

Stereotactic Body Radiotherapy in Ultra-Central Lung Tumors using Radixact-X9 Tomotherapy with Artificial Intelligence based Synchrony Technology: An Institutional Experience

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Abstract

Background: Stereotactic Body Radiation Therapy (SBRT) is presently the most effective modality of treatment for early-stage, locally advanced and oligometastatic Non-Small-Cell Lung Carcinoma (NSCLC). SBRT offers ultra-hypofractionation radiation with proven superiority over Conventional Fractionation Radiation Therapy (CF-RT) by delivering high tumoricidal dosage to cancer cells through very compact target margins compared to CF-RT thus reducing life-threatening Adverse Effects/events (AE) and long-term toxicities in surrounding critical tissues/ Organs at Risk (OARs).

Materials and methods: Lung cancer RT is challenged by the continuous movement of tumors caused by respiration. Conventional SBRT relies on breath holding techniques causing patient discomfort, static treatment plans which often require large Internal Target Volume (ITV) margins to compensate for motion, thereby increasing radiation exposure to Proximal Bronchial Tree (PBT), healthy lung and heart tissues. This is of utmost importance especially in Ultra-Central Lung Tumors (UCLT) which are typically hilar or mediastinal lymph-node (LN) metastasized from a primary lung lesion. SBRT for UCLT is a highly challenging modality throughout the world as it poses unique safety considerations compared to Central (CLT) and Peripheral Lung Tumors (PLT). The Synchrony® real-time motion management system, integrated with Radixact® Tomotherapy platform, addresses this problem by combining fiducial-free tracking with internal imaging. Artificial Intelligence (AI) plays a central role in enabling accurate, adaptive tumor targeting. From January 2024 to December 2025, total 21 lung tumor cases including 14 primary and seven secondary metastatic cases were treated at our institute; 12/21 (57.14 %) were PLTs, 06/21 (28.57 %) were CLTs and 03/21 (14.28 %) cases were UCLTs.

Results: We hereby present our cases of UCLTs with successful clinical implementation and institutional experience of delivering SBRT lung with excellent clinical and radiological outcomes through the novel real-time motion tracking and correction system using dynamic binary Multi-Leaf-Collimator (MLC) and jaws with helical RT delivered by Artificial Intelligence (AI) based Synchrony® system on Radixact-X9® Tomotherapy; Accuray, Inc® by combining fiducial-free external LED marker tracking with internal imaging.

Conclusion: Synchrony® overcomes the challenges of delivering SBRT in UCLTs by accurately tracking tumor motion internally and externally in real time, adjusting radiation beamlets dynamically with irregular breathing patterns, thus omitting patient's breath hold or treatment interruption as seen during conventional and traditional breath holding techniques. Tomotherapy with Synchrony® results in improved patient comfort, shorter treatment times, better sparing of healthy tissues/OARs and higher target precision.

Keywords: Stereotactic Body Radiation Therapy; Non-Small Cell Lung Carcinoma; Ultra-Central Lung Tumor; Helical; Tomotherapy; Synchrony

Introduction

The Lungs are a very common seeding site for many primary tumors mostly from the colon, rectum, lung, head and neck, breast and kidney. Due to its ablative effect and high tumor control rates, Stereotactic Body Radiotherapy (SBRT) has emerged as a potential alternative to traditional surgical approach in patients with lung tumors. Available evidence in form of case control studies, population-based studies have shown equivalence between sub-lobar resection and SBRT, indicating that SBRT when performed by a trained and experienced team should be offered to all high-risk patients. SBRT is crucial for treating early primary cancer and oligometastatic disease, with the goal of inducing complete cancer remission in both. As appropriate patient selection is a major issue, today's challenge is to determine conditions where SBRT can improve Progression-Free Survival (PFS) and Overall Survival (OS), thus impacting overall prognosis. Chaudhuri, et al., first coined the term Ultra-Central Lung Tumors (UCLT) for lesions directly abutting the central airway structures like trachea and Proximal Bronchial Tree (PBT) [1]. Tekatli, et al., defined UCLT as tumors where RT Planning Target Volume (PTV) overlaps trachea or main bronchi, while Daly, et al., described UCLTs as lesions with PTV overlapping PBT or esophagus [2,3]. Central Lung Tumors (CLT) are located within 2 cm of the PBT and/or abutting mediastinal pleura while Peripheral Lung Tumors (PLT) are located > 2 cm from the PBT and trachea. Due to the critical location of UCLTs surgery may result in high morbidity or even mortality, with SBRT being the most viable choice albeit with high chances of serious radiation induced AEs [4]. Ultra-central location along with mobility of the tumor with respiratory motion further demands the need of highly precise and highly conformal SBRT technique with pin-point accuracy to prevent RT induced severe toxicities like fatal pneumonitis and hemoptysis [5,6]. These cases explore our clinical experience, methodology and outcomes in implementing this cutting-edge technique especially for UCLT using AI-based Synchrony® technology integrated with Radixact-X9® Tomotherapy Accuray Inc®, an advanced helical RT platform with real-time tumor tracking and motion correction without *in-situ* fiducial implantation. We used 60 Gy in 8 fractions for all UCLT cases which were nodal targets known to be associated with higher risk of bronchopulmonary hemorrhage [7]. This method resulted in increased precision, enhanced safety and most importantly improved patient comfort as compared to conventional SBRT techniques.

Stereotactic Body Radiotherapy (SBRT) Cases Description

Case 1

A 70-years-old male was evaluated for severe cough and breathlessness in our Out-Patient Department (OPD). Whole body Positron Emission Tomography (WB-PET) scan showed 4.5 x 3.8 cm lung mass Left Upper Lobe (LUL) with Standardized Uptake Value (SUV) 19.6 with nodal metastasis. Lung biopsy showed NSCLC adenocarcinoma. Next-Generation Sequencing (NGS) showed Anaplastic Lymphoma Kinase (ALK) positive, Tumor Protein p53 (TP53) positive and Programmed Death Ligand-1 (PDL1) 40%. Patient was advised Ceritinib, however he did not comply due to financial constraints. Started on weekly palliative chemotherapy paclitaxel and carboplatin. WB-PET after six cycles of chemotherapy showed resolution of the primary lung lesion, FDG avid hypodense 1.1 x 0.83 cm left pulmonary ligament LN with increased SUV and size compared to earlier scan suggestive of (s/o) oligo-progression. The left pulmonary ligament LN was targeted with SBRT dose 60 Gy/8 fractions. Three months post SBRT patient had significant symptomatic relief. WB-PET scan showed Complete Metabolic Resolution (mCR) of the left pulmonary ligament LN.

Case 2

A 75-years-old male with co-morbidities of HTN, COPD, DM-2 and CAD, presented with persistent cough, breathlessness. WB-PET showed lesion 53 x 60 x 58 mm (SUV 14.2) Right Upper Lobe (RUL), multiple FDG avid nodular opacities in LUL. Multiple pre-carinal, peri-hilar and sub-carinal LNs were seen. Lung biopsy revealed adenocarcinoma. NGS showed PDL-1 positive, combined positive score (CPS Score) 80%. Received three weekly Pembrolizumab 200 mg 12 cycles. WB-PET showed resolution of right lung mass and left lung nodules but with persistent FDG avid mediastinal LN measuring 1.4 x 1.0 cm SUV 18 s/o oligo-progression. He was treated with SBRT to the UCLT using 60 Gy/8 fractions and was continued on Pembrolizumab post SBRT. WB-PET scan three months post SBRT showed mCR of the mediastinal UCLT. Patient experienced no episodes of cough or hemoptysis.

Case 3

A 6- years-old lady presented with cough, breathlessness and hemoptysis. WB-PET showed a FDG avid lesion RUL 3.2 x 3.0 cm (SUV 16.8), multiple nodules with low FDG uptake in left lung and sub-centimetric mediastinal LNs. Lung biopsy was s/o squamous cell carcinoma. Patient refused to do any NGS panel due to financial limitations. Started on palliative chemotherapy paclitaxel and carboplatin. WB-PET scan after four cycles of chemotherapy showed complete resolution of RUL mass and left

lung nodules but increase in size and FDG uptake of mediastinal LNs 1.8 x 1.2 cm SUV 12.4. She received SBRT 60 Gy/8 fractions to the largest mediastinal LN. Post SBRT patient was continued on chemotherapy. Four months post SBRT, WB-PET scan showed mCR of the mediastinal disease, however developed new onset vertebral metastasis. Patient had low back ache but no episode of cough, fever or hemoptysis.

Patient Simulation and Treatment Planning

Immobilization of patients were achieved using vaclok bag in the supine position, with arms overhead. No breath holding instructions were given to patient and a free-breathing Computed Tomography scan (CT) with 1.25 mm slice thickness was acquired using a 16-slice scanner to avoid motion blur. WB-PET scans were co-registered with the planning CT for precise target delineation using rigid registration tools. Treatment planning was performed using the Accuray Precision® Treatment Planning System (TPS), with a field width of one cm, dynamic jaw and Tomo-Helical mode for high-resolution dose shaping. The Gross Tumor Volume (GTV) was outlined on sequential axial CT images using the lung window. PTV was prescribed with a 5 mm expansion to GTV. Full PBT was contoured as per Radiation Therapy Oncology Group (RTOG) guidelines.

Synchrony® Model and Monitoring

Synchrony is like an AI driven automatic pilot for RT. It monitors a patient's breathing pattern, knows the tumor position within the lungs, moves the radiation beam/ beamlets to match the tumor's motion in real time. The patient just has to breath normally without holding their breath. The rationale for Synchrony® simulation is to evaluate stability of the patient's breathing pattern, visibility of the tumor on radiographs and suitable imaging angles and model parameters. Respiratory external Light-Emitting Diode (LED) markers were attached to patient surface over the xiphisternum where maximum respiratory motion can be detected by a respiratory camera array fixed on the ceiling. Using mMGavoltage CT scans (MVCT) for alignment and radiographs from four gantry angles (15°, 105°, 186°, 285°), a motion model was built to correlate external breathing signals to internal tumor movement (Fig. 1). Image registration is performed to align the patient's real-time imaging data with the reference planning images, ensuring accurate tracking of tumor position throughout respiration and treatment delivery by matching live kV images with reference Digitally Reconstructed Radiographs (DRR) from the planning CT to accurately correlate external surrogate motion with internal tumor position. Following image registration, the Synchrony® system constructs a respiratory motion model using real-time tracking data from respiratory cycle and 2D-radiographic imaging (Fig. 2). Once Synchrony® tracking is enabled; the binary Multi-Leaf-Collimators (MLCs) and jaws dynamically synchronize with the patient's respiratory motion, allowing the radiation beam to be accurately delivered in real time according to the tumour's position.

LED Marker Tracking and Artificial Intelligence

LED marker tracking provides a continuous respiratory signal, which Synchrony correlates with tumor motion from kV imaging, allowing the Tomotherapy system to adapt beam delivery in real time for precise lung tumor treatment. LED markers placed on the patient's chest or abdomen provide a non-invasive, continuous respiratory signal. Infrared cameras track these markers with high temporal resolution, capturing breathing cycles without additional radiation dose. However, external motion alone does not perfectly represent tumor motion, especially in the lung. AI algorithms establish and continuously refine a correlation between external LED signals and internal tumor position, measured intermittently with kV radiographs. This correlation model enables the system to predict tumor location in real time, compensating for system latency, adapt to irregular breathing patterns, such as pauses, sighs or coughing, detect drift or mismatches between external and internal motion, prompting recalibration when necessary (Fig. 3).

Prescription and Dose Delivery

SBRT dose 60 Gy/8 fractions (7.5 Gy/fraction) was delivered using 6MV Flattening Filter Free (FFF) beams with average beam-on-time of seven minutes per session. A Tracking Tumor Volume (TTV) was defined within the PTV, allowing Synchrony® to lock onto the internal target throughout the respiratory cycle to make tracking more successful. The system automatically pauses treatment if the predicted tumor position deviates beyond tolerance (>2 mm). If excessive patient movement or internal drift occurs (e.g., coughing), a new model is built mid-treatment using rapid imaging and verification. Synchrony® ensures precise beam delivery using MLCs (for X/Z axis) and dynamic jaws (for Y-axis) to follow tumor motion. SBRT dose constraints were based on SUNSET and EORTC Lung-Tech trial [8] which were achieved in all three cases (Table 1) [4].

S. No	OAR	Median Dose Achieved	
		Mean	Max
1	Esophagus	Mean	5.13 Gy
		Max	36.84 Gy
2	PBT	Mean	10.93 Gy
		Max	39.8 Gy
		D0.33 cc	35.45 Gy
		D0.2 cc	37.2 Gy
		D1cc	30.11 Gy
3	Trachea	Mean	0.45 Gy
		Max	1.57 Gy
		D0.2cc	1.33 Gy
		D1cc	1.03 Gy
4	Great vessels	Max	61.99 Gy
5	Heart	Mean	35.3 Gy
		Max	38.57 Gy
		V4	33.50%
		V5	16.70%
6	Lung (combined)	Mean	2.59Gy
		V5	1.20%
		V20	16.80%
7	Spinal cord	Max	14.17 Gy

OAR: Organ at Risk
PBT: Proximal Bronchial Tree
Vx: Volume of the organ receiving at least x% of the prescribed dose
Dx: x cc volume of organ receiving at least x Gy radiation dose

Table 1: Median OAR dose constraints achieved in all three cases.

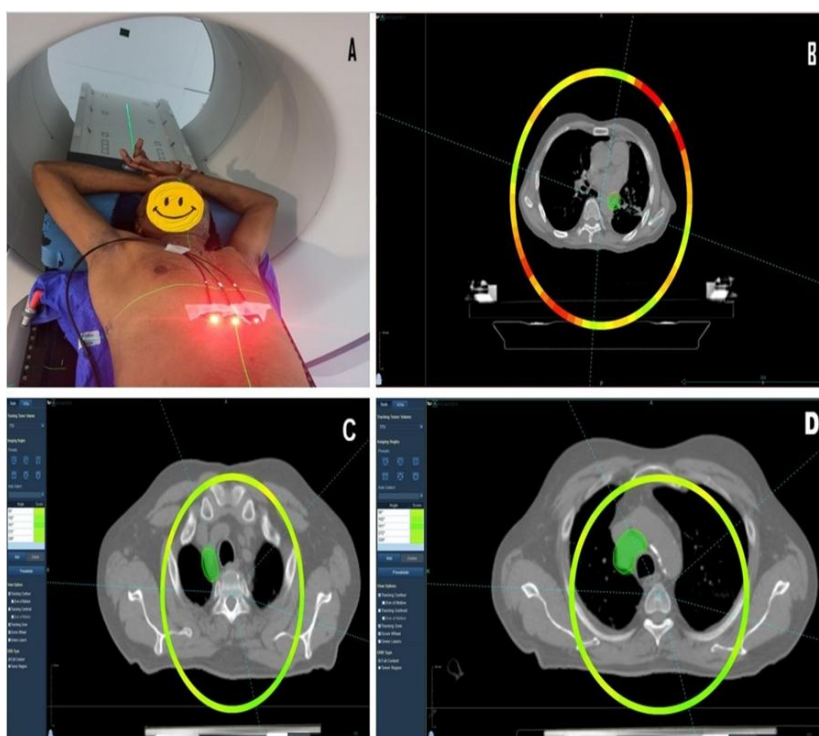


Figure 1: (A) Fiducial-free external LED marker tumor tracking; (B), (C), (D) Score-wheel display indicating tracking accuracy of the target with colour coding representing agreement between predicted and measured positions in all three cases.

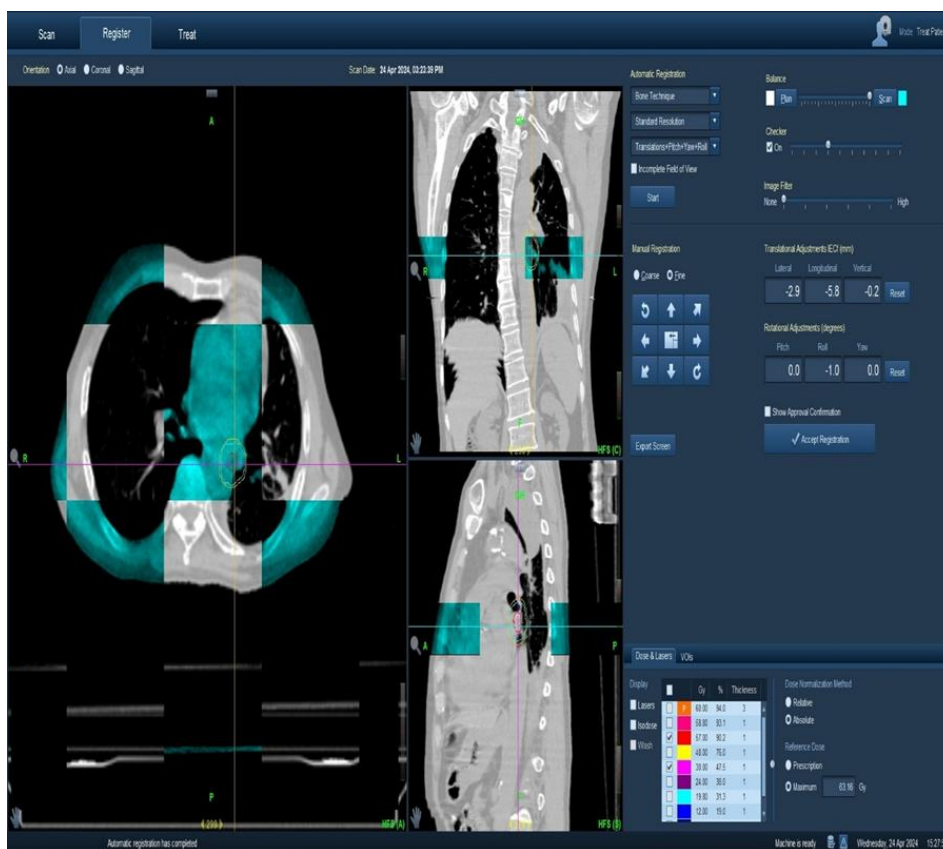


Figure 2: Image registration step in the Radixact Synchrony work flow, aligning planning CT with treatment images to ensure accurate target positioning before irradiation.

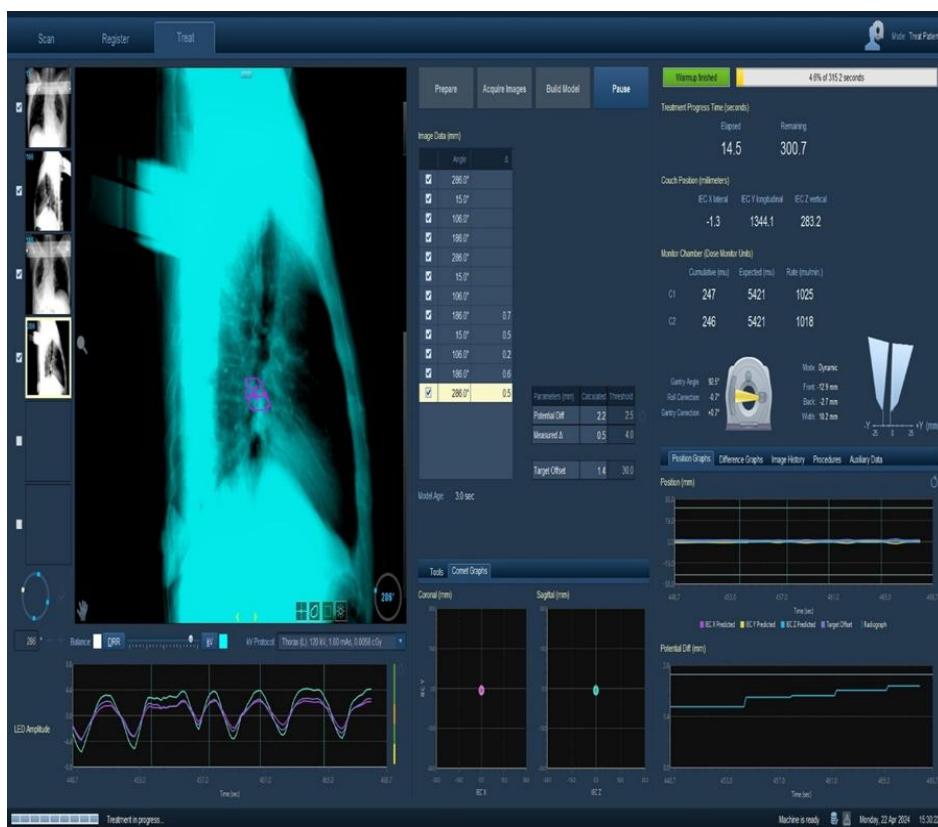


Figure 3: Treatment-time display of Synchrony showing real-time tumor tracking and respiratory motion management during irradiation.

Discussion

Stereotactic Body Radiation Therapy (SBRT) is an image-guided radiation technique that delivers high radiation doses with high precision to small target volumes in lesser number of fractions than Conventional Fractionation Radiation Therapy (CF-RT) while minimizing radiation exposure to non-targeted tissue or nearby critical structures. Motion management is of utmost importance in lung SBRT, taking the breathing cycle into account in planning and delivery of radiation in order to lower treatment-related toxicity as amplitude of lung movements is greatest in cranio-caudal direction and can sometimes exceed 2 cm. For UCLT cardiac induced motion can exceed respiratory motion due to large inter patient variability. Targets in proximity to the central airway and mediastinal structures pose increased risks due to dose tolerances of Organs at Risk (OAR) especially PBT substructures and nearby airway anatomy. Techniques like 4DCT is crucial for planning but does not manage motion during treatment [9], abdominal compression, Deep Inspiration Breath-Hold (DIBH), optical surface imaging systems and Active Breathing Coordinator (ABC) require patient's active co-operation, cause discomfort for an already compromised lung status plus longer treatment delivery time. Synchrony overcomes these limitations by tracking tumor motion internally and externally in real time, adjusting the radiation beam continuously and dynamically, without interrupting treatment or requiring patient breath control. The most common dose-fractionations used in lung SBRT are 50 Gy/5 fractions (PLT), 60 Gy/8 fractions (CLT, UCLT) and 60 Gy/12 fractions (CLT, UCLT) with Biological Effective Dose (BED10) ranging from 52.5-180 Gy, although the optimal dose-fractionation regimen for UCLT is still unknown [4,6,8,10]. For UCLT 60 Gy/8 fractions administers slightly higher effective tumor control dose ($\alpha:\beta=10$) but with slightly lower BED for late effects ($\alpha:\beta=3$), whereas 60 Gy/ 12 fractions offer much lower risks of late AEs albeit with much lower chances of long-term disease control [11]. The RTOG-defined "no-fly-zone" comprising the 2 cm radius of the trachea, PBT and mediastinum based on the extremely high-grade AEs observed in phase-II HILUS trial using 56 Gy/8 fractions and the Indiana University trial which used 60-66 Gy/3 fractions [6,12-14]. The HILUS trial reported 15% grade-5 toxicity, which could be attributed to Dmax in PTV reaching 150 % with prescription isodose line at 67 %. with large 15 mm PTV margin [6,15]. This study highlighted the importance of keeping PTV margins as low as possible with permissible PTV confined hot-spot up-to 120% apart from increasing number of fractions and reducing dose per fraction to reduce SBRT induced AEs especially in UCLT [4,10].

RT induced AEs are classified as acute (≤ 3 months from RT completion) like cough, dyspnea, esophagitis, hemoptysis and late (>3 months) like bronchospasm, bronchial stenosis, bronchopulmonary and endobronchial hemorrhage, bronchial-esophageal fistula, radiation pneumonitis and respiratory failure. Common Toxicity Criteria (CTC) and Common Terminology Criteria for Adverse Events (CTCAE) versions have been employed in various studies to determine the grades of AEs (1-5) as per increasing severity with grade-5 being death. Most studies on conventional Linear Accelerator (LINAC) based SBRT for UCLT have reported grade 3-4 toxicities with radiation pneumonitis being the commonest while bronchopulmonary hemorrhage with hemoptysis resulting in grade-5 deaths primarily due to overlapping of large PTV with PBT and less superior respiratory motion management techniques [4,14]. Several studies have also shown that larger PTV volumes have been associated with lower one-year local control (LC) rates as low as 54% [14].

With Synchrony® we achieved optimal PTV coverage and OAR constraints by keeping high BED of 105 Gy (EQD2=87.50 Gy) and smaller PTV by delineating the TTV. TTV was contoured separately over the visible tumor along the GTV to make tracking more successful. Synchrony® utilizes TTV instead of ITV to track the lesion in real time free breathing to match the prescription target volume/PTV or a structure that has the same center/ centroid. After achieving optimal matching of TTV centroid, PTV was further reduced (up to 3 mm) compared to initial PTV (5 mm). GTV was adequately covered with 100% prescribed dose while PTV received 80%. We achieved V95 95.60%, V90 97% and max dose of 62.79 Gy (104.65%) which was less than 105% confined within tumor resulting in no hot-spots. We achieved median PBT Dmax 39.8 Gy (EQD2₍₃₎ 87.55Gy), D0.2 cc 37.2Gy (EQD2₃ 82.168 Gy) and D1 cc 30.11 Gy (EQD2₍₃₎ 66.50 Gy) compared to PBT Dmax 59.2-140.4 Gy (EQD2(3) 123.1-291.8 Gy), D0.2 cc 36.8-132.2 Gy (EQD2(3) 76.6-274.3 Gy) and D1cc 27.2-109.9 Gy (EQD2(3) 56.6-228.0 Gy) in HILUS-trial and other studies with grade-5 hemoptysis [14]. We achieved median PBT BED (3) 145.93 Gy as per International stereotactic radiosurgery society guidelines of PBT BED (3) < 150 Gy [6,14,15]. Our patients experienced symptomatic relief and attained mCR (Fig. 4) suggestive of excellent LC without experiencing any acute or late AEs.

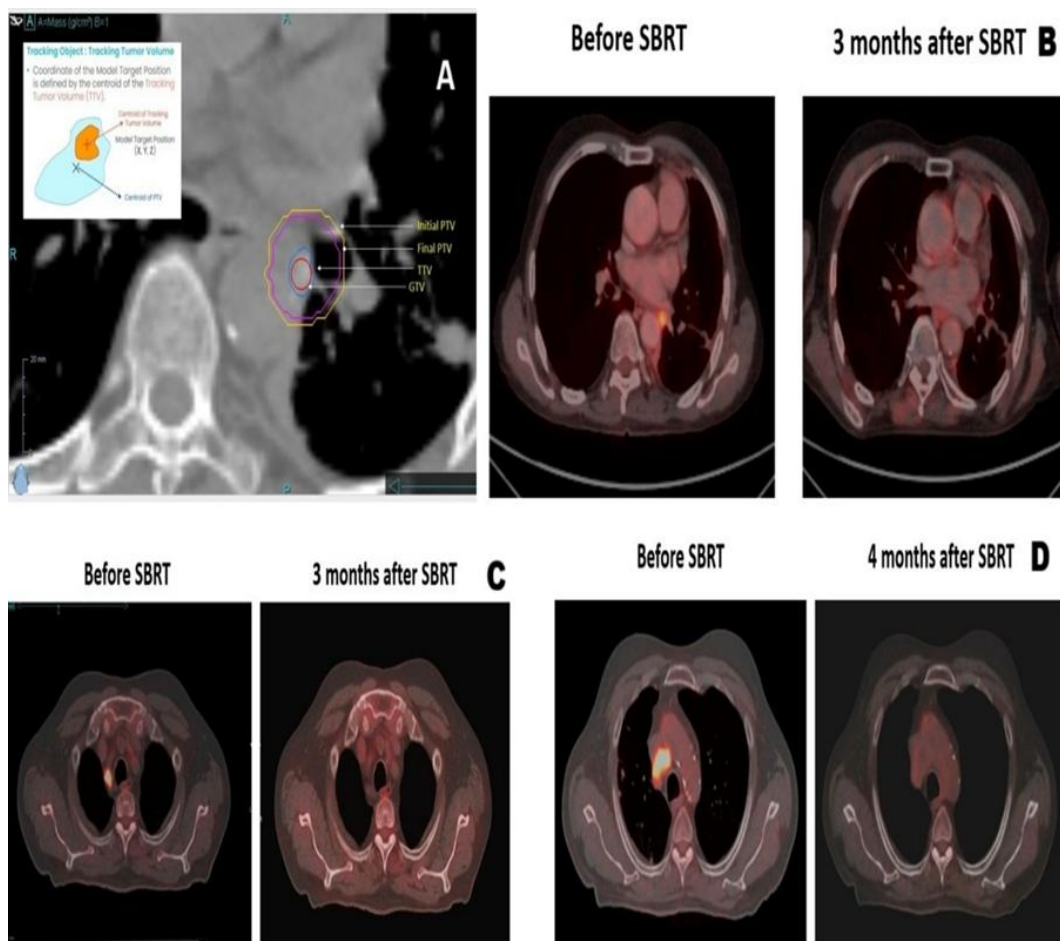


Figure 4: (A) TTV and PTV delineation in Synchrony, (B), (C), (D) Pre-SBRT and post-SBRT comparative WB-PET scans showing complete metabolic response in all three cases.

Conclusion

Synchrony® delivers SBRT with utmost precision in UCLT using smaller PTVs, targeting the tumor while sparing surrounding highly critical tissues thereby preventing life-threatening AEs, helps in attaining better LC and improved Overall Survival (OS). Real-time motion adjustments minimize the risk of missing the target, resulting in more effective treatment outcomes. Synchrony's ability to adapt patient's breathing movements reduces the need for breath-holding or immobilization techniques, enhancing patient comfort and improving treatment compliance. Our institutional experience supports its use as a frontline modality in treating high-risk central, ultra central thoracic oncology cases combining precision, safety and patient comfort for curative, symptomatic relief and consolidation of a good response to palliative chemotherapy/ immunotherapy.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

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Data Availability Statement

Not applicable.

Ethical Statement

The project did not meet the definition of human subject research under the purview of the IRB according to federal regulations and therefore was exempt.

Informed Consent Statement

Informed consent for publication was obtained from the patient involved in this case report, as documented in the manuscript.

Authors' Contributions

All authors contributed equally to this paper.

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