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Scientific Article

Optimizing Dose Reduction to the Left Anterior Descending Artery in Patients With Locally Advanced Lung Cancer Treated With Definitive Radiation Therapy: A Feasibility Study of Coplanar Treatments Using Double-Stacked Multileaf Collimator

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Purpose: Recent studies have shown that cardiac substructures and particularly left anterior descending artery (LAD) dose strongly correlates with the incidence of late adverse cardiac events. We evaluated whether greater cardiac and, importantly, LAD dose sparing could be achieved using a newly introduced closed bore (O-ring gantry) linac with a double-stacked multileaf collimator (Varian Ethos) relative to conventional linacs.

Methods and Materials: Twenty patients with locally advanced non-small cell lung cancer previously treated with definitive chemoradiotherapy were retrospectively evaluated. Volumetric modulated arc therapy plans were retrospectively generated for the Ethos system using optimization criteria focused on reducing overall heart and LAD doses (Heart_Ethos). Plans were also reoptimized using the same optimization criteria on a conventional C-arm linac (Heart_TB). Investigational plans were compared with the original plans and with each other using standard dose-volume histogram metrics such as percentage (V) volume receiving a specific dose (x) in Gy (Vx) or mean dose (Dmean) in Gy.

Results: Statistically significant decreases existed between the Heart_Ethos and original plans for mean heart dose (11.3 vs 14.8 Gy; $P < .001$) and V5, V30, and V50 (63.6% vs 75.2%; $P < .001$, 7.1% vs 12.3%; $P < .001$, 2.1% vs 2.9%; $P = .03$, respectively) and also for LAD mean dose (4.8 Gy vs 12.0 Gy [$P < .001$]) and V15 (4.9% vs 21.5%; $P < .001$). Compared with Heart_TB, Heart_Ethos plans had significantly less mean heart dose (11.6 vs 12.2 Gy; $P = .006$), and less heart V5 (64.4% vs 67.2%; $P = .049$) and V30 (7.7% vs 8.8%; $P = .03$), whereas other parameters were not significant. Optimal target coverage and other organs at risk constraints were maintained for all generated plans.

Conclusions: Heart_Ethos plans showed significant reduction in cardiac and LAD doses in comparison to the original plans while maintaining target and organ at risk goals. Our findings suggest that Ethos technology has the potential for better cardiac toxicity safety because Heart_Ethos plans were still able to reduce cardiac dose compared with Heart_TB plans.

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Introduction

Lung cancer continues to be the leading cause of cancer death for both men and women in the United States. The most common type of lung cancer is non-small cell lung cancer (NSCLC), which comprises 80% to 85% of all lung cancer cases.[1] The prognosis for unresectable, patients with locally advanced NSCLC, who are mainly managed with definitive chemoradiotherapy, is poor with 5-year overall survival rates in the range of ~15% to 30%, with a recent improvement by the addition of immunotherapy reaching up to 43%.[2,3] Traditionally, efforts to improve outcomes for this set of patients focused on escalating the radiation therapy dose to the tumor. The best example of this is the phase 3 randomized Radiation Therapy Oncology Group (RTOG) 0617 trial, which compared a 74 Gy dose regimen with the conventional 60 Gy dose regimen with a primary endpoint of local progression.[4] Unexpectedly, patients receiving the escalated dose performed significantly worse for overall survival compared with the conventional arm with a mean survival of 20.3 months vs 28.7 months, respectively.

The data analysis indicated a correlation between cardiac dose and reduced overall survival rates. Specifically, the percentage volume of the heart receiving at least 5 Gy (V5) and 30 Gy (V30) were significant factors after adjusting for total dose and the other variables.[5] In a secondary analysis study, they also found that heart dose was correlated to quality of life at 12 months.[6] In contrast to other types of cancer such as breast cancer,[7-9] minimizing cardiac dose had not been a major focus for patients with locally advanced NSCLC because of their relatively poor prognosis. Typically, avoiding more acute toxicities such as radiation pneumonitis or acute esophagitis by minimizing lung or esophagus dose, respectively, was the focus during optimization because of the shorter expected life span of patients.[10] In RTOG 0617, the only heart constraint was to limit dose to the entire heart to < 40 Gy.[4] Based on these findings, and improved diagnosis as well as integration of new therapies such as immunotherapy,[11] there has been a renewed emphasis on investigating the relationship between cardiac dose exposure, cardiac toxicity, and patient outcomes.

Several groups have investigated whether that link between cardiac dose and overall survival could be replicated in independent groups with mixed results. Trials such as the phase III ESPATUE (ESPATUE being an acronym for Essen-Paris-Tuebingen, representing the initially planned study centers) trial[12] were not able to verify the link between cardiac dose and overall survival. However, a series of retrospective institutional studies[13-17] and meta-analyses[18] were able to support the link between cardiac dose and the incidence of grade 3 or higher Common Terminology Criteria for Adverse Events-defined major adverse cardiac events. Although mean heart dose correlated with a statistically significant increase in major cardiac events in some studies, there is evidence that rather than correlating with dose to the whole heart, the relationship between cardiac dose and adverse[19] cardiac events can be more accurately characterized by correlating dose to specific cardiac substructures. In particular, studies have indicated that dose to the left anterior descending artery (LAD) provides the strongest correlation with an increase in major adverse cardiac events.[20] In a retrospective evaluation of patients with NSCLC that had undergone radiation therapy at Stanford, it was found that an approximate 2.5 × increase in adverse cardiac events correlated with an elevated LAD V15.[21] Similarly, a Harvard study also showed that LAD V15 > 10% was an independent estimator of major adverse cardiac events and all-cause mortality.[22] Additionally, the RTOG 0617 trial data was retrospectively reanalyzed with the finding that LAD V15 > 10% was associated with an increased risk of all-cause mortality.[23]

In a previous study, we retrospectively introduced a set of radical treatment techniques that were designed on a conventional linac to avoid dose to the whole heart without compromising target coverage or increasing dose to traditional organ at risk (OAR) dose levels when compared with the original plan.[24] In this study, we evaluate whether similar cardiac dose reduction, with a specific focus on reducing LAD dose, can be achieved on plans generated using a newly introduced cylindrical bore linac design that uses a double-stacked multileaf collimator (MLC) design that can also be used for online adaptive radiation therapy.

Methods and Materials

Patients

Retrospective analysis was performed for 20 patients with locally advanced NSCLC (T3-T4, N0-N3) with central lesions treated between 2018 and 2021. This cohort was selected from the population of patients that received a significant level of heart dose (mean heart dose > 10 Gy) in their clinical treatment plans because of proximity of target to the cardiac structures. The patient population consisted of 7 men and 13 women with a median age of 70 years (range, 59-81) with either adenocarcinoma (n = 11) or squamous cell carcinoma (n = 9). Treatment site ranged from 10 left-sided (6 lower lobe and 4 upper lobe), 8 right sided (6 lower lobe, 1 upper lobe, and 1 middle lobe), and 2 mediastinal lesions. All patients underwent radiation therapy using volumetric modulated arc therapy (N = 18) or intensity modulated radiation therapy

(N = 2) to a total dose of 60 to 66 Gy in 2 Gy per fraction (30-33 fx).

Computed tomography acquisition

All patients underwent computed tomography (CT) simulation using Brilliance Big Bore (Philips Health Care) CT scanners to acquire phase-based 4-dimensional CT thorax images with 10 phases reconstructed. The following parameters were used for scan acquisition: 120 kVp, 800 mAs, 512 × 512 in-plane image dimensions, 1.17 mm × 1.17 mm in-plane resolution, and 3 mm slice thickness. The phase images were used to derive an average image that was used for treatment planning and a maximum intensity projection image to aid in contouring. A motion encompassing method was employed for target volume generation using an internal target volume (ITV) based approach. Based on individual patient characteristics, the expansion from the ITV to the planning target volume (PTV) ranged from an isotropic expansion of 0.5 cm on the low end to asymmetric expansions of 0.5 cm axially and 1 to 1.5 cm along the cranial-caudal axis.

Auto-segmentation

In other studies, newer automatic segmentation software has been used to efficiently plan for LAD dose during initial treatment planning by auto-segmenting the LAD and adding a planning organ-at-risk volume (PRV) structure.[25,26] Within our system, a commercial deep-learning based auto-contouring software (Limbus AI) is used for initial normal tissue segmentation. The LAD contours provided by the Limbus AI software was verified by comparison to the physician drawn contours using Dice similarity coefficient, Hausdorff distance, and mean distance to agreement. The LAD structure segmented by Limbus was compared with the LAD structure contoured by the physician, which was used as the gold standard.

Treatment planning

Patients were treated using plans generated in the Eclipse treatment planning system (Version 16.01.00, Varian Medical Systems). Original plans used for patient treatment used between 2 and 4 coplanar volumetric modulated arc therapy beams. The patients had been originally planned on machines at different treatment sites within the hospital system. To determine the amount of cardiac dose sparing that could be achieved using a cardiac dose optimization approach on a conventional linac, we reoptimized each patient's plan on a single Varian TrueBeam treatment machine with a Millenium 120 MLC. The 6 MV energy was used for all plans, and plans were optimized using jaw tracking with objectives iteratively selected focusing on the minimization of cardiac and LAD dose while matching the target coverage from the original plans.

Ultimately, we intended to determine whether the double-stacked MLCs used by the cylindrical bore linac design was able to reduce cardiac dose relative to that of a conventional linac. Therefore, new plans were retrospectively generated in Eclipse for the Ethos (Varian Medical Systems) linac that uses a double-stacked MLC on an O-ring gantry. A volumetric modulated arc therapy approach was used for all Ethos plans (Heart_Ethos). Plans were optimized so that the prescribed prescription isodose covered at least 95% of the target volume. In this study, the normal tissue constraints from protocol RTOG 1106-6697[27] were used, and prescribing a target dose of 60 to 66 Gy (2 Gy fxn) as per physician request. Typical criteria listed include the percent volume of a structure receiving greater than × Gy dose (V_{xGy}) and the max dose to × volume of a structure ($D_{x\%}$) in Gray (Gy). The full list of normal tissue constraints is given in Table 1. The planning strategy used was intended to reduce heart and, specifically LAD dose while maintaining target coverage and without increasing dose to noncardiac OARs. For clinical reasons, not all original plans were optimized to meet this coverage criterion. In order to minimize the effect of the difference in coverage goals between the original and Heart_Ethos plans, the Heart_Ethos plans were normalized to match the ITV D95 target coverage in the original plans as closely as possible. The resulting dose-volume histogram metrics for these Normalized Heart_Ethos plans were evaluated against the original plan.

Dosimetric differences between the Heart_Ethos and the original and Heart_TB planning strategies were compared. The Normalized Heart_Ethos results were also compared with confirm that differences between the Ethos and original plans were not because of different target coverage strategies. Conformity of the Rx isodose to the target and dose fall-off from the target were assessed using conformity index (CI = volume of Rx isodose / target volume) and gradient index (GI = volume of 50% of the Rx isodose / volume of Rx isodose), respectively. The statistical significance of the change in dosimetric measurements between each of the trial planning strategies and the original plan was assessed using a paired t test with a significance level of $P = .05$.

Results

Auto-segmentation

Calculated Dice similarity coefficient (0.3 ± 0.1) was low, and Hausdorff distance (31.1 mm ± 18.8 mm) and distance to agreement (4.9 mm ± 3.2 mm) were high.

Table 1 Comparison of organ at risk doses between the original, Truebeam, and Ethos plans

OARs	Clinical goals	Original plan Mean (SD)	Heart_TB		Heart_Ethos		
			Mean (SD)	Truebeam-original	Mean (SD)	Ethos-original	Ethos-Truebeam
Esophagus	D0.03cc (Gy) ≤ 68	51.1 (15.7)	52.6 (15.7)	1.5 (3.8)	51.6 (16.5)	0.5 (3.4)	−1.0 (2.0)*
Esophagus	D2cc (Gy) ≤ 63	43.2 (15.8)	43.8 (16.3)	0.6 (6.5)	42.8 (17.4)	−0.4 (6.5)	−1.0 (2.9)
Esophagus	Dmean (Gy) ≤ 34	19.9 (9.7)	19.8 (9.9)	−0.1 (4.6)	19.1 (10.3)	−0.8 (4.5)	−0.7 (0.9)*
Heart	D0.03cc (Gy) ≤ 70	62.4 (5.9)	63.1 (5.8)	0.8 (3.8)	62.9 (5.7)	0.5 (4.2)	−0.3 (1.2)
Heart	V5Gy (%)	75.2 (20.4)	67.2 (17.3)	−8.1 (11.1)*	64.4 (20.9)	−10.8 (13.2)*	−2.7 (5.8)*
Heart	V30Gy (%) ≤ 50	12.3 (7.1)	8.7 (5.8)	−3.6 (5.7)*	7.7 (4.7)	−4.7 (5.3)*	−1.1 (2.1)*
Heart	V50Gy (%) ≤ 25	2.9 (2.7)	2.3 (2.2)	−0.6 (1.5)	2.2 (2.2)	−0.7 (1.5)	−0.1 (0.3)
Heart	Dmean (Gy) ≤ 20	14.8 (4.2)	12.2 (3.5)	−2.6 (3.1)*	11.6 (3.5)	−3.2 (2.9)*	−0.6 (0.9)*
LAD	V15 (%) ≤ 10	21.5 (21.1)	4.8 (7.0)	−16.7 (19.5)*	3.6 (8.3)	−17.8 (18.3)*	−1.1 (6.6)
LAD	Dmean (Gy)	12.0 (6.0)	5.2 (2.3)	−6.8 (4.8)*	5.0 (2.5)	−7.0 (4.8)*	−0.2 (0.6)
Lungs-ITV	V20Gy (%) ≤ 35	22.0 (6.4)	22.4 (7.3)	0.5 (3.5)	21.7 (6.8)	−0.3 (2.7)	−0.7 (1.6)
Lungs-ITV	V5Gy (%) ≤ 65	59.4 (8.6)	61.2 (11.0)	1.8 (9.0)	57.8 (12.4)	−1.6 (9.9)	−3.3 (4.2)*
Lungs-ITV	Dmean (Gy) ≤ 20	12.7 (2.5)	13.1 (3.1)	0.4 (1.5)	12.5 (3.0)	−0.2 (1.3)	−0.6 (0.4)*
Spinal cord	D0.03cc (Gy) ≤ 45	32.3 (9.8)	29.6 (7.6)	−2.8 (5.9)*	28.6 (7.7)	−3.7 (5.8)*	−1.0 (1.0)*

Abbreviations: ITV = internal target volume; LAD = left anterior descending artery; OAR = organ at risk.
*Statistically significant difference.

Table 2 Comparison of target coverage parameters between the original, Truebeam, and Ethos plans

Targets		Original plan Mean (SD)	Heart_TB		Heart_Ethos		
			Mean (SD)	Truebeam-original	Mean (SD)	Ethos-original	Ethos-Truebeam
PTV	D95 (Gy)	58.3 (5.3)	60.5 (4.2)	2.2 (2.9)*	60.6 (4.2)	2.3 (3.2)*	0.1 (0.4)
PTV	D98 (Gy)	56.4 (5.9)	59.4 (4.2)	3.0 (4.0)*	59.5 (4.2)	3.1 (4.4)*	0.1 (0.5)
PTV	Dmax (Gy)	65.1 (4.4)	67.0 (4.3)	1.8 (2.2)*	67.2 (4.4)	2.1 (2.2)*	0.3 (0.5)
PTV	CI_{95}	0.54 (0.3)	0.89 (0.05)	0.3 (0.3)*	0.89 (0.05)	0.35 (0.29)*	0.00 (0.02)
PTV	GI	29.8 (60.9)	4.7 (0.8)	−25.1 (60.8)	4.4 (0.7)	−25.4 (60.9)	−0.3 (0.4)
ITV	D95 (Gy)	60.5 (4.0)	62.4 (4.2)	2.0 (1.2)*	62.3 (4.0)	1.9 (1.3)*	−0.1 (0.2)
ITV	D98 (Gy)	60.0 (3.9)	62.0 (4.1)	2.0 (1.4)*	61.9 (4.0)	1.9 (1.3)*	−0.1 (0.2)
ITV	Dmax (Gy)	65.0 (4.7)	66.5 (4.3)	1.6 (1.7)*	66.9 (4.3)	1.9 (1.7)*	0.3 (0.4)*

Dmax values give max dose to 0.03cc volume.
Abbreviations: CI = conformity index; GI = gradient index; ITV = internal target volume; PTV = planning target volume.
*Statistically significant difference.

One reason was that the Limbus-generated LAD structures were typically segmented more generously than the physician contoured structures. As a result, by adding a 2 mm planning organ-at-risk volume (PRV) expansion, the Dice similarity coefficient score increased to 0.5 without changing the Hausdorff distance and distance to agreement. Physician review of any automatically generated LAD structure is essential before using for dose optimization and evaluation but has the potential to increase the efficiency of initial treatment planning.

Treatment planning

Tables 1 and 2 provide a comparison of the dosimetric values between the original plan and the Heart_Ethos and Heart_TB plans for OARs and targets, respectively. The percentage difference between the value for the original plan and that of the Heart_Ethos plans is also listed in the table. As can be seen in Table 2, no statistically significant differences were observed between original and Heart_Ethos plans in terms of PTV or ITV coverage or conformity values. By contrast, the reduction in cardiac dose is clearly displayed in Table 1. The dosimetric measurements for the heart are listed at the top of Table 1 where there were statistically significant decreases between the Heart_Ethos and original plans in Heart V5, V30, and mean dose (64.4% vs 75.2% [$P < .001$], 7.7% vs 12.3% [$P < .001$], 11.6 Gy vs 14.8 Gy [$P < .001$], respectively) and LAD V15 and mean dose (3.6% vs 21.5% [$P < .001$], 5.0 Gy vs 12.0 Gy [$P < .001$], respectively). For the remaining OARs, there were no statistically significant differences except for the spinal cord, where there was a decrease in max dose to 0.35cc (28.6 Gy vs 32.3 Gy [$P = .009$]). As the plans were all normalized down, the same OAR metrics for the Normalized Heart_Ethos plans as in the Heart_Ethos plans showed a slightly larger, statistically significant decrease from the original plans (Heart V5, V30, V50, and mean dose [63.6% vs 75.2% ($P < .001$), 7.1% vs 12.3% ($P < .001$), 2.1% vs 2.9% ($P = .03$), and 11.3 Gy vs 14.8 Gy ($P < .001$), respectively], LAD V15 and mean dose [3.4% vs 21.5% ($P < .001$), and 4.8 Gy vs 12.0 Gy ($P < .001$), respectively], and spinal cord max dose to 0.35cc [27.7 Gy vs 32.3 Gy ($P = .002$)]).

Tables 1 and 2 also provide a comparison between the Heart_Ethos and Heart_TB planning strategies. As can be seen in Table 2, there is no statistically significant difference between target coverage for either PTV or ITV except for a small but clinically irrelevant increase in PTV max dose (67.2 Gy vs 67.0 Gy [$P = .029$]) and ITV max dose (66.9 Gy vs 66.6 Gy [$P < .001$]). Although there was no significant difference in CI, there was a significant decrease in the GI for the Heart_Ethos relative to the Heart_TB (4.4 vs 4.7 [$P = .006$]). The dose to the heart and LAD structures was lower in the Heart_Ethos plan for every metric, but the difference was only statistically significant for the Heart V5, V30, and Dmean (64.4% vs 67.2% [$P = .049$], 7.7% vs 8.8%, [$P = .03$], and 11.6 Gy vs 12.2 Gy [$P = .006$], respectively). As shown in Table 1, that general trend is consistent across all OARs with statistically significant decreases in esophagus (max and mean dose), lung (V5 and mean dose), and spinal cord (max dose). In Fig. 1, a comparison of the original and normalized Ethos dose distribution is shown, where the 25% (15 Gy) isodose line can be seen carving around the LAD in the normalized Ethos plan while maintaining coverage of the PTV.

Discussion

In this study, we demonstrated that in the treatment of locally advanced NSCLC tumors, a significant decrease in heart and LAD dose could be achieved on a conventional

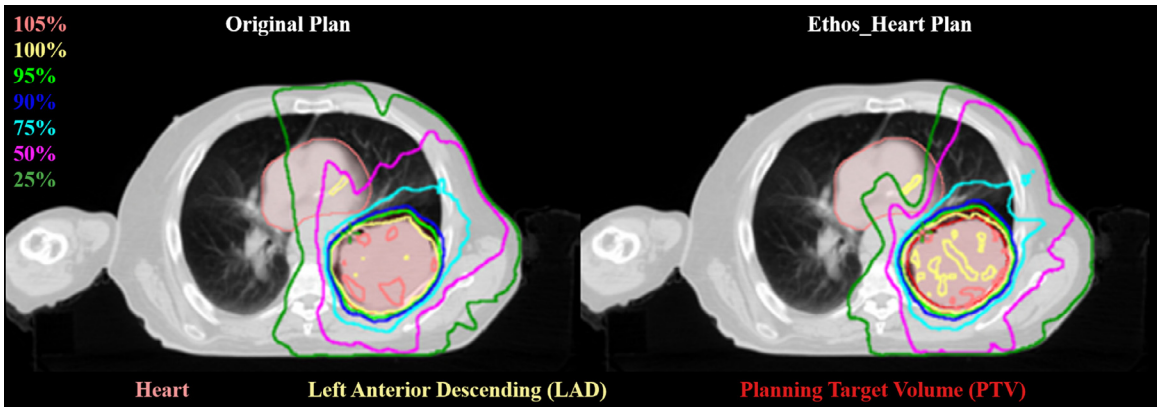

Figure 1 Comparison of the original and Ethos_Heart dose distribution for patient 6. The LAD V15Gy decreased from 63.20% to 0.1%, and the mean dose to the LAD decreased from 20.33 to 4.72 Gy, between the original and Ethos_Heart plans, respectively.
Abbreviation: LAD = left anterior descending artery.

linac relative to the original plan through the implementation of a straightforward cardiac dose optimization strategy. Additionally, Heart_Ethos treatment plans using the cylindrical bore with double-stacked MLCs compared with Heart_TB plans, had on average, lower doses to the heart and LAD, with significantly lower heart V5, V30, and Dmean doses. This reduction in heart and LAD doses was achieved while maintaining coverage, with no significant difference in CI, and maintaining OAR dose constraints when compared with both the original and Heart_TB plans. Additionally, the Heart_Ethos plans had a significantly lower GI dose than the Heart_TB plans. This indicates that even while reducing the heart and LAD doses, the plan quality could not only be maintained but also improved on. These results suggest that treatment planning in the Eclipse treatment planning system (TPS) for the Ethos platform allows for a reduction in cardiac dose for lung radiation therapy, while maintaining, if not improving, plan quality.

One probable reason for the improved dosimetric results provided from the Ethos plans is the reduced leakage from the double-stacked MLCs for the Ethos system. The Ethos platform is a jawless system that uses a primary and secondary collimator followed by 2 layers of MLCs where each leaf is 1cm thick projected at isocenter. The 2 layers are staggered to provide an effective leaf width of 0.5 cm at isocenter. Similarly to the Truebeam, leakage through the MLCs for the Ethos system in Eclipse is modeled primarily through a single intraleaf transmission factor as well as a dosimetric leaf gap intended to represent leaf tip transmission that corrects for dose uncertainties resulting from modeling the rounded leaf edges as straight ends. Nominal leaf transmission of 0.47% is consistent with commissioning measurements of transmission through a single layer and higher than the 0.01% measured through both layers. This is substantially better than transmission observed for the Millenium MLCs of around 1.5%. Similarly, the dosimetric leaf gap of 0.1 mm used for the Ethos system and confirmed by measurement is substantially lower than the ∼1.1 mm selected after measurements used for the Truebeam at our institution, indicating better leaf end modeling than in the Truebeam system.

Evidence indicates a direct association of cardiac events, which are predictive of mortality in patients with lung cancer, with cardiac radiation doses[28,29]. Additionally, recent studies show poor cardiac outcomes with cardiac substructure radiation exposure, independent of mean heart dose.[30,31] Specifically, a study of 701 patients with NSCLC showed a significant increase in major adverse cardiac events when the LAD volume receiving 15 Gy was >10%.[20] This finding was supported with a retrospective reanalysis of the data of RTOG 0617, which found an association between the LAD V15 >10% with an increased risk of all-cause mortality.[23] These studies highlight the importance of not only reducing the dose to the heart in lung radiation therapy, but also limiting the dose to the LAD. In this context, the reduction of LAD V15 on average from 21.5% to ∼5% is not only statistically significant but also large enough to be clinically meaningful. Our work, comparing Ethos treatment plans to conventional C-arm linac treatment plans, is to our knowledge, the first work evaluating Ethos's capability of reducing cardiac exposure in lung radiation therapy.

It is assumed that original plans were not generated with cardiac dose reduction specifically in mind. Additionally, there is a high level of variability for the GI (SD, 60.9) in the original plans. This was caused by 3 patients, who, in the original plans, were normalized to a higher isodose to cool dose to the OARs (specifically, the lung). As the volume of the Rx isodose was very small, the GIs became very large and sensitive to small changes in uniformity. This variability in plan quality across original

plans was not taken into consideration in the comparison of the original and Heart_Ethos plans. However, this variability in plan quality and planning strategy was mitigated in the comparison of Heart_Ethos to Heart_TB plans. Heart_TB plans were generated to reduce cardiac dose in the same manner as the Heart_Ethos plans, however, they still resulted in higher cardiac doses in comparison to those plans. Despite variability in plan quality and planning strategies in the original plans, we successfully reduced cardiac doses using Ethos compared with plans with similar target coverage and planning strategies. Limitations of this study include the sample size and uncertainties in LAD contouring. The LAD is a tubular artery supplying blood to the anterior portion of the left ventricle. It can be hard to visualize on CT images and depends on the imaging protocol used.[32] Assessment of LAD dose is challenging without verification of the accuracy of the contouring of the LAD structure. Although the LAD was not segmented in the original treatment plan, it was retrospectively manually segmented for each patient by an experienced radiation oncologist for this study.

Although cardiac doses are lowered during planning, there is still variability in the delivered dose because of interfraction and intrafraction variability. Setup uncertainties during fractionated radiation therapy have been correlated with cardiac toxicities. Specifically, 2 retrospective studies using radical radiation therapy and stereotactic body radiation therapy have shown an increased risk in cardiac toxicity with uncorrected residual setup errors in the direction of the heart and baseline shifts toward the heart after image guidance.[33,34] The increase in cardiac toxicities because of setup uncertainties may be mitigated with the use of online adaptive radiation therapy. Specifically, Ethos cone beam computed tomography images using HyperSight, may offer improved image quality to not only evaluate whole heart doses, but also cardiac substructure doses throughout online adaptive radiation therapy. Future work will include the design of a clinical protocol to reduce whole heart doses using adaptive radiation therapy on Ethos, allowing for the evaluation of the accuracy of cardiac substructure segmentation on HyperSight images. This will facilitate further work on cardiac substructure sparing in adaptive radiation therapy for patients with lung cancer.

Conclusions

In this study, planning using a cardiac dose optimization strategy with a specific focus on reducing LAD dose led to a significant reduction in cardiac dose while maintaining target coverage compared with clinically treated plans. The use of a newly introduced cylindrical bore linac design with a double-stacked, double-focused MLC was able to further reduce cardiac and other OAR doses in comparison to planning using conventional C-arm linac designs.

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