Original Article

Assessment of Organ-at-risk Sparing in Esophageal Cancer: A Comparative Dosimetric Evaluation of Hybrid, Noncoplanar, and Coplanar RapidArc Plans

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Abstract

Aim: The purpose of this study is to improve the precision of radiation treatment and sparing of organ-at-risk (OAR) in patients with thoracic esophageal cancer (EC) affecting the heart, lung, and spinal cord. To improve and personalize cancer treatment plans, it assesses the dosimetric benefits of coplanar RapidArc (RA_c), hybrid arc (RA_{Hyb}), and noncoplanar RapidArc (RA_{nc}). **Materials and Methods:** Fourteen patients with EC were chosen for our investigation from our hospital's database. RapidArc (RA) plan patients had already received treatment. Retrospectively, additional RA_{nc} and RA_{Hyb} plans were made with a prescription dose of 50.4 Gy in 28 fractions for the planning target volume (PTV). A prescription dose of 95% of PTV was used, so that three different treatment planning procedures could be compared. The cumulative dose-volume histogram was used to analyze the plan quality indices homogeneity index (HI), conformity index (CI), conformation number (CN) as well as the OARs doses to the lung, heart, and spinal cord. **Results:** In comparison to RA_c and RA_{nc} techniques, the study indicated that RA_{Hyb} plans significantly increased D95%, CI and HI; Dmax and CN did not differ substantially. In addition, compared to RA_c (lung: 16.15 ± 0.03 Gy and heart: 23.91 ± 4.67 Gy) and RA_{nc} (lung: 15.24 ± 0.03 Gy and heart 23.82 ± 5.10 Gy) plans, RA_{Hyb} resulted in significantly lower mean lung doses (15.10 ± 0.03 Gy) and heart doses (21.33 ± 6.99 Gy). Moreover, the RA_{Hyb} strategy showed a statistically significant ($P < 0.05$) lower average MU (452.7) than both the RA_c (517.5) and RA_{nc} (566.2) plans. **Conclusion:** The D95%, conformity, and homogeneity indices were better for hybrid arc plans compared to RA_c and RA_{nc} plans. They also successfully managed to reduce the lung and heart doses as well as the mean MU per fraction.

Keywords: Esophageal cancer, hybrid, noncoplanar, radiotherapy, volumetric modulated arc therapy

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Introduction

Esophageal cancer (EC) poses a significant global health challenge, ranking seventh in cancer incidence and sixth in mortality worldwide. With over 600,000 new cases and 500,000 deaths annually,[1] addressing this aggressive disease requires innovative treatment approaches. Risk factors for EC include tobacco, alcohol, spicy foods, and betel nut chewing, prevalent in the Indian subcontinent.[2] Radical resection is only possible in 20% of patients, so in these situations, radiotherapy remains the primary treatment option for the majority.[3]

For several decades, conventional radiation therapy (2DRT), usually delivered in two stages, has been the norm. Phase 2 three fields (one anterior and two posterior oblique fields), with or without wedges are used, whereas Phase 1 frequently uses parallel opposing, anterior, and posterior (AP/PA) fields. Nevertheless, the dose delivery restrictions of this 2DRT technique affect normal structures such as the heart, lung, and spinal cord, making it difficult to achieve dosage homogeneity in the target volume and comply with limitation for OAR. The challenge of increasing the local esophageal dose with 2DRT has contributed to the poor treatment success in EC, as evidenced by 5-year disease survival rate of approx 10.9%.[4]

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Recent developments in radiotherapy include the availability of multileaf collimators (MLCs) and improvements in treatment planning algorithms. The most important of these developments is intensity-modulated radiation therapy (IMRT), which stands out as a significant achievement in radiotherapy history, and as a major advance in radiation oncology and EC treatment.[5] According to numerous studies,[5-7] IMRT emerged as a revolutionary advancement in radiotherapy and offered superior dose distribution and prognosis compared to three-dimensional conformal radiotherapy (3DCRT). Despite its benefits, IMRT comes with drawbacks such as prolonged treatment times and potentially increased risks of secondary cancer development.[8] RapidArc is a type of volumetric modulated arc therapy (VMAT) representing advanced dynamic volumetric IMRT technology developed by Varian Medical Systems. It provides a dynamic MLC, gantry speed adjustment, and variable dose-rate adjustment, even during gantry movement. Renowned for its efficiency, speed, and precision, RapidArc reduces treatment times while achieving comparable dose distributions to IMRT through single or multiple arc rotations of the gantry. Recent studies have showcased the superiority of RapidArc over traditional IMRT in terms of planning target volume (PTV) conformity and minimizing doses to OARs.[9,10]

In addition, hybrid arc plans combining static and dynamic beams have shown potential for optimizing dose distribution.[11-14] When comparing these methods with traditional IMRT and VMAT designs, better dosimetric results have been shown. To enhance OAR dose sparing in the treatment of EC, noncoplanar IMRT, noncoplanar VMAT, and VMAT schemes have been suggested.[15,16] Although patients with neurological or cardiovascular diseases should be treated with caution, these strategies seek to balance PTV coverage with dose reduction to adjacent organs.[15] The feasibility and effectiveness of noncoplanar VMAT plan to achieve ideal dose distributions with few side effects were shown by Martini *et al*.[16] In this study, we conducted a dosimetric comparison of conventional RapidArc (RA_c), noncoplanar RapidArc (RA_{nc}), and hybrid arc (RA_{Hyb}) plans. The purpose of this study was to establish whether the RA_{nc} and RA_{Hyb} plans have a dosimetric advantage over the RA_c plans and find out which is optimal for EC patients.

Materials and Methods

This retrospective study was conducted in the Department of Radiation Oncology, State Cancer Institute, IGIMS, Patna, Bihar on 14 patients who were treated for thoracic EC between September 2021 and October 2023. All patients had previously received a RA_c technique plan on a TrueBeam SVC linear accelerator machine with 6MV photon beam. This machine is equipped with a 120-millennium MLC from Varian Medical Systems, Palo Alto, CA, USA. The institutional ethics committee approved this study. Patient characteristics are summarized in Table 1.

Target volume and organ-at-risk delineation

Positron emission tomography-computed tomography (PET-CT) simulation was utilized to exclude distant metastases. Patients were positioned supine with hands placed above the heads to create a thoracic mold using a uniform thermoplastic cast. CT simulation with a slice thickness of 2.5 mm was performed from C2 to L4 vertebrae. The gross tumor volume (GTV), clinical target volume (CTV), PTV, lymph nodes and OARs including the lungs, heart, and spinal cord, were delineated on the Eclipse Somavision contouring workstation version 16.0.14 according to the Radiation Therapy Oncology Group (RTOG) 0436 protocol.[17] The GTV was identified based on visible tumors or lymph nodes on CT scans, aided by fusion with PET-CT simulation images, and confirmed by a radiologist. The CTV was delineated with 3–4.5 cm superior-inferior margins and a 1.5 cm radial margin relative to the GTV. Lymph nodes were contoured

Table 1: Patient characteristics and tumor location

Patient	Age (years)	Sex (male/female)	Tumor location	PTV long axis (cm)	PTV volume (cm^3)
1	83	Male	Middle and lower one-third	18.95	525.5
2	51	Male	Middle and lower one-third	20.52	553.4
3	78	Male	Middle and lower one-third	23.93	877.3
4	51	Female	Middle and lower one-third	20.04	503.4
5	78	Female	Middle one-third	25.2	862.3
6	76	Male	Middle one-third	25.61	783.0
7	41	Female	Middle one-third	21.34	898.1
8	57	Female	Middle one-third	14.87	301.0
9	54	Female	Upper and middle one-third	20.87	699.4
10	68	Female	Upper and middle one-third	19.2	323.9
11	73	Male	Upper and middle one-third	18.24	594.8
12	63	Male	Upper and middle one-third	21.54	636.9
13	42	Female	Lower one-third	14.3	260.2
14	76	Male	Lower one-third	15.26	766.7
Mean±SD (cm)				19.99±3.57	613.28±215.33

PTV: Planning target volume, SD: Standard deviation

with 1 cm margins in all directions, considering anatomical boundaries such as lungs and bones. The PTV was defined with an additional 0.5 cm margin to the CTV, considering GTV delineation and nearby critical structures. The prescribed dose (PD) was 50.4 Gy delivered in 28 fractions with 1.8 Gy per fraction. OARs included the heart, lungs, spinal cord, liver, spleen, and trachea. Dose constraints for OARs are given in Table 2 and were used in optimization for treatment planning.

Treatment planning

Radiation therapy for RA is a novel treatment approach that involves a single 360° gantry rotation to deliver radiation to the patient. This method produces an intensity-modulated dose distribution by adjusting the gantry speed, dose rate, and MLC locations and velocities. To optimize the RA dose, an aperture-based technique is used, which considers the monitor unit (MU) weights and MLC leaf positions as optimization parameters. One hundred and seventy-seven control points are used to define the entire gantry rotation. The optimization procedure is separated into five distinct multiresolution levels (MRs) and is based on the photon optimizer (PO) algorithm (Version 16.0.1). To get to a convergent solution, the PO method uses fewer control points. Version 16.0.1 of the PO software was utilized to carry out inverse optimization for all planning strategies. The Eclipse treatment planning system (Version 16.0.14, Varian Medical System, Palo Alto, CA, USA) was utilized to build treatment plans for each patient for delivery with a Varian TrueBeam SVC linear accelerator, and the dose calculation was done using anisotropic analytical algorithm (AAA, 16.0.14).

Conventional RapidArc plan (RA_c)

The two coplanar full-arc beams in this design are oriented 181° to 179° clockwise and 179° to 181° counterclockwise, with a collimator angle (CA) of 30° and 330°, respectively.

Noncoplanar RapidArc plan

This plan also contains two coplanar full arc and one noncoplanar partial arc beam with a range of 45° to 315° and a couch rotation of 315° ± 5°, based on the spatial relationship between the PTV and OARs. The two coplanar full arcs have a CA of 3° or 357°, whereas the one noncoplanar partial arc has a CA of 45°±10°.

Table 2: Dose constraints for organ at risk used for treatment plans

PTV/OARs	Dose constraint
Combined lungs	
D_{mean}	≤20 Gy
V5 Gy	≤65%
V10 Gy	≤45%
V20 Gy	≤25%
V30 Gy	≤20%
Heart	
D_{mean}	≤26 Gy
V30 Gy	≤40%
V40 Gy	≤30%
Spinal cord	
D_{max}	≤45 Gy

PTV: Planning target volume, OARs: Organs at risk, D_{mean}: Average dose, Vxx Gy: Volume receiving xx Gy of dose, D_{max}: Maximum dose inside the organ

Hybrid RapidArc plan

To generate hybrid arc plans for the treatment of EC, this study combines two different radiation techniques: 3D-CRT and RapidArc plans. Two steps are involved in preparing the hybrid arc plans.

Step 1: (Three-dimensional conformal radiotherapy using a 10MV/15 MV photon photons)

The 3D-CRT approach makes use of a static anteroposterior beam (AP-0°) and a posteroanterior (PA-180°). To achieve a two-beam configuration that complies with the PTV with a margin of 0.5 cm, MLCs are added. 33% dose prescription is used to calculate the dose for the AP-PA beam configuration, and the plan is normalized to the target mean.

Step 2: (RapidArc using 6 MV photon beam)

The RA method makes use of two complete arc beams. The two full arc beams are rotated from 179° to 181° and from 181° to 179°, respectively. For these arcs, the CAs are 30° and 330°, respectively. The full treatment prescription dose value is set. The procedure for optimization: hybrid arc plan optimization is performed using the 3D-CRT (AP-PA) plan from Step 1 as a base dose plan. After calculating the RA plan final dose, the beam arrangement is transferred to the two complete arc RapidArc plans from Step 2 after calculating the 3D-CRT dose distribution. The MUs of the AP-PA beam are matched to those from the initial 3D-CRT plan once the final dose calculation is completed. About one-third of the treatment comes from the 3D-CRT technique, and the remaining two-third uses the RapidArc approach. This means the Hybrid plan is composed of 33% and 67% of 3D-CRT and RapidArc plans, respectively. All hybrid arc plans are normalized to deliver 100% dose coverage to 50% of the target volume (PTV). This normalization ensures that the PD is adequately delivered to the target area.

Dosimetric analysis

Cumulative dose-volume histograms (c-DVHs) based on the International Commission on Radiological Units and Measurements Report 83, 2010 were used to evaluate the dosimetric parameters of each plan. The planned objective was to provide 95% of the PD to 95% of the PTV volume, with a maximum dose (Dmax) of <110% of the PD and no more than 2% of the PTV volume receiving 107% of the PD. The quality of the plan was further assessed using the homogeneity index (HI), the conformity index (CI),[18] and the conformation number (CN);[18,19] uniformity index.[20]

CI is defined as:

CI = Volume of reference isodose (RI)/Volume of planning target volume (1)

CI is a measure of how well the PD conforms to the PTV, CI ideal value is one.

HI is defined as:

$$HI= (D_{2\%}–D_{98\%})/D_{50\%} \quad (2)$$

This index represents the difference between the dose delivered to 2% of the target volume ($D_{2\%}$) and that delivered to 98% of the target volume ($D_{98\%}$) divided by 50% of the target volume ($D_{50\%}$). HI evaluates the dose homogeneity within the PTV. A value of zero is ideal and the closer the HI is to zero, the better the homogeneity.

CN is defined as:

$$CN= (TV_{RI}/TV) \times (TV_{RI}/V_{RI}) \quad (3)$$

where, TV, TV_{RI}, and V_{RI} represents the treatment volume, the treatment volume at RI of the PD, and the total volume at RI of the PD. The RI was defined as 95% of PTV PD. The maximum value for CN is 1 which corresponds to perfect PTV coverage.

Uniformity index

It is defined as a ratio between minimum doses reached in 5% of the PTV volume (D 5%) and the minimum dose reached in 95% of the PTV volume (D 95%).

$$\text{Uniformity index (UI)} = D_{5\%}/D_{95\%} \quad (4)$$

Integral dose

It refers to the total amount of energy absorbed within an organ.[8] It is calculated using the mean organ dose (D_{mean}), mean organ volume (V_{mean}), and mean organ density (ρ_{mean}) with the formula:

$$\text{Integral dose (ID)} = D_{mean} \times V_{mean} \times \rho_{mean} \text{ (Gy-L)} \quad (5)$$

In this study, all organs have the same density (ρ =1), simplifying the calculation to:

$$ID = D_{mean} \times V_{mean} \text{ (Gy-L)} \quad (6)$$

Statistical analysis

The statistical difference between the dose–volume data for RA_c, RA_{nc}, and RA_{Hyb} was determined using a one-way ANOVA test. The mean and standard deviation (SD) of the data were displayed. The three plans were compared using Wilcoxon signed-rank tests. A significance level of $P < 0.05$ was considered statistically achievable. The Jamovi software 2.3.28 was used for all statistical analyses.

Results

The patients' characteristics and demographics are shown in Table 1. A total of 14 patients were chosen for our study including 7 male and 7 female patients. The patients' ages ranged from 41 to 83 years. The PTVs long axis had an average length of 19.99 ± 3.57 cm and a range of 14.3–25.61 cm. The volume of the PTVs varied from 260.2 and 898.1 cm^3, averaging 613.28 ± 215 cm^3. Table 3 presents the target coverage analysis for three different treatment plans (RA_C, RA_{NC}, RA_{Hyb}: 3DCRT with RapidArc). Table 3 shows the mean and SDs for various DVH parameters related to the PTV. The *P* values were reported to indicate significant differences between delivery methods.

No statistically significant difference was found between the three delivery methods (RA_C, RA_{NC}, and RA_{Hyb}) as the Dmax received by the PTV was 54.28 Gy, 54.79 Gy, and 54.42 Gy respectively ($P > 0.05$). D95% (dose received from 95% of PTV volume) was significantly higher in RA_{Hyb}, 96.85% compared to RA_c, 96.58% and RA_{nc}, 96.28%. There was no statistically significant difference in the dose received by 95% of the PTV volume among the three delivery methods ($P > 0.05$). The CI of RA_{Hyb} showed a statistically significant improvement in conformity, 0.983 compared to RA_c, 0.977 and RA_{nc}, 0.979 ($P < 0.05$). The HI of RA_{Hyb} demonstrated a statistically significant improvement in dose homogeneity, 0.079 within the PTV compared to RA_c, 0.082 and RA_{nc}, 0.088 ($P < 0.05$). No statistically significant difference was observed in the UI between the three delivery methods ($P > 0.05$). The UI values reported were 1.064 ± 0.013 for RA_c, 1.068 ± 0.011 for RA_{nc}, and 1.060 ± 0.010 for RA_{Hyb}. No statistically significant difference was observed in the CN between the three plan delivery methods RA_c versus RA_{nc} versus RA_{Hyb}, 0.857 versus 0.921 versus 0.846 ($P > 0.05$). However, the average of MUs per fraction was statistically lower in RA_{Hyb}, 452.7 compared to RA_c, 517.5 and RA_{nc}, 566.2 ($P < 0.05$).

Table 4 presents the extracted parameters comparing OAR doses, specifically focusing on the lungs and heart, obtained from the

Table 3: Average and standard deviation of the dosimetric and plan quality indices for the planning target volume and monitor unit for three different RapidArc planning schemes

PTV	RA_c, mean±SD	RA_{nc}, mean±SD	RA_{Hyb}, mean±SD	RA_c versus RA_{nc} (*P*)	RA_c versus RA_{Hyb} (*P*)	RA_{nc} versus RA_{Hyb} (*P*)
D_{max}	54.28±1.163	54.79±0.489	54.42±0.905	0.328	0.626	0.241
$V_{105\%}$ (cc)	2.44±1.86	3.23±3.32	2.57±1.42	0.246	0.411	0.815
$D_{95\%}$	96.58±0.967	96.28±0.921	96.85±0.929	0.296	0.173	0.017
HI	0.082±0.017	0.088±0.014	0.079±0.014	0.104	0.153	0.002
UI	1.064±0.013	1.068±0.011	1.060±0.010	0.622	0.678	0.190
CI	0.979±0.015	0.977±0.018	0.983±0.016	0.529	0.119	0.011
CN	0.857±0.060	0.921±0.264	0.846±0.055	0.576	0.119	0.241
MU	517.5±84.43	566.2±131.7	452.7±63.15	0.081	0.002*	<0.001

RA_c: Coplanar RapidArc, RA_{nc}: Noncoplanar RapidArc, RA_{Hyb}: Hybrid arc (three-dimensional conformal radiotherapy + Arc), D_{max}: Maximum dose, $D_{95\%}$: Dose received by 95%, SD: Standard deviation, CI: Conformity index, HI: Homogeneity index, UI: Uniformity index, CN: Conformation, MU: Monitor unit, PTV: Planning target volume

c-DVH as shown in Figure 1. Significantly V5 Gy of both lungs was 85.62% in RAHyb plan compared to RAc (89.15%)and RAnc(86.76%) , and no statistical difference was observed in RAnc versus RAHyb plan ($P > 0.05$). V10 Gy, RA_{Hyb} shows a statistically significant reduction of 60.85% compared to RA_c, 72% and RA_{nc}, 64.14% ($P < 0.01$). There was a significant difference between RA_c versus RA_{nc} (P value = 0.003) and RA_{nc} vs. RA_{Hyb} ($P < 0.001$). No significant difference was observed between RA_{nc} and RA_{Hyb} ($P = 0.217$). V20 Gy for each lung was statistically lower by 23.52% in the RA_{Hyb} plan compared to the RA_c plan, 25.51%; however, there was no statistically significant difference in V20 Gy when considering all three delivery methods together ($P > 0.05$). V30 for both lung volumes showed a statistically significant increase of 11.53% in RA_{Hyb} plan compared to RA_c, 10.01% and RA_{nc}, 9.94% ($P < 0.001$). The mean of the RA_{Hyb} plan resulted in a statistically significant reduction in the mean lung dose of 15.10 Gy compared to RA_c, 16.15 Gy and RA_{nc}, 15.24 Gy with $P < 0.01$. The ID for the lungs showed a statistically insignificant increase in ascending order for $RA_{Hyb} < RA_{nc} < RA_c$.

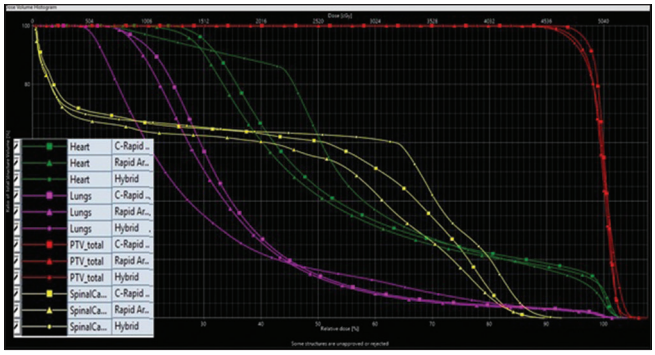

Figure 1: The dose–volume histogram comparison for planning target volume and various organs at risk between conventional arc (RAc), noncoplanar arc (RAnc), and hybrid (RA_{Hyb}) Arc plans

Heart V30 Gy resulted in a statistically significant increase of 33.92 Gy in the RA_{Hyb} plan compared to RA_c, 27.82 Gy and RA_{nc}, 28.38 Gy ($P < 0.001$). The Heart V40 Gy showed a statistically significant increase of 18.85 Gy in the RA_{Hyb} plan compared to RA_c (17.31 Gy) and RA_{nc} (17.54 Gy) ($P < 0.01$). No statistically significant difference in V40 Gy was observed between the RA_c and RA_{nc} plans ($P > 0.05$). The mean heart dose in the RA_{Hyb} plan demonstrated a statistically significant increase to 26.25 Gy compared to RA_c (23.91 Gy) and RA_{nc} (23.82 Gy) ($P < 0.001$). There was no statistically significant difference in the mean heart dose between the RA_c and RA_{nc} plans ($P > 0.05$). The ID for hearts was $1.128 \pm 0.419 \times 10^4$ (Gy-L) for RA_c, $1.132 \pm 0.456 \times 10^4$ (Gy-L) for RAn_c, and $1.254 \pm 0.468 \times 10^4$ (Gy-L) for RA_{Hyb}, respectively, with no statistically significant difference.

There was no statistically significant difference between the three delivery methods (RA_c, RA_{nc}, and RA_{Hyb}) for the Dmax (44 Gy, 45.35 Gy, and 44.28 Gy, respectively) received by the spinal cord ($P > 0.05$).

Discussion

Dose escalation was found to improve survival in the RTOG94-05 trial; however, the study was constrained by the investigator's use of standard 2DRT techniques, which resulted in greater doses being delivered to nearby OARs.[21] In EC, local failures and residual disease present persistent therapeutic problems that this study was intended to address. This study compared RA_{Hyb} plans with RA_c and RA_{nc} plans to examine the dosimetric characteristics of these treatment options for esophageal malignancies. Compared to RA_c and RA_{nc} plans, the results showed that RA_{Hyb} plans significantly

Table 4: The comparison of different dose levels between conventional and noncoplanar and hybrid RapidArc plan for various organs at risk

OARs parameters	RA_c, mean±SD	RA_{nc}, mean±SD	RA_{Hyb}, mean±SD	RA_c versus RA_{nc} (P)	RA_c versus RA_{Hyb} (P)	RA_{nc} versus RA_{Hyb} (P)
Both lung						
V5 Gy (%)	89.15±12.1	86.76±13.19	85.62±14.85	0.032	0.014	0.625
V10 (%)	72±16.97	64.14±18.98	60.85±16.64	0.003	<0.001	0.217
V20 Gy (%)	25.51±9.66	23.75±9.57	23.52±10.01	0.011	0.217	0.761
V30 Gy (%)	10.01±5.87	9.947±6.15	11.53±6.06	0.442	<0.001	<0.001
D_{mean} (Gy)	16.15±0.03	15.24±0.035	15.10±0.037	0.004	0.011	1
ID (Gy-L) × 10^4	3.95±1.19	3.66±1.11	3.63±1.18	0.822	0.789	0.997
Heart						
V30 Gy (%)	27.82±8.75	28.38±8.78	33.92±9.77	0.442	<0.001	<0.001
V40 Gy (%)	17.31±6.39	17.54±6.62	18.85±6.68	0.484	0.002	0.003
D_{mean} (Gy)	23.91±4.67	23.82±5.10	26.25±4.89	0.625	<0.001	<0.001
ID (Gy-L) × 10^4	1.128±0.419	1.132±0.456	1.254±0.468	0.991	0.772	0.783
Spinal cord						
D_{max} (Gy)	44.0±5.47	45.4±3.12	44.28±4.15	0.174	0.114	0.671

RA_c: Coplanar RapidArc, RA_{nc}: Noncoplanar RapidArc, RA_{Hyb}: Hybrid arc (three-dimensional conformal radiotherapy + Arc), D_{mean}: Mean dose, SD: Standard deviation, Vxx: XX Gy dose received by % of the volume, Gy-L: Gray-liter, ID: Integral dose

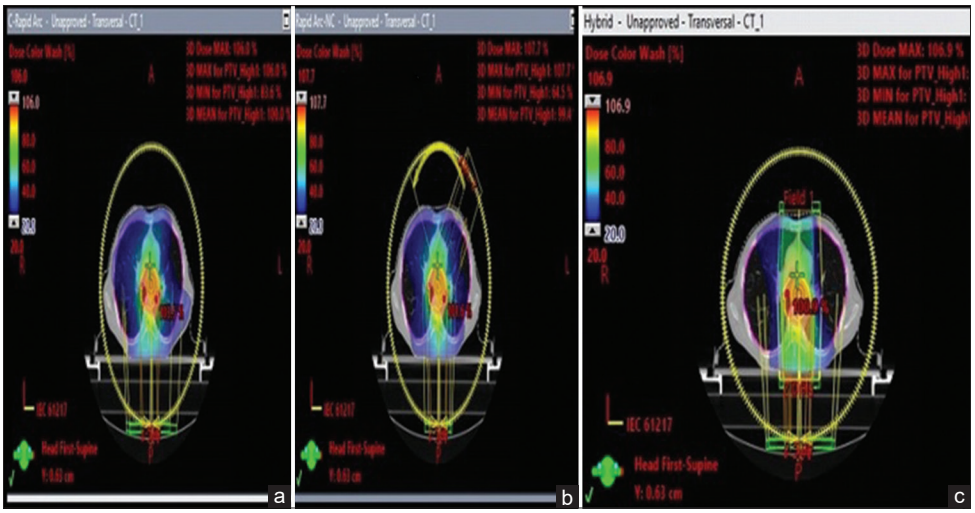

Figure 2: The maximum dose to 20% color dose wash comparison between (a) conventional arc (RAc), (b) noncoplanar arc (RA_{nc}), (c) hybrid (RAHyb) treatment plans for one of the patients

improved dose conformance, homogeneity, and PTV coverage as shown in Figure 2. However, as shown in Figure 3a, RA_{nc} plans had a higher CN value than both RA_c and RA_{Hyb} plans, whereas the difference was not statistically significant. RA_{Hyb} shows the better uniformity of doses compared to RA_c and RA_{nc} treatment plans. In addition, from Figure 3b, average MUs of the Hybrid plan (RA_{Hyb}) were significantly lower than those of the RA_c and RA_{nc} plans. Scatter dose is directly related to MU, resulting in higher MU in a treatment plan with more scattered dose to the surrounding healthy tissue. In our study, the RA_{Hyb} plan shows the 25% and 14% less MU compared to RA_{nc} and RA_c treatment plans, respectively.

When evaluating treatment regimens for EC, pulmonary toxicity represents a significant problem that shows the need for dose restrictions for both lungs. Comparing the results of many studies is difficult since different, contradictory measures have been used for predicting pulmonary toxicity.[22,23] In this investigation, measures including V10 Gy, V20 Gy, and V30 Gy were used to assess pulmonary toxicity. According to M. V. Graham *et al*.,[24] a total lung V20 Gy of 25% indicates a minimal risk of pneumonitis. On the other hand, Asakura *et al*.[25] found that radiation pneumonitis during radiotherapy for EC is significantly more likely when the V20 Gy is higher than 37%. Furthermore, a correlation between Dmean values in the lungs and pneumonitis was found,[26] with suggested values ranging from 20 to 23 Gy. Tonison et al reported that their institutional data for esophageal cancer showed no patient with a V5 Gy greater than 71% developed grade 2 or higher pulmonary toxicity.[27] Milano data analysis revealed that the suggested ranges for Dmean and V30 Gy were 10–20 Gy and 10%–15%, respectively. Moreover, keeping V20 Gy below 25%–30% was associated with a lower risk of late Grade 3 toxicity, to < 5%–10%.[28] As illustrated in Figure 4a, the lung dosimetric parameters in our investigation were within the limits indicated by the Milano data for toxicity evaluation.

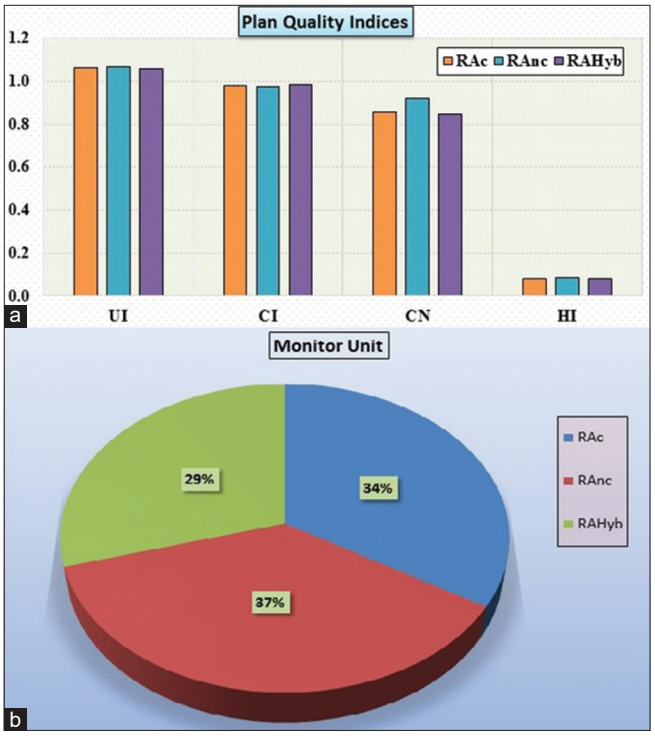

Figure 3: (a) Shows the comparison of various plan quality indices and (b) shows the monitor unit for conventional arc (RAc), noncoplanar arc (RAnc), and hybrid (RA_{Hyb}) arc plans

Pneumonitis on RT for lung lesions is associated with a higher incidence of V5 Gy of >65%, according to I.Y. Jo *et al*.[29] The maximum V5 Gy was achieved by the RA_c plan (89.15%), followed by the RA_{nc} (81.8%) and hybrid plan (85.62%). While RA_c and RA_{nc} planning techniques provide improved target dose painting capabilities, they also expose a large lung volume to a large number of low doses of radiation. Figure 5a shows the comparison of ID between RA_c, RA_{nc}, and RA_{Hyb} for lungs. RA_{Hyb} plans exhibited the lowest ID values for the lungs. A 9.30% increase in ID was

observed for the lungs in RA_c plans compared to RA_{Hyb} treatment plans.

The significant incidence of radiation-induced cardiac damage at doses higher than 40 Gy has been reported in a number of studies, highlighting the significance of lowering V40 Gy to minimize cardiac toxicities. Strong correlations between V30 Gy exceeding 33% and Dmean exceeding 20 Gy and different grades of myocardial effusion in IMRT for EC were shown by Pao *et al*.[26] In addition, the results of their analysis showed that cardiac effusion Grade 3 or higher could be significantly predicted when V30 Gy exceeds 65% and V40 Gy exceeds 55%. Wei *et al*.[30] reported that the retention of cardiac effusion following chemotherapy-radiation therapy for esophageal cancer was associated with V30 Gy of 46% and Dmean of less than 26 Gy. According to our analysis, the RA_{Hyb} exhibits higher mean doses to the heart compared to both the RA_c and RA_{nc} plans. In contrast to RA_c and RA_{nc} plans, RA_{Hyb} also results in a statistically significant increased V30 Gy and V40 Gy for the heart. This increase in heart doses is due to the inclusion of AP-PA 3DCRT beam into the hybrid RA planning. In spite of this, in all plans, we have achieved a heart mean dose of less than 26 Gy, V30 Gy, and V40 Gy of <30%. In contrast to the RA_c plans, the RA_{nc} plans in our study resulted in somewhat better dose distribution, except for the heart and spinal cord. This is mainly due to the constraints imposed by the noncoplanar arc beams. For the spinal cord, the National Comprehensive Cancer Network Guidelines propose a dose limit of no more than 45 Gy. At total spinal cord doses of 50 Gy, 60 Gy, and 69 Gy, respectively, Kirkpatrick *et al*.[31] showed that myelopathy rates were 0.2%, 6%, and 50% with standard fraction doses of 2 Gy per day. As illustrated in Figure 4b, our investigation sustained a maximum spinal cord exposure of 45 Gy and found no statistically significant variations. Figure 5b shows the comparison of ID between RA_c, RA_{nc}, and RA_{Hyb} for the heart. RA_{Hyb} plans exhibited the highest ID values for the hearts among RA_c and RA_{nc}. A 12.51% increase in ID was observed for the hearts in RA_{Hyb} plans compared to RA_c treatment plans.

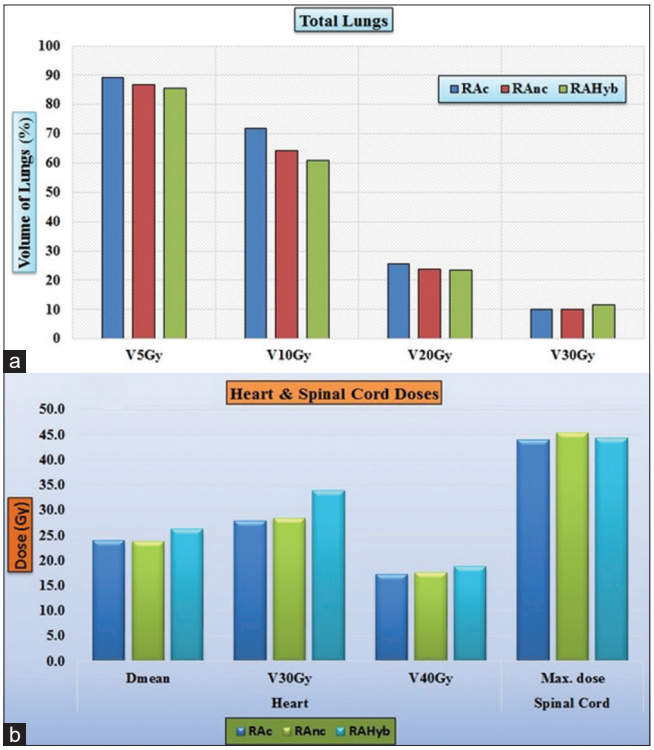

Figure 4: (a) Compares various dose–volume parameters for the lungs, and (b) compares the heart and spinal cord between conventional arc (RA_c), noncoplanar arc (RA_{nc}), and hybrid arc (RA_{Hyb}) plans

Conclusion

Compared to RA_c and RA_{nc} plans, hybrid arc plans demonstrated better dose coverage, homogeneity, lower mean lung doses, and lung volume reduction at low doses such as V5 Gy, V10 Gy, and V20 Gy. In addition, each fraction uses fewer MUs. Based on these findings, hybrid arc planning can potentially reduce radiation toxicity and improve treatment outcomes for EC. Complete integration of the hybrid arc plan into clinical practice requires additional study and clinical validation.

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Nil.

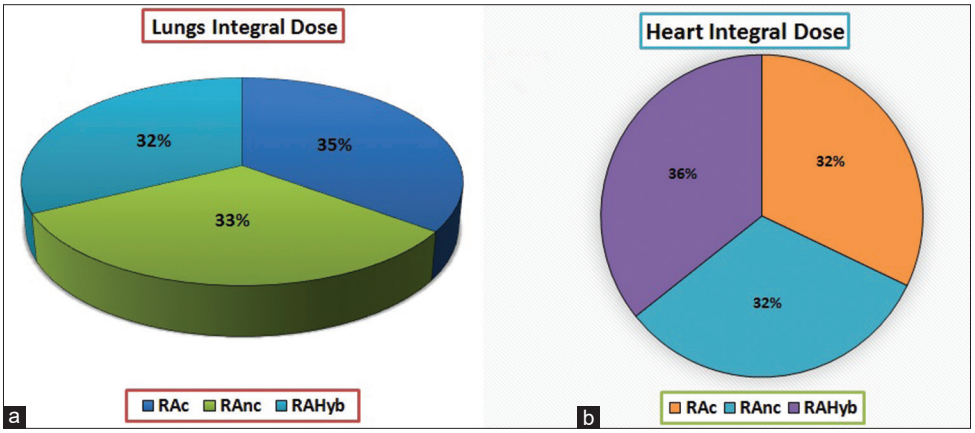

Figure 5: (a) Compares the integral dose distribution for the whole lung, whereas (b) compares the integral dose distribution for the heart between conventional arc (RAc), noncoplanar arc (RAnc), and hybrid arc (RAHyb) plans

Conflicts of interest

There are no conflicts of interest.

References

1. Sung H, Ferlay J, Siegel RL, Laversanne M, Soerjomataram I, Jemal A, *et al*. Global cancer statistics 2020: GLOBOCAN estimates of incidence and mortality worldwide for 36 cancers in 185 countries. CA Cancer J Clin 2021;71:209-49.
2. Phukan RK, Ali MS, Chetia CK, Mahanta J. Betel nut and tobacco chewing; potential risk factors of cancer of oesophagus in Assam, India. Br J Cancer 2001;85:661-7.
3. Hao Q, Kailiang W. Practical Radiotherapy for Thoracic Tumors. China: Shanghai Fudan University press; 2006. p. 271-409.
4. Cooper JS, Guo MD, Herskovic A, Macdonald JS, Martenson JA, Al-Sarraf M, *et al*. Chemoradiotherapy of locally advanced esophageal cancer: Long-term follow-up of a prospective randomized trial (RTOG 85-01). Journal of Clinical Oncology 2003;21:2204-2210. Available from: https://doi.org/10.1200/JCO.2003.10.021.
5. Xu D, Li G, Li H, Jia F. Comparison of IMRT versus 3D-CRT in the treatment of esophagus cancer: A systematic review and meta-analysis. Medicine (Baltimore) 2017;96:e7685. doi: 10.1097/MD.0000000000007685.
6. Saroj DK, Ghosh G, Shukla S, Yadav S, Paliwal N. Dosimetric Evaluation of Various Radiation Therapy Treatment Techniques for Carcinoma Esophagus: A Treatment Planning Study. Turkish Journal of Oncology/Türk Onkoloji Dergisi 2022;37.
7. Palma D, Vollans E, James K, Nakano S, Moiseenko V, Shaffer R, *et al*. Volumetric modulated arc therapy for delivery of prostate radiotherapy: Comparison with intensity-modulated radiotherapy and three-dimensional conformal radiotherapy. Int J Radiat Oncol Biol Phys 2008;72:996-1001.
8. Saroj DK, Yadav S, Paliwal N, Haldar S, Jagtap A, Kumar A. Assessment of treatment plan quality between flattening filter and flattening filter free photon beam for carcinoma of the esophagus with IMRT technique. J Biomed Phys Eng 2023;13:227-38.
9. Wu Z, Xie C, Hu M, Han C, Yi J, Zhou Y, *et al*. Dosimetric benefits of IMRT and VMAT in the treatment of middle thoracic esophageal cancer: Is the conformal radiotherapy still an alternative option? J Appl Clin Med Phys 2014;15:93-101.
10. Vivekanandan N, Sriram P, Kumar SA, Bhuvaneswari N, Saranya K. Volumetric modulated arc radiotherapy for esophageal cancer. Med Dosim 2012;37:108-13.
11. Mayo CS, Urie MM, Fitzgerald TJ, Ding L, Lo YC, Bogdanov M. Hybrid IMRT for treatment of cancers of the lung and esophagus. Int J Radiat Oncol Biol Phys 2008;71:1408-18.
12. Chan OS, Lee MC, Hung AW, Chang AT, Yeung RM, Lee AW. The superiority of hybrid-volumetric arc therapy (VMAT) technique over double arcs VMAT and 3D-conformal technique in the treatment of locally advanced non-small cell lung cancer – A planning study. Radiother Oncol 2011;101:298-302.
13. Verbakel WF, van Reij E, Ladenius-Lischer I, Cuijpers JP, Slotman BJ, Senan S. Clinical application of a novel hybrid intensity-modulated radiotherapy technique for stage III lung cancer and dosimetric comparison with four other techniques. Int J Radiat Oncol Biol Phys 2012;83:e297-303.
14. Abbas AS, Moseley D, Kassam Z, Kim SM, Cho C. Volumetric-modulated arc therapy for the treatment of a large planning target volume in thoracic esophageal cancer. J Appl Clin Med Phys 2013;14:4269.
15. Li Y, Liu B, Zhai F, Yang Y, Liu M, Bao C, *et al*. Dosimetric study of coplanar and non-coplanar intensity-modulated radiation therapy planning for esophageal carcinoma. Int J Med Phys Clin Eng Radiat Oncol 2013;2:133-8.
16. Martini S, Arcadipane F, Strignano P, Spadi R, Contu V, Fiandra C, *et al*. Volumetric modulated arc therapy (VMAT) in the treatment of esophageal cancer patients. Med Oncol 2018;35:150.
17. Ilson DH, Moughan J, Suntharalingam M, Dicker A, Kachnic LA, Konski AA. RTOG 0436: A phase III trial evaluating the addition of cetuximab to paclitaxel, cisplatin, and radiation for patients with esophageal cancer treated without surgery. J Clin Oncol 2014;32:15.
18. Hodapp N. The ICRU Report 83: Prescribing, recording and reporting photon-beam intensity-modulated radiation therapy (IMRT). Strahlenther Onkol 2012;188:97-9.
19. Van't Riet A, Mak AC, Moerland MA, Elders LH, van der Zee W. A conformation number to quantify the degree of conformality in brachytherapy and external beam irradiation: Application to the prostate. Int J Radiat Oncol Biol Phys 1997;37:731-6.
20. Hsieh CH, Liu CY, Shueng PW. Comparison of coplanar and noncoplanar intensity-modulated radiation therapy and helical tomotherapy for hepatocellular carcinoma. Radiat Oncol 2010;5:40. doi:10.1186/1748-717X-5-40.
21. Minsky BD, Pajak TF, Ginsberg RJ, Pisansky TM, Martenson J, Komaki R, *et al*. INT 0123 (Radiation Therapy Oncology Group 94-05) phase III trial of combined-modality therapy for esophageal cancer: High-dose versus standard-dose radiation therapy. J Clin Oncol 2002;20:1167-74.
22. Allehyani SH, Sharyan HA, Tolba AR. 3DCRT versus RapidArc in terms of iso-dose distribution, dose volume histogram (DVH) and organs at risk for esophageal cancer (EC) dosimetric study. AJECR 2017;5:123-33.
23. Zhang Y, Wang H, Huang X, Zhang Q, Ren R, Sun R, *et al*. Dosimetric comparison of TomoDirect, helical tomotherapy, VMAT, and ff-IMRT for upper thoracic esophageal carcinoma. Med Dosim 2019;44:167-72.
24. Graham MV, Purdy JA, Emami B, Harms W, Bosch W, Lockett MA, *et al*. Clinical dose-volume histogram analysis for pneumonitis after 3D treatment for non-small cell lung cancer (NSCLC). Int J Radiat Oncol Biol Phys 1999;45:323-9.
25. Asakura H, Hashimoto T, Zenda S, Harada H, Hirakawa K, Mizumoto M, *et al.* Analysis of dose-volume histogram parameters for radiation pneumonitis after definitive concurrent chemoradiotherapy for esophageal cancer. Radiother Oncol 2010;95:240-4.
26. Pao TH, Chang WL, Chiang NJ, Lin CY, Lai WW, Tseng YL, *et al*. Pericardial effusion after definitive concurrent chemotherapy and intensity modulated radiotherapy for esophageal cancer. Radiat Oncol 2020;15:48.
27. Tonison JJ, Fischer SG, Viehrig M, Welz S, Boeke S, Zwirner K, *et al*. Radiation pneumonitis after intensity-modulated radiotherapy for esophageal cancer: Institutional data and a systematic review. Sci Rep 2019;9:2255.
28. Lee S, Cao YJ, Kim CY. Physical and Radiobiological Evaluation of Radiotherapy Treatment Plan [Internet]. Evolution of Ionizing Radiation Research. InTech; 2015. Available from: http://dx.doi.org/10.5772/60846.
29. Jo IY, Kay CS, Kim JY. Significance of low-dose radiation distribution in development of radiation pneu monitis after helical-tomotherapy-based hypofractionated radiotherapy for pulmonary metastases. J Radiat Res 2014;55:105-12.
30. Wei X, Liu HH, Tucker SL, Wang S, Mohan R, Cox JD, *et al*. Risk factors for pericardial effusion in inoperable esophageal cancer patients treated with definitive chemoradiation therapy. Int J Radiat Oncol Biol Phys 2008;70:707-14.
31. Kirkpatrick JP, van der Kogel AJ, Schultheiss TE. Radiation dose-volume effects in the spinal cord. Int J Radiat Oncol Biol Phys 2010;76:S42-9.