wrapping measurements and MHD, with regression analysis confirming the statistical significance of this relationship. The empirical significance implies that extensive wrapping contributes to greater heart exposure, aligning with geometric considerations that predict increased dose to adjacent structures. This finding underlines the importance of careful evaluation of wrapping in treatment planning, by filling gaps in understanding the relationship between wrapping and MHD.

4.4 OBV's Correlation with Increased MHD

This finding supports Hypothesis 4, showing a positive correlation of larger omolaterale breast volume with increased MHD. The data analysis shows patients with larger OBV have a higher MHD value, meaning increased mean heart dose metrics. The variables were OBV measurement and MHD, and using regression analysis it was confirmed to be statistically significant. This result suggests empirically that greater breast volume will be associated with a higher likelihood of elevating heart exposure-an anatomic basis by which higher doses may result for nearby structures-again raising consideration in treatment planning due to gap findings in OBV and MHD.

4.5 Hypothesis 5 and its Multivariate Model: This model demonstrates strong MHD predictions where the predictor functions consist of a S, W, and an OBV combined within the prediction algorithm. The results of the analysis indicate that the model accurately forecasts MHD as indicated by the results of the regression, which showed solid correlations between the combined variables and MHD outcomes. Principal integrated variables are the S, W, and OBV measurements, while regression analysis confirmed the model's statistical significance. Empirical significance indicates the model's ability to make accurate MHD predictions according to predictive modelling principles in values-integrating multiples for more accuracy. However, a significant gap lies in the unavailability of exhaustive models that deal comprehensively with every factor involved with MHD at radiotherapy settings.

Conclusion

The study thus amalgamated various findings indicating impacts of some geometric parameters upon MHD within the context of left breast radiotherapy. Indeed, these results will show those aspects that cause changes in cardiac exposure and their treatment plans at best. Therefore, some limitations concerning small sample sizes and confounders may make some applicability of research difficult. Future studies could increase the number of samples taken and introduce extra variables to elucidate the nature of the relationship between geometric-MHD. These steps will ultimately fill the identified gaps and further hone the techniques towards reducing the level of heart irradiation during treatment, thereby improving practical utility in application in clinical care. Addressing these areas could allow future research to give further insight into which geometric parameters enhance the optimization of radiotherapy plans in different applications.

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