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Dosimetric impact of uncorrected systematic yaw rotation in VMAT for peripheral lung SABR

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ABSTRACT

Aim: This study aimed to evaluate the dosimetric impact of uncorrected yaw rotational error on both target coverage and OAR dose metrics in this patient population.

Background: Rotational set up errors can be difficult to correct in lung VMAT SABR treatments, and may lead to a change in planned dose distributions.

Materials and methods: We retrospectively applied systematic yaw rotational errors in 1° degree increments up to −5° and +5° degrees in 16 VMAT SABR plans. The impact on PTV and OARs (oesophagus, spinal canal, heart, airway, chest wall, brachial plexus, lung) was evaluated using a variety of dose metrics. Changes were assessed in relation to percentage deviation from approved planned dose at 0 degrees.

Results: Target coverage was largely unaffected with the largest mean and maximum percentage difference being 1.4% and 6% respectively to PTV D98% at +5 degrees yaw.

Impact on OARs was varied. Minimal impact was observed in oesophagus, spinal canal, chest wall or lung dose metrics. Larger variations were observed in the heart, airway and brachial plexus. The largest mean and maximum percentage differences being 20.77% and 311% respectively at −5 degrees yaw to airway D0.1cc, however, the clinical impact was negligible as these variations were observed in metrics with minimal initial doses.

Conclusions: No clinically unacceptable changes to dose metrics were observed in this patient cohort but large percentage deviations from approved dose metrics in OARs were noted. OARs with associated PRV structures appear more robust to uncorrected rotational error.

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1. Background

Stereotactic Ablative Radiotherapy (SABR) has become the standard of care for inoperable patients diagnosed with early NSCLC.[1] The excellent outcomes, both in efficacy and toxicity, are the result of combining ablative radiation schedules (ultra hypofractionated high dose radiation schedule) with high precision in radiotherapy design and delivery, to allow for maximum normal tissue sparing and an optimal therapeutic ratio. Treatment delivery is one of the crucial steps in the process where accuracy is paramount. Volumetric Image Guided Radiotherapy (IGRT) is mandatory in the delivery of SABR treatments[2,3] and where possible, online correction of all set-up errors should be implemented.

Whilst translational errors in the lateral, longitudinal and vertical directions can be easily corrected using bed shifts, rotational errors can be more challenging to correct without the addition of a 6 degrees of freedom (6DoF) treatment couch, which is not available in all centres. The magnitude and impact of rotational errors is debated within the literature and studies report conflicting findings depending on technique and site being evaluated.[4–10]

Rotational errors occurring during a short course of SABR in lung cancer were measured and reported in one study.[4] In this population, mean rotational errors between 2° and 3° were observed in one third of the patients. A more recent study[5] evaluated the magnitude of translational and rotational set up errors in lung SABR patients and noted the maximum values of the pitch, roll, and yaw rotations were 4.2°, 5.9° and 7.2° respectively. 95% of the errors were less than 3°.

The dosimetric impact of rotational errors has also been investigated. One such study evaluated roll rotational set up errors on lung SABR, using a Volumetric Modulated Arc Therapy (VMAT) technique.[6] Roll rotational setup errors considerably increased the dose to organs at risk (OARs) in this study, despite accounting for translational correction. This study notes that further work should be carried out evaluating rotations in different planes. They conclude from their findings that the impact observed was patient specific and that roll rotation errors should be carefully corrected for in lung SBRT.

These findings are somewhat contradicted by an analysis,[7] which evaluated rotation in all 3 planes for Intensity Modulated Radiotherapy (IMRT) or 3D Conformal Radiotherapy (3DCRT) lung SABR plans. This study reported that rotation of less than 5 degrees only resulted in minimal dosimetric effects on target and OAR dose metrics.

The impact of rotational error has also been evaluated in different treatment sites and similarly there are conflicting results.[8,9] One such study[10] looked at the effect of rotations on VMAT prostate treatments. It was reported that up to 16% of targets could be under-dosed when correcting for translational error alone, however, they also concluded that this was not directly correlated to the rotation but could be patient specific indicating that some patients are more sensitive to the effect of rotation than others.

A recent publication reports the impact of uncorrected roll and yaw rotation on lung SBRT,[11] however this study only evaluates the impact of uncorrected rotation on PTV D95% dose coverage and does not assess the potential impact on surrounding OARs. Additionally, this work looked at static field IMRT plans rather than VMAT therefore further evaluation is warranted.

Without the addition of any specialised equipment, rotation in the yaw plane is easily corrected by applying a couch rotation after CBCT at the treatment unit. We hypothesised that this may be beneficial to both the coverage of the target volumes as well as the adjacent OARs. The purpose of this study is to evaluate the impact of uncorrected yaw rotation in the VMAT lung SABR setting to assess if it is dosimetrically desirable to correct for these errors during daily RT delivery.

2. Aim

The primary aim of this study was to evaluate the dosimetric differences in the planned dose to both target coverage and organ at risk (OAR) dose in VMAT lung SABR in the presence of uncorrected systematic yaw rotation.

A secondary endpoint was to assess the impact of other clinical variables, particularly plan complexity, on this dosimetric difference.

This study builds on the work of prior studies by evaluating more fully the variation to the target volume in line with volumetric planning recommendations. Furthermore including OAR dose metrics in our assessment of clinical impact adds novelty to this study. Additionally, we only assess a directly correctable error using a standard couch top so our findings are applicable to all clinical centres regardless of resource availability.

3. Materials and methods

3.1. *Study population*

20 patients were selected at random from an institutional database for this retrospective planning study. 16 patients were included in the final analysis due to technical issues with 4 datasets.

All included patients completed VMAT SABR for peripheral pulmonary tumours, treated in a single institution. The main patient characteristics are summarised in Table 1. Institutional ethical approval was granted prior to study commencement

3.2. *Positioning, motion management and simulation*

As per protocol, all patients were positioned in a supine position with both arms extended cranially. Patients were immobilised using a custom-made body VAC-Q-FIX cushion (WFR-Aquaplast/Q-Fix Systems, Avondale, PA, USA) moulded around the WingSTEP (Innovative Technologie-Volp, Innsbruck, Austria). To maintain lower extremity reproducibility and prevent caudal displacement patients were additionally immobilised via indexed Pro-Step (Innovative Technologie-Volp, Innsbruck, Austria) ± knee support depending on patient comfort.

Patients then underwent a whole thorax respiratory correlated 4DCT scan on a 16 slice CT scanner (General Electric

Table 1 – Study population characteristics.

Pt study ID	Age	Sex	Histology	Stage	Tumour LOCATION	PTV volume (cc)	CTV-PTV margin	Prescription	No. of ARCs
1	65	F	SCLC	T1N0M0	RLL (Peripheral)	15.06	5 mm	54 Gy/3#	2
2	62	M	Adeno	T1N0M0	RUL (Pleural)	33.86	5 mm	60 Gy/5#	3
4	68	M	Squamous	T1N0M0	LUL (Pleural)	42.48	5 mm	60 Gy/5#	3
5	77	M	Unknown	T1N0M0	RLL (Pleural)	36.71	5 mm	60 Gy/5#	3
10	69	M	Met	n/a	LLL (Pleural)	17.98	5 mm	60 Gy/5#	3
6	69	M	Unknown	T1N0M0	LUL (Peripheral)	16	5 mm	54 Gy/3#	3
7	69	M	Squamous	T1N0M0	RLL (Pleural)	56.96	5 mm	60 Gy/5#	3
11	66	F	Squamous	T3N0M0	RLL (Pleural)	71.55	5 mm	60 Gy/5#	3
12	84	F	Squamous	T3N0M0	LUL (Pleural)	27.52	5 mm	60 Gy/5#	3
8	68	F	Adeno	T1N0M0	RUL (Peripheral)	11.77	5 mm	54 Gy/3#	2
9	71	M	Adeno	T1N0M0	RUL (Pleural)	10.65	5 mm	60 Gy/5#	2
15	79	M	Adeno	T1N0M0	RUL (Pleural)	20.6	5 mm	60 Gy/5#	2
16	73	M	Squamous	T2N0M0	RLL (Pleural)	53.78	5 mm	60 Gy/5#	2
17	66	M	Unknown	T1N0M0	RLL (Pleural)	18.38	5 mm	60 Gy/5#	2
18	65	F	Squamous	T1N0M0	RML (Pleural)	8.12	5 mm	60 Gy/5#	2
20	71	M	Squamous	T2N0M0	RML (Pleural)	58.79	5 mm	60 Gy/5#	2

Medical System, Milwaukee, USA). Patient breathing was monitored by real time position management (RPM) respiratory gating software which tracks the motion of an external surrogate (Varian Oncology Systems, Palo Alto, CA, USA). No abdominal compression or patient coaching was employed. Acquired 4D datasets were subsequently processed in Advantage 4DCT application on Advantage Workstation 4.1 (General Electric Medical System, Milwaukee, USA). Target and OAR delineation was carried out in Eclipse™ treatment planning system (TPS) version 8.9 (Varian Oncology Systems, Palo Alto, CA, USA). Gross Tumour Volume (GTV) delineation was created from a combination of volume delineation on the maximum intensity projection (MIP) and the maximum inspiration and expiration phases (0% and 50% binned phases) and resulted in an ITV (Internal Target Volume). OAR delineation was carried out on the average intensity projection (Ave-IP) dataset. All volumes were peer-reviewed by two physicians.

3.3. *Planning*

The CTAveIP structure set was used for planning. The ITV was expanded using a 5 mm isotropic expansion to create the planning target volume (PTV). Target and organ at risk (OAR) delineation was carried out in Eclipse™ (Varian Oncology Systems, Palo Alto, CA, USA) treatment planning system.

A risk adapted dose fractionation schedule strategy was applied using 2 schedules for peripherally located tumour, 54 Gy in 3 fractions or 60 Gy in 5 fractions, depending on tumour location and ability to meet dose volume constraints.

Treatment plans consisted of two partial arc coplanar fields or three partial arc non-coplanar fields. Typical arc length was 200 degrees. Deviations were possible where organ at risk sparing or reduction in modulation was necessary. Collimator angles of 30° and 330° were used to limit inter-leaf leakage and allow for additional modulation of the beam.

Plans were optimised using AcurousXB Algorithm with heterogeneity correction.[12] Modulation was controlled to limit interplay effects.

All treatments were normalised such that 95% of the PTV received 100% of the prescription dose. Plans were evaluated using dose volumes constraints derived from pooled published data from the ROSEL trial recommendations RTOG protocols and the UK SABR Consortium Guidelines.[13–15]

3.4. *Simulation of systematic yaw rotational error*

The approved and delivered treatment plan was used as the reference. Systematic rotational set up error in the yaw plane was simulated by rotating the couch parameter on the treatment planning system off 0° in 1° degree increments up to −5° and +5° degrees. The plan was then recalculated using the same MU without re-optimisation to simulate dose distribution with the uncorrected error. All plans were exported from Eclipse™ and imported into Radialogica fullAccess™ where a plan evaluation report extracted all the relevant dose metrics for each offset plan.

The potential impact of systematic uncorrected yaw rotation was evaluated in relation to target coverage utilising the dosimetric parameters of PTV D2%, D98%, D95% as endpoints in line with ICRU 83.[16]

The effect on normal tissue was evaluated for oesophagus, spinal canal, heart, airway (defined as trachea and proximal main bronchi), chest wall, brachial plexus and lung (Combined lung – GTV). All measured endpoints are reported in Table 2.

Table 2 – Dosimetric endpoints measured for each structure.

Structure	Dose parameter
PTV	D2%, D98%, D95%
Oesophagus	D0.35cc, D0.1cc
Oesophagus PRV	D0.35cc
Spinal canal	D0.35cc, D0.01cc
Spinal canal PRV	D0.35cc
Heart	D0.35cc, D0.1cc
Airway	D0.35cc, D0.1cc
Chest wall	D0.35cc, D30cc, D0.1cc
Brachial plexus	D0.35cc, D0.1cc
Lung – GTV	V20Gy, V12.5Gy

PRV – Planning Organ at Risk Volume.

3.5. Statistical analysis

For each patient and degree of rotation (−5, −4, −3, −2, −1, 1, 2, 3, 4, 5) the percentage change from the dose measured at 0 degrees was measured. The average and maximum percentage change for each angle and structure were then calculated and converted to absolute values. To account for the variability of percentage change both within patients (i.e. differences in change for the same person) and between patients (differences in change between people) a linear mixed model was used.[17] The linear mixed model is an extension of linear regression for clustered or repeated measures data situations such as the one described here. Coefficients are interpreted in the same way as regression, with the inclusion of a random intercept term allowing individuals to vary about the sample average change, taking care of the non-independence of the data.

We use the linear mixed model to study the effect of other clinical variables on the change in dose per degree, these variables are number of ARCs (2 or 3), sex (female = 0, male = 1), distance from airway (cm), prescription dose (Gy), age (years), PTV volume (cc) and histology (adeno, metastases, SCLC, squamous, unknown). All analyses were carried out in R v3.4 (R Core Team, 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL: https://www.R-project.org/).

4. Results

The absolute values of mean and maximum percentage changes for each angle and dose parameter are summarised in Tables 3 and 4. The statistically significant findings from the secondary data analysis are summarised in Table 5.

The complete secondary analysis data and plots of percentage changes per degree rotation are available as supplementary materials.

All dose deviations from planned doses were reported as percentage differences to facilitate comparisons across a variety of dose levels and dose metrics. Additionally, the percentage differences were converted to absolute values to accurately reflect the magnitude of change, therefore in some cases the percentage change can represent a decrease rather than an increase in dose.

4.1. Primary analysis

4.1.1. Target coverage

Target coverage was largely unaffected, mean differences to PTVD2%, D98% and D95% were minimal with the largest mean difference being 1.4% to D98% at +5 degrees yaw. Maximum percentage differences in individuals were more variable between subjects, with a maximum of 6% difference at +5 degrees for PTVD98% occurring in one patient.

4.1.2. Organs at risk

Large variation in the dosimetric effect of uncorrected yaw rotation was observed between OARs. OARs were reviewed in the population as a whole, looking at mean differences, and on a patient specific basis to measure the maximum observed variations. Yaw rotation had a low impact on oesophagus, spinal canal, chest wall or lung dose metrics (Tables 3 and 4). The effect was more notable in the heart, airway and brachial plexus.

It should be noted that these percentages usually related to small actual dose changes in the relevant OAR dose metric, as the approved plans had a minimal dose at 0 degrees.

4.1.2.1. Heart. Average effect on the heart was high, with the largest mean difference being 18.39% difference at +5 degrees rotation for D0.1cc. This effect was more marked in individuals, with a maximum percentage difference of 236% noted to the D0.35cc DVC at +5 degrees. An 86% difference in the same DVC was noted at +3 degrees.

4.1.2.2. Airway. Average effect on the Airway dose was high, with the largest mean difference being 20.77% difference at −5 degrees rotation for D0.1cc. This effect was more marked in individuals, with a maximum percentage difference of 311% noted to the D0.1cc DVC at −5 degrees. A 167% difference in the same DVC was noted at −3 degrees.

4.1.2.3. Brachial plexus. Average effect on the Brachial Plexus was notable, with the largest mean difference being 10.69% difference at +5 degrees rotation for D0.35cc. This effect was more marked in individuals, with a maximum percentage difference of 75% noted to the D0.35cc DVC at +4 and 5 degrees. A 30% difference in the same DVC was noted at −3 degrees.

4.2. Secondary analysis

Secondary analysis suggests that prescription dose was significantly associated with the impact of rotational error on oesophagus D0.35cc, oesophagus D0.1cc and heart D0.1cc. PTV volume was associated the impact of rotational error on oesophagus D0.1cc and Distance from Airway was associated the impact of rotational error on spinal canal D0.35cc.

No evidence was found to suggest that the variables examined [number of ARCs (2 or 3), distance from airway (cm), prescription dose (Gy) and volume (cc)] had an impact on the effect of systematic yaw rotation for the remaining dose metrics or OARs.

Statistically significant findings are summarised in Table 5, all other results are available in Supplementary Materials.

In the brachial plexus OAR, a qualitative review of the plots of percentage changes per degree rotation highlighted that 3 arc plans appear to be more robust to rotational error than 2 arc plans (Fig. 1) Number of arcs was not found to be a statistically significant variable. This was not observed in other OARs (all plots available in Supplementary Materials).

5. Discussion

This study evaluated the dosimetric impact of uncorrected systematic yaw errors up to ±5 degrees, on target coverage and OARs in peripheral lung tumours, treated with VMAT SABR.

It was found that the impact of yaw rotational errors on PTV coverage was minimal. Given that this study evaluated

Table 3 – Mean dose difference in % measured per degree rotation. For absolute values please see supplementary materials.

Dose metric	Degree = −5	Degree = −4	Degree = −3	Degree = −2	Degree = −1	Degree = 1	Degree = 2	Degree = 3	Degree = 4	Degree = 5
PTV.D2%	0.28	0.23	0.16	0.09	0.04	0.08	0.13	0.21	0.29	0.37
PTV.D98%	0.90	0.68	0.48	0.31	0.18	0.19	0.42	0.70	1.01	1.40
PTV.D95%	0.51	0.39	0.27	0.19	0.10	0.13	0.28	0.45	0.65	0.89
Oesoph.D0.35cc	2.23	1.85	1.44	1.10	0.52	0.64	1.30	1.86	2.37	2.93
Oesoph.D0.1cc	2.40	2.10	1.61	1.29	0.65	0.70	1.40	1.93	2.60	3.21
Oesoph.PRV.D0.35cc	1.87	1.59	1.17	0.92	0.55	0.48	0.96	1.33	1.76	2.27
Spinal.Canal.D0.35cc	2.04	1.71	1.38	1.01	0.60	0.49	0.86	1.17	1.55	1.93
Spinal.Canal.D0.01cc	3.13	2.48	2.11	1.62	0.83	0.87	1.19	1.74	2.45	2.67
Spinal.Canal.PRV.D0.35cc	2.20	1.83	1.49	1.06	0.61	0.56	1.03	1.48	1.87	2.28
Heart.D0.35cc	13.36	10.35	6.84	3.78	2.17	1.58	4.66	8.95	14.66	20.66
Heart.D0.1cc	14.20	10.79	7.78	4.24	1.90	1.79	4.18	7.78	12.93	18.39
Airway.D0.35cc	19.51	13.28	8.70	3.74	0.71	1.73	2.16	3.05	4.14	4.61
Airway.D0.1cc	20.77	15.52	11.35	7.21	2.83	1.19	1.89	3.30	4.23	4.77
Chestwall.D0.35cc	0.91	0.72	0.51	0.34	0.17	0.17	0.32	0.45	0.61	0.77
Chestwall.D30cc	0.31	0.24	0.18	0.12	0.07	0.07	0.13	0.18	0.25	0.32
Chestwall.D0.1cc	1.04	0.75	0.54	0.37	0.16	0.19	0.34	0.53	0.73	0.98
Lung.GTV.V20Gy	0.72	0.59	0.41	0.28	0.15	0.07	0.27	0.37	0.50	0.57
Lung.GTV.V12.5Gy	0.93	0.70	0.51	0.32	0.18	0.21	0.41	0.57	0.76	0.92
Brach.Plex.D0.35cc	9.26	7.18	5.57	4.35	1.80	2.19	3.17	5.81	9.78	10.69
Brach.Plex.D0.1cc	9.38	8.24	4.31	3.62	2.20	1.88	2.84	5.33	9.56	7.28

Table 4 – Maximum dose difference in % measured per degree rotation. For absolute values please see supplementary materials.

Dose metric	Degree = −5	Degree = −4	Degree = −3	Degree = −2	Degree = −1	Degree = 1	Degree = 2	Degree = 3	Degree = 4	Degree = 5
PTV.D2%	1	0	0	0	0	0	0	0	0	1
PTV.D98%	3	3	2	1	1	1	2	3	4	6
PTV.D95%	2	1	1	1	0	1	1	2	3	4
Oesoph.D0.35cc	5	5	4	3	2	2	4	5	7	8
Oesoph.D0.1cc	6	5	4	3	1	2	4	6	8	9
Oesoph.PRV.D0.35cc	5	4	3	3	1	2	3	6	8	11
Spinal.Canal.D0.35cc	7	6	5	4	2	2	2	3	4	4
Spinal.Canal.D0.01cc	8	8	9	7	3	3	4	5	7	8
Spinal.Canal.PRV.D0.35cc	7	6	5	4	3	2	4	4	4	5
Heart.D0.35cc	108	74	38	14	9	6	36	86	156	236
Heart.D0.1cc	128	88	55	15	10	7	24	60	122	189
Airway.D0.35cc	289	193	123	48	5	22	23	32	43	45
Airway.D0.1cc	311	231	167	103	40	13	19	35	44	47
Chestwall.D0.35cc	3	2	2	1	0	1	1	1	2	2
Chestwall.D30cc	1	1	1	0	0	0	0	1	1	1
Chestwall.D0.1cc	3	2	2	1	0	1	1	2	2	3
Lung.GTV.V20Gy	2	1	1	1	1	0	1	1	1	1
Lung.GTV.V12.5Gy	2	2	1	1	1	1	1	1	2	2
Brach.Plex.D0.35cc	48	39	30	20	8	11	20	25	75	75
Brach.Plex.D0.1cc	39	32	22	17	11	9	13	25	75	25

Table 5 – Impact of variables in % dose difference following systematic yaw rotation error (statistically significant findings only).

Dose Metric	Variable	Effect on % change in dose	95% confidence interval	*p*-Value
Oesoph.D0.35cc	Prescription dose (Gy)	−0.239	−0.422, −0.056	0.027
Oesoph.D0.1cc	Prescription dose (Gy)	−0.249	−0.425, −0.073	0.018
Oesoph.D0.1cc	Volume (cc)	0.028	0.005, 0.052	0.036
Spinal.Canal.D0.35cc	Distance from airway (cm)	0.43	0.157, 0.703	0.01
Heart.D0.1cc	Prescription dose (Gy)	−2.741	−5.17, −0.311	0.049

patients with peripherally located tumours, surrounded by low-density lung tissue, this is unsurprising. It has been reported that the absorbed dose will follow the density of the lung tumour in the PTV.[18] Within this low-density region, rotation resulted in minimal changes to the tissue within which the PTV is located and so little impact on the dose metrics was observed.

The dosimetric impact of uncorrected rotation on OARs was found to be variable across both individual patients and individual structures.

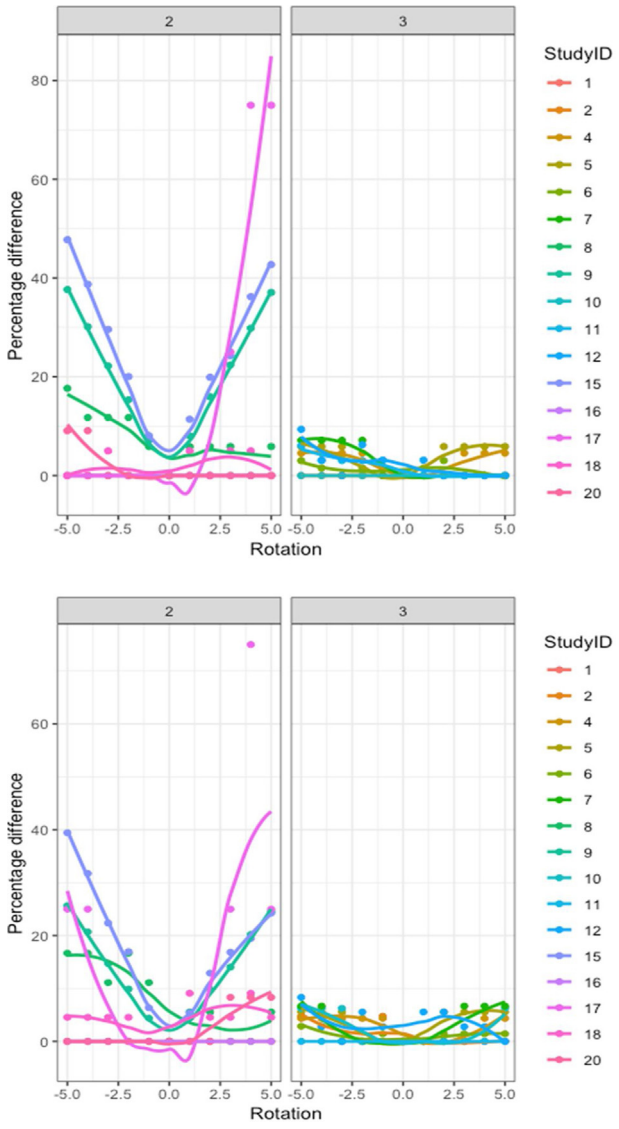

Fig. 1 – Brachial plexus D0.35cc and D 0.1cc, 2 vs. 3 Arc plans.

The effect on various dose metrics for the oesophagus, spinal canal, chest wall and lung was found to be relatively low. Considerable percentage differences were observed in the heart, airways and brachial plexus, in both the population as a whole and on an individual level. No clear reason for a larger effect on these OARs was discovered. All metrics in these OARs were small volume doses (D0.1cc and D0.35cc), however these metrics were also recorded for spinal cord and oesophagus and a similar effect was not seen. Planning Organ at Risk Volumes (PRVs) were created for spinal cord and oesophagus OARs. A potential explanation of this difference is that the use of PRV structures can improve the robustness of these OARs to set up errors.

Some moderate differences were observed within individual cases. In Patient 9 the brachial plexus dose increased from 10.09 Gy to 13.8 Gy at +5 degrees rotation. Again, whilst this is not clinically significant for this patient this is a 37% deviation from the approved plan parameter, which may be unacceptable to the physician.

The initial approved dose metric was often low in these cases, due to the peripheral location of the tumours and steep dose fall off associated with SABR VMAT plans. For example, a 236% change in heart D0.35cc metric was observed in Patient 8 at 5 degrees rotation, however, the dose difference was an increase from 1.4 Gy to 4.7 Gy. Similarly, the large observed variation of 310% change to the airway D0.1cc for Patient 17 was an increase from 0.95 Gy to 3.9 Gy. While these increases are well below acceptable dose volume constraints, and therefore appear to be clinically insignificant for these specific patients, the relative change to an approved plan parameter is still large and may not be acceptable in all cases. Patients with centrally located tumours or undergoing re-irradiation could be impacted in a clinically meaningful way.[19]

Dose to the heart is increasingly considered as a potentially critical factor in patient outcomes during lung radiation therapy.[20,21] More recent evidence has proposed that even low dose increases to the heart during radiotherapy may be clinically relevant to patient outcomes as reported in a study which evaluated the impact of residual uncorrected translational errors on overall survival.[22] The data presented suggests there is a decrease in overall survival when uncorrected errors result in dose that is shifted towards the heart. Whilst these data were related to conventionally fractionated lung radiation therapy, the doses in SABR are much higher and so it may also be relevant to this population. Although further investigation is required in this area to identify clearly the relevance of these findings, it may indicate a need to implement stricter IGRT protocols in the future.[22] If this effect is shown to be significant in follow up studies the small dose changes observed in this study may be considered clinically relevant.

The clinical impact of uncorrected systematic yaw rotation in this patient group is presumed to be minimal, as the changes did not breach established dose volume constraints. However, these target volumes were peripheral and therefore critical OARs were not in close proximity. The approved treatment plan generally reported dose metrics well below established constraints. Should this methodology be repeated in centrally located tumours, this percentage difference could be cause for clinical concern. Conversely, the proximity of central OARs to the target volume could also mitigate the impact of rotational error, as the simulated error is rotation about the isocentre therefore the actual rotation of a proximal OAR could be less.

Consideration should also be given to a qualitative evaluation of the dose distribution when an error is simulated. As all dose parameter data lacks spatial information, it is not sufficient to make clinical decisions based solely on these metrics. Volumetric Arc RT generally offers improved conformity to the target in comparison to static field IMRT.[23] This should render it more resistant to the impact of rotational error as it does not have the dose spikes of a static field plan. Qualitative analysis of the new dose distribution was beyond the scope of this study, but warrants further investigation.

Our findings highlighted the individualised impact of uncorrected yaw rotation on patients, with no predictable responses in either structures or patients. One potential solution to counteract this issue is the use of individualised IGRT

protocols during treatment verification for plans that may be impacted by rotational errors. Perhaps, a more desirable solution may be to consider the impact of these errors at an early stage and create a plan that is resistant to these changes. Robust treatment planning optimises the dose distribution by considering potential set up errors during treatment delivery.[24] This concept has been explored in a number of treatment sites[25,26] including lung SABR,[27,28] but the errors studied are translational and not rotational. Incorporation of rotational robustness into routine treatment planning could mitigate the risk associated with uncorrected rotational errors. Real time adaptive radiotherapy (ART) may play a role in the management of set up errors in the future. Current guidelines note that ART is recommended only where large anatomical changes are noted.[29] With the advent of MRI guided radiotherapy true plan of the day adaptation to daily set up may become routine practice.[30,31]

In the secondary analysis, none of the factors investigated had a strong relationship with the impact of yaw rotation on dose metrics. However, some association was observed between prescription dose and oesophageal and heart metrics. As the prescription was risk adapted depending on tumour location it is likely this demonstrates the impact of tumour location rather than dose. The number of arcs was not found to statistically correlate with the changes in dose observed in any structure, however, in the brachial plexus, it appears clear that the 3 arc plans are more robust to rotational errors than 2 arc plans. Less variation was observed in the D0.35cc and D0.1cc metrics in all patients planned with this non-coplanar technique. Non-coplanar VMAT planning has been shown to increase the conformity index of Lung SABR plans[32] and this may explain the differences seen in the brachial plexus dose metrics.

Collecting 11 measurements of dose from each subject allowed the patients to act as their own controls, and increased the power to detect a rotation effect. Linear mixed models were used to control for the non-independence of dose within individuals. Random intercept term allowed individual patients to vary in their average change in dose per degree of rotation.

Multiple testing was an issue in this study, with eleven areas and six metrics of dose measurement. This meant the number of models[20] was higher than the number of patients.[16] However, the small sample size of patients our results should counterbalance this with larger standard errors, and a full Bonferroni correction would be conservative given the likely strong correlation between metrics and areas of measurement.

6. Conclusions

This work suggests that the impact of systematic yaw rotational error was variable in both patients and structures. No clinically unacceptable changes to dose metrics were observed in this patient cohort of non-central lung tumours, treated using a VMAT SABR technique. Large percentage deviations from approved dose metrics in some individual OARs were noted and recent research suggests that uncorrected errors may have an impact on patient outcomes. Further work is required in this field to determine the optimal correction strategy for these errors. In the interim, a personalised approach could be adopted to evaluate the impact of such errors on an individual basis or robust treatment planning approaches could be implemented.

Conflict of interest

None declared.

Financial disclosure

None declared.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.rpor.2019.07.010.

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