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ORIGINAL RESEARCH

Bronchoscopic Lung Volume Reduction as the Treatment of Choice versus Robotic-Assisted Lung Volume Reduction Surgery in Similar Patients with Emphysema – An Initial Experience of the Benefits and Complications

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Objective: There is an assumption that because EBLVR requires less use of hospital resources, offsetting the higher cost of endobronchial valves, it should therefore be the treatment of choice wherever possible. We have tested this hypothesis in a retrospective analysis of the two in similar groups of patients.

Methods: In a 4-year experience, we performed 177 consecutive LVR procedures: 83 patients underwent Robot Assisted Thoracoscopic (RATS) LVRS and 94 EBLVR. EBLVR was intentionally precluded by evidence of incomplete fissure integrity or intra-operative assessment of collateral ventilation. Unilateral RATS LVRS was performed in these cases together with those with unsuitable targets for EBLVR.

Results: EBLVR was uncomplicated in 37 (39%) cases; complicated by post-procedure spontaneous pneumothorax (SP) in 28(30%) and required revision in 29 (31%). In the LVRS group, 7 (8%) patients were readmitted with treatment-related complications, but no revisional procedure was needed. When compared with uncomplicated EBLVR, LVRS had a significantly longer operating time: 85 (14–82) vs 40 (15–151) minutes ($p<0.001$) and hospital stay: 7.5 (2–80) vs 2 (1–14) days ($p<0.01$). However, LVRS had a similar total operating time to both EBLVR requiring revision: 78 (38–292) minutes and hospital stay to EBLVR complicated by pneumothorax of 11.5 (6.5–24.25) days. Use of critical care was significantly longer in RATS group, and it was also significantly longer in EBV with SP group than in uncomplicated EBV group.

Conclusion: Endobronchial LVR does use less hospital resources than RATS LVRS in comparable groups if the recovery is uncomplicated. However, this advantage is lost if one includes the resources needed for the treatment of complications and revisional procedures. Any decision to favour EBLVR over LVRS should not be based on the assumption of a smoother, faster perioperative course.

Keywords: lung volume reduction, lung volume reduction surgery, bronchoscopic lung volume reduction, endobronchial valve, emphysema

Introduction

Lung volume reduction (LVR) has developed considerably since the original description in the modern era.[1] It can now be performed successfully by bronchoscopic lung volume reduction with endobronchial valves (EBLVR)[2] or minimally invasive lung volume reduction surgery (LVRS)[3] and the two methods can be combined.[4] Despite a clear benefit in survival rate and durable improvement in symptoms following LVRS, the number of LVRS procedures performed has declined significantly.[5] The reason for this decline remains unclear. Instead, minimally invasive techniques such as EBLVR have emerged. Doom et al suggest that if the patients are eligible for both LVR techniques then EBLVR is

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preferable as the valves can be removed and thus the treatment remains reversible.[6] Both methods have been shown in a prospective, randomized comparison to give similar improvements in BODE index in patients with symptomatic emphysema receiving maximal non-invasive therapy.[7] However, Mansfield et al report that the patients perceive EBLVR to be more desirable than LVRS due to the "minimally-invasive" nature.[8] This perception is further encouraged by the assumption that because EBLVR requires less use of hospital resources, offsetting the higher cost of EBVs, it should therefore be the first treatment of choice where possible.[9] We have tested this hypothesis in a retrospective analysis of the two in similar groups of patients.

Method

We offered patients either robot-assisted thoracoscopic surgery (RATS LVRS) or EBLVR with Zephyr® endobronchial valves (Pulmonx Corporation, Redwood City, California). EBLVR was the treatment of choice in patients with no evidence of collateral ventilation (CV), while CV positive patients or those with imaging evidence of fissure integrity <90% or paraseptal emphysema proceeded directly to unilateral RATS LVRS. We compared the use of the hospital resources, including theatre time, critical care, hospital stay, readmission to hospital and further procedures. Patients' demographics, information about operative procedures or mortalities were retrieved retrospectively through the UK National Health Service's Care Record Service (NHS CRS).

Pre-Operative Patient Selection

All patients were selected in line with the UK National Institute for Health and Care Excellence (NICE) guidance[10] and were discussed at a multidisciplinary team (MDT) meeting dedicated for assessment and identifying suitable candidates for LVR.[4] Our LVR MDT remained in a continuous and uniform format according to the NICE guidance[10] in the presence of a thoracic surgeon, respiratory physician, radiologist, and a specialist nurse with appropriate administrative support.

Patient selection followed a 4-step process: cardiorespiratory assessment; selection of target areas for LVR; assessment of collateral ventilation and risk assessment. Standard criteria for dynamic and static lung volumes and exercise tolerance were applied. Exclusion criteria included echocardiographic evidence of pulmonary hypertension with right ventricular dysfunction and type II respiratory failure.[10]

All patients underwent quantitative-computed tomography (QCT), which was analysed by the StratX software. The StratX lung report provides fissure completeness, emphysema density and inspiratory volumes to allow identifications of target lobes that are good candidates for treatment with Zephyr valves.[11] The level of emphysema destruction scoring is calculated as the percentage of voxels in Hounsfield units (HU) in a lobe that fall below a threshold value. Lobes with <50% destruction are usually not considered as potential targets. Furthermore, large inspiratory volume represents hyperinflation and help to identify the lobes which may be a good target for Zephyr valve treatment.[12] The findings of the StratX report were correlated with the results of semi-quantitative single-photon emission computed tomography (SPECT) analysis of radionuclide lung scintigraphy. Lobar target areas were required to be both areas of severe emphysema and areas of relative under perfusion.

We initially assessed suitability for EBLVR also using the StratX report. Fissure completeness indicates absence of CV between the target and the neighbouring lobes and it has been shown to be a predictor of success for Zephyr valve therapy.[13] The StratX report displays fissure completeness computed as a percentage of the total area of the fissure across the lobar boundary. We used a fissure completeness score of <90% to suggest the presence of CV in the lobe and therefore to exclude treatment with Zephyr valves.

We attempted to individualize the predicted procedural risk of mortality using the published Glenfield risk model.[14] This was calculated for LVRS but in the absence of any comparator for EBLVR this was used to exclude any patient in the "High-Risk" category.

Operative Technique

Endobronchial Lung Volume Reduction (EBLVR)

EBVs were inserted under general anaesthesia using a laryngeal mask via a flexible video bronchoscope. Prior to a valve insertion, fissure integrity was confirmed by the absence of CV using the Chartis endobronchial catheter and the measurement

of bronchial air flow.[12] CV status was confirmed by a gradual decrease and eventual cessation of expiratory airway flow, in addition to a parallel increase in resistance.[15] EBV insertion followed in standard fashion into one lobe only.[16]

Robot-Assisted Lung Volume Reduction Surgery (LVRS)

Robot-assisted LVRS was performed under general anaesthesia using single-lung ventilation. The robotic platform used was DaVinci Xi (Intuitive surgical, Inc., Sunnyvale, California, USA) with a 3-arm setup. To identify target areas for resection in-vivo, an intravenous bolus injection of the fluorescent dye indocyanine green (ICG) was given at 5mg/body weight (kg). ICG is a near-infrared (NIR) fluorescent contrast agent with fluorescence absorption of 820nm, which is visible with appropriate cameras with high tissue penetration.[17] Demarcation lines between underperfused target areas, of assumed most damaged lung, and adjacent fluorescent lung to be preserved were used to guide resection of target areas using the 60mm SureForm surgical stapler (Intuitive Surgical, Inc., Sunnyvale, CA. ©2022 Intuitive Surgical Operations, Inc.). Bioglue was used to cover the staple lines and two 36Fr chest. Drains were inserted, in which 5kPa suction was applied post-operatively. In total, the operations were performed by an experienced operator and 4 thoracic surgeons under supervision. All patients received a continuous extrapleural, paravertebral infusion of bupivacaine. Opioid analgesia was used judiciously under close observation.

Post-Operative Management

Two chest x-rays were done on the day of EBLVR: one was done soon after the procedure and the second one 3–4 hours later. Further serial chest x-rays were done early in the morning on day 1 and 2 post-procedure and if they demonstrated no pneumothorax then the patients were discharged on day 2. Emergency intercostal chest drain insertion kits were present near the patients' bedside for rapid decompression during this period. When demonstrated, spontaneous pneumothorax (SP) was managed by the standard British Thoracic Society (BTS) algorithm.[18] We proceeded to closure of the air leak by video-assisted thoracic surgery (VATS) and talc pleurodesis for persistent air leak (PAL) longer than 7 days, but we did not remove the EBVs.

All patients were electively extubated in the operating room and cared for on the general ward after a period of postoperative observation in a theatre recovery unit. Transfer for subsequent care in high dependency was reserved for those requiring continuing arterial blood gas monitoring or non-invasive ventilation at the discretion of the anaesthetist.

Data Collection

Patients' demographics, information about operative procedures or mortalities were retrieved retrospectively through the National Health Service's Care Record Service (NHS CRS) and collected on an Excel spreadsheet. All data were anonymised to preserve the privacy of the patients.

Ethics

This study is registered as a clinical audit in the department of Thoracic Surgery at Barts Health NHS Trust with an audit ID 13175. The Ministry of Ethics of the UK states that when clinical audits do not alter patients' usual clinical management, it does not require additional patient consent or formal ethical review or approval from the NHS Research Ethics Service.[5]

Statistical Analysis

R Core Team (R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria 2022) was used for all statistical analyses. Distributions of quantitative variables were summarised with mean, standard deviation (SD), median quartiles and range (minimum-maximum), whereas distributions of qualitative variables were summarised with number and percentage of occurrence for each of their values. Chi-squared test (with Yates' correction for 2×2 tables) was used to compare qualitative variables among groups. In case of low values in contingency tables, Fisher's exact test was used instead. Kruskal–Wallis test (followed by Dunn post-hoc test) was used to compare quantitative variables in groups. R 4.2.1 was used for computations. Significance level for all statistical tests was set to 0.05.

Results

In a 4-year experience, from October 2017 to November 2022, we performed 177 consecutive LVR procedures, 83 patients (54M:29F), median age 66(57–71) years underwent RATS LVRS and 94 EBLVR (52M:42F), median age 69(43–82) years. EBLVR was uncomplicated in 37 (39%) cases; complicated by post-procedure spontaneous pneumothorax (SP) in 28(30%) and required revision in 29 (31%). In the LVRS group, 7 (8%) patients were readmitted with treatment-related complications, but no revisional procedure was needed.

The patients who had a complicated EBLVR were older than the typical RATS LVRS patient (p=0.03) but not older than those with an uncomplicated EBLVR. Patients undergoing RATS LVRS were more hyperinflated with a higher RV (p=0.04) but all other parameters were similar for all (Tables 1 and 2).

Right-sided procedures [57/83, 68.7%] were more frequent in RATS LVRS, whilst EBLVR was more frequently performed on the left [62/94, 66%]. (p<0.001). The upper lobes were more common targets than the lower lobes: 126 vs

Table 1 Pre-Operative Patient Characteristics

Parameter		EBLVR (N=94)	LVRS (N=83)	p
Age [years]	Mean (SD) Median (quartiles) Range Missing	68.26 (8.33) 70 (64–74) 43–82 0	63.96 (9.82) 66 (57.5–71) 38–82 0	p=0.003*
Gender	Male Female	53 (56.38%) 41 (43.62%)	54 (65.06%) 29 (34.94%)	p=0.306
BMI [kg/m²]	Mean (SD) Median (quartiles) Range Missing	23.92 (5.5) 23.22 (20.05–27.45) 13–36.95 4	24.37 (5.24) 24.62 (19.79–27.69) 14.7–45 9	p=0.639
FEV1 [%]	Mean (SD) Median (quartiles) Range Missing	34.22 (13.58) 31 (26–39) 13.8–86.2 1	34.05 (13.16) 31 (26–40) 13.8–90.1 2	p=0.99
DLCO [%]	Mean (SD) Median (quartiles) Range Missing	38.96 (14.21) 38 (27.6–48) 10.7–84 5	35.9 (17.06) 34 (25–40.25) 12–137 8	p=0.059
RV [%]	Mean (SD) Median (quartiles) Range Missing	213.17 (48.53) 208 (185.02–239.25) 43.21–350.6 6	239.99 (70.23) 224.5 (197.4–262.25) 127–506.6 13	p=0.014*
Hypertension	No Yes	49 (52.13%) 45 (47.87%)	55 (66.27%) 28 (33.73%)	p=0.079
Ischaemic Heart Disease	No Yes	87 (92.55%) 7 (7.45%)	75 (90.36%) 8 (9.64%)	p=0.801
Cerebrovascular disease	No Yes	85 (90.43%) 9 (9.57%)	81 (97.59%) 2 (2.41%)	p=0.097
Diabetes Mellitus	No Yes	85 (90.43%) 9 (9.57%)	79 (95.18%) 4 (4.82%)	p=0.357

Note: * statistically significant (p<0.05).
Abbreviations: LVRS, indicates lung volume reduction surgery; EBLVR, endobronchial valve lung volume reduction; BMI, body mass index; FEV1, forced expiratory volume in one second; DLCO, carbon monoxide diffusion capacity; RV, residual volume.

Table 2 Subgroup Analysis of Pre-Operative Patient Characteristics

Parameter		RATS LVRS (N=83)	Uncomplicated EBLVR (N=37)	EBLVR with SP (N=28)	EBLVR with Redo Procedures (N=35)	p value
Age [years]	Mean (SD) Median (quartiles) Range	63.96 (9.82) 66 (57.5–71) 38–82	67.76 (8.35) 69 (64–73) 43–81	68.07 (8.3) 70.5 (63.75–74) 50–82	68.74 (8.24) 70 (63.5–75.5) 50–82	p=0.03* C,D>A
Gender	Male Female	54 (65.06%) 29 (34.94%)	18 (48.65%) 19 (51.35%)	18 (64.29%) 10 (35.71%)	18 (51.43%) 17 (48.57%)	p=0.256
BMI [kg/m²]	Mean (SD) Median (quartiles) Range	24.37 (5.24) 24.62 (19.79–27.69) 14.7–45	23.68 (5.43) 21.88 (19.36–27.65) 15.8–33.9	23.23 (5.32) 23.3 (21.13–26.33) 13–36.95	24.35 (5.67) 24.6 (20.2–27.8) 13–36.95	p=0.78
FEV1 [%]	Mean (SD) Median (quartiles) Range	34.05 (13.16) 31 (26–40) 13.8–90.1	33.28 (13.24) 31 (24–42) 15–86.2	33.09 (14.64) 30.5 (25–36) 13.8–82.8	37.06 (12.76) 34.85 (27.88–43.77) 17–63	p=0.389
DLCO [%]	Mean (SD) Median (quartiles) Range	35.9 (17.06) 34 (25–40.25) 12–137	38.51 (12.95) 38 (27.3–41.5) 21–76	38.17 (14.72) 38.05 (30–48) 17.7–84	39.56 (15.16) 38.3 (28.33–50) 10.7–84	p=0.274
RV [%]	Mean (SD) Median (quartiles) Range	239.99 (70.23) 224.5 (197.4–262.25) 127–506.6	220.41 (48.63) 208 (186.9–234) 152–350.6	214.52 (54.73) 216 (186.6–241) 179.4–340.5	203.1 (38.26) 205.05 (179.25–221) 130–289	p=0.04* A>D
Hypertension	No Yes	55 (66.27%) 28 (33.73%)	22 (59.46%) 15 (40.54%)	14 (50.00%) 14 (50.00%)	17 (48.57%) 18 (51.43%)	p=0.228
Ischaemic heart disease	No Yes	75 (90.36%) 8 (9.64%)	34 (91.89%) 3 (8.11%)	26 (92.86%) 2 (7.14%)	33 (94.29%) 2 (5.71%)	p=0.978
Cerebrovascular disease	No Yes	81 (97.59%) 2 (2.41%)	33 (89.19%) 4 (10.81%)	25 (89.29%) 3 (10.71%)	32 (91.43%) 3 (8.57%)	p=0.134
Diabetes Mellitus	No Yes	79 (95.18%) 4 (4.82%)	32 (86.49%) 5 (13.51%)	27 (96.43%) 1 (3.57%)	32 (91.43%) 3 (8.57%)	p=0.315

Note: * statistically significant (p<0.05).
Abbreviations: RATS, indicates robot-assisted thoracoscopic surgery; LVRS, lung volume reduction surgery; EBLVR, endobronchial valve lung volume reduction; SP, spontaneous pneumothorax; BMI, body mass index; FEV1, forced expiratory volume in one second; DLCO, carbon monoxide diffusion capacity; RV, residual volume.

51 (p=0.139) but in those requiring revision of EBLVR there were disproportionately more lower lobe procedures: 17 upper vs 14 lower (p=0.139) (Tables 3 and 4).

The 83 patients who underwent RATS LVRS had the following indications: 34 had intralobar heterogeneity in perfusion and no lobar target for EBLVR; 25 had an incomplete fissure on imaging; 21 had CV on intraoperative assessment by Chartis and 3 had paraseptal emphysema.

Use of Hospital Resources (Tables 5 and 6)

Operation Time

When compared with both uncomplicated and complicated EBLVR, RATS LVRS had a significantly longer operating time of 84.5 (72–115) minutes (p<0.001). There was no difference between the time taken for the initial EBLVR procedure in the uncomplicated or complicated groups. However, when cumulative theatre times including further

Table 3 Peri-Operative Clinical Features

Parameter		EBLVR (N=94)	LVRS (N=83)	p
Laterality	Left Right	64 (68.09%) 30 (31.91%)	26 (31.33%) 57 (68.67%)	p<0.001*
Target lobe	Lower Upper	33 (35.11%) 61 (64.89%)	17 (20.48%) 66 (79.52%)	p=0.047*

Note: *statistically significant (p<0.05).
Abbreviations: LVRS, indicates lung volume reduction surgery; EBLVR, endobronchial valve lung volume reduction.

Table 4 Subgroup Analysis of Peri-Operative Clinical Features

Parameter		RATS LVRS (N=83)	Uncomplicated EBLVR (N=37)	EBLVR with SP (N=28)	EBLVR with Redo Procedures (N=35)	pvalue
Laterality	Left Right	26 (31.33%) 57 (68.67%)	26 (70.27%) 11 (29.73%)	19 (67.86%) 9 (32.14%)	21 (60.00%) 14 (40.00%)	p<0.001 *
Target lobe	Lower Upper	17 (20.48%) 66 (79.52%)	14 (37.84%) 23 (62.16%)	8 (28.57%) 20 (71.43%)	13 (37.14%) 22 (62.86%)	p=0.139

Note: *statistically significant (p<0.05).
Abbreviations: RATS, indicates robot-assisted thoracoscopic surgery; LVRS, lung volume reduction surgery; EBLVR, endobronchial valve lung volume reduction; SP, spontaneous pneumothorax; BMI, body mass index; FEV1, forced expiratory volume in one second; DLCO, carbon monoxide diffusion capacity; RV, residual volume.

Table 5 Use of Peri-Operative Hospital Resources

Parameter	Group	N	Mean	SD	Median	Min	Max	Q1	Q3	p
1st LOS [days]	EBLVR LVRS	94 82	5,89 10,85	8,02 10,82	2,0 7,5	1 2	42 80	2 4	5,00 14,00	p<0.001*
Total LOS [days]	EBLVR LVRS	94 82	10,63 11,29	14,79 10,93	4,0 8,0	1 2	84 80	2 4	11,75 14,00	p=0.003*
1st Op. time [min]	EBLVR LVRS	91 78	45,05 94,32	24,13 31,58	39,0 84,5	7 32	151 180	31 72	52,50 115,00	p<0.001*
Total Op. time [min]	EBLVR LVRS	93 78	71,41 94,32	55,00 31,58	52,0 84,5	14 32	292 180	38 72	83,00 115,00	p<0.001*

Note: *statistically significant (p<0.05).
Abbreviations: LVRS, indicates lung volume reduction surgery; EBLVR, endobronchial valve lung volume reduction; SD, standard deviation.

procedures are taken into account, EBLVR requiring redo procedures required a total operation time of 78(55.5–112) minutes, which was not significantly different from RATS LVRS [84.5(32–180) minutes] but was significantly greater than uncomplicated EBLVR (p<0.001).

Use of Critical Care

Use of critical care was significantly longer in RATS group than in other groups, and it was also significantly longer in EBV with SP group than in uncomplicated EBV group (p<0.001).

Length of Stay

Initial length of stay (LOS) was the longest in EBLVR with SP [8(3–15.2) days] or RATS LVRS group [7.5(2–80) days] than EBLVR requiring redo procedures [2(1–42) days] or uncomplicated EBLVR [2(1–14) days] (p<0.001). In contrast,

Table 6 Subgroup analysis of use of peri-operative hospital resources

Parameter		RATS LVRS (N=83)	Uncomplicated EBV (N=37)	EBV with SP (N=28)	EBV with Redo Procedures (N=35)	p
1st LOS [days]	Mean (SD) Median (quartiles) Range	10.85 (10.82) 7.5 (4–14) 2–80	2.65 (2.19) 2 (2–2) 1–14	10.79 (10.39) 8 (3–15.25) 1–42	6.97 (10.05) 2 (2–5.5) 1–42	p<0.001* C,A>D>B
Total LOS [days]	Mean (SD) Median (quartiles) Range	11.29 (10.93) 8 (4–14) 2–80	4.54 (9.83) 2 (2–3) 1–61	17.71 (17.78) 11.5 (6.5–24.25) 2–84	14.66 (18.62) 5 (4–18.5) 2–84	p<0.001* C,A,D>B
1st Operation time [minutes]	Mean (SD) Median (quartiles) Range	94.32 (31.58) 84.5 (72–115) 32–180	42.17 (15.71) 38.5 (30.75–51.25) 14–82	50.11 (29.08) 40 (32.5–61) 15–151	43.32 (25.93) 38.5 (30.5–50) 7–151	p<0.001* A>C,D,B
Total Operation time [minutes]	Mean (SD) Median (quartiles) Range	94.32 (31.58) 84.5 (72–115) 32–180	42.17 (15.71) 38.5 (30.75–51.25) 14–82	75.93 (52.03) 58.5 (40.25–105) 22–264	100.97 (65.71) 86 (55.5–112) 38–292	p<0.001* D,C>B A>C,B
Use of Critical Care [days]	Mean (SD) Median (quartiles) Range	1.04 (1.56) 1 (0–1) 0–7	0 (0) 0 (0–0) 0–0	1.5 (4.02) 0 (0–0.25) 0–18	0.1 (0.41) 0 (0–0) 0–2	p<0.001* C>B A>C,D,B

Note: *statistically significant (p<0.05).
Abbreviations: RATS, indicates robot-assisted thoracoscopic surgery; LVRS, lung volume reduction surgery; EBLVR, endobronchial valve lung volume reduction; SP, spontaneous pneumothorax; SD, standard deviation.

Table 7 Pre-Operative Patient Demographics

Parameter		No Redo Bronchoscopy (N=43)	Redo Bronchoscopy (N=29)	p value
Gender	Male Female	25 18	16 13	0.8031
Age (Year)	Median (Range)	63(43–81)	72(54–82)	0.0499*
BMI (Kg/m^2)	Median (Range)	22.1(13–37)	24.6(15.8–34.4)	0.1614
LUL:LLL		24:10	8:7	0.2422
RUL:RLL		7:2	9:5	0.4925
Upper:Lower		31:12	17:12	0.2342
FEV1 (%)	Median (Range)	30(13.8–63)	35.3(17–62)	0.0110*
DLCO (%)	Median (Range)	36.9(10.7–84)	38(19–61)	0.3144
RV (%)	Median (Range)	200(43.2–350.6)	211(130–289)	0.1316

Note: *statistically significant (p<0.05).
Abbreviations: BMI, indicates body mass index; LUL, left upper lobe; LLL, left lower lobe; FEV1, forced expiratory volume in one second; DLCO, carbon monoxide diffusion capacity; RV, residual volume.

when the cumulative stay including further admissions is taken into account, EBLVR with SP [11.5(2–84) days] had the longest LOS than ELBVR requiring redo procedures [5(2–84) days] or RATS LVRS group [3(2–80) days]. Uncomplicated EBLVR group [2(1–61) days] had the shortest total LOS (p<0.001) (Table 7).

Post-Endobronchial Lung Volume Reduction Spontaneous Pneumothorax

SP as a result of EBLVR was seen in 32.2% (28/87) at a median post-operative interval of 1 day. In 5 patients, no intervention was required whilst intercostal drainage was needed in the remaining 23 patients for a median duration of 8 (3–30) days. VATS bullectomy and pleurodesis were required for control of PAL in 7 of these cases.

Prediction of Spontaneous Pneumothoraces (Table 8)

Analysis of the pre-operative StratX reports found no association between post EBLVR-SP and the relative volume of the non-target lobe (p=0.345). However, there was an association between post EBLVR-SP and a higher emphysema score (as measured by Voxel density) in the non-target lobe: <910 HU 55% (49.8–64.5) (p=0.007, OR=1.055); <950 HU 31% (24.3–37.3) (p=0.007, OR=1.064).

SP was associated with a lower ratio of emphysema severity between target and non-target lobes: voxel density <950 HU 1.16 (0.96–1.59) (p=0.011). However, there was no difference in the ratio of target to non-target group in quantitative radionuclide perfusion on SPECT scan between the two groups (p=0.834).

Readmission to Hospital

After RATS LVRS, 8.4% (7/83) were readmitted with treatment-related complications with time interval of median 9(1–69) days: 3 for medical management of COPD exacerbation and 4 with a new ipsilateral pneumothorax. Of these 4 patients, 2 were managed with intercostal drainage alone; 1 required a further VATS procedure and 1 was managed conservatively.

Readmission for revisional bronchoscopy was required in 30.8% (29/94) at a median post-operative interval of 6(1–40) months. The indications were as follows: loss of initial benefit in 18 (64%); no initial benefit in 4 (14%); symptomatic intolerance, such as worsening breathlessness in 3 (11%); haemoptysis in 2 (7%) and secondary infection in 1 (4%). The findings at redo bronchoscopy were: valve obstruction in 15 (8 due to mucus, 7 due to granulation tissue),

Table 8 Factors Predicting Post EBLVR-SP from the StratX Report

Parameter		No SP (N=59)	SP (N=28)	OR	95%CI		p value
Laterality	Left Right	39 (66.10%) 20 (33.90%)	19 (67.86%) 9 (32.14%)	1 0.924	0.354	2.41	0.871
Target Lobe	Lower Upper	23 (38.98%) 36 (61.02%)	8 (28.57%) 20 (71.43%)	1 1.597	0.604	4.224	0.345
Volumetric Ratio	Median (quartiles)	1.09 (0.89–1.3)	1.06 (0.92–1.16)	1.041	0.197	5.506	0.962
% <910 HU Target	Median (quartiles)	60 (53–66)	63 (60–68.5)	1.02	0.975	1.067	0.383
% <910 HU Non-Target	Median (quartiles)	40 (31–55)	55 (49.75–64.5)	1.055	1.015	1.097	0.007*
% <910 HU Target: Non-Target Ratio	Median (quartiles)	1.5 (1.17–1.64)	1.09 (0.98–1.25)	0.555	0.203	1.516	0.251
% <950 HU Target	Median (quartiles)	35 (20–50)	41 (35–45.25)	1.018	0.982	1.055	0.34
% <950 HU Non-Target	Median (quartiles)	16 (9–31)	31 (24.25–37.25)	1.064	1.017	1.113	0.007*
% <950 HU Target: Non-Target Ratio	Median (quartiles)	2 (1.4–2.41)	1.16 (0.96–1.59)	0.276	0.102	0.745	0.011*
Perfusion Ratio	Median (quartiles)	0.36 (0.28–0.67)	0.46 (0.24–0.77)	0.996	0.959	1.034	0.834

Note: *statistically significant (p<0.05).
Abbreviations: HU indicates Hounsfield units; SP, spontaneous pneumothorax; OR, odds ratio; CI, confidence interval.

valve expectoration 6, perivalvular leakage 5 and bacterial valve colonisation 1. In 2 there were no specific findings. Radiological abnormalities of the valves were reported prior to redo bronchoscopy in only 12 (41.4%) cases and included: loss of volume reduction in 7 and valve migration in 5. The need for revisional bronchoscopy after EBLVR was associated with an older population with less airway obstructions (Table 8).

After revision, there was radiological response (lobar collapse) in 22 patients and both radiological and symptomatic improvement in 19 (65.5%) patients.

Mortality

There was no correlation between mortality and the peri-operative complications. 30-day or 90-day mortality were the highest (8.1%) with the patients with uncomplicated EBV, followed by the patients with SP and RATS LVRS. The patients who underwent EBV requiring redo procedures had 0% 30-day or 90-day mortality (Table 9).

Discussion

We have continued to offer EBLVR rather than LVRS as the preferred option to all suitable patients including making the final decision intraoperatively having consented them for both procedures. We have not reserved EBLVR for higher risk patients. We acknowledge that EBLVR can be performed under sedation in a non-operating theatre setting, but we have no experience of this in our institution. We acknowledge that our comparison deals strictly with EBLVR under GA. This also enables us to offer both options of EBLVR or LVRS under the same anaesthetics. Our results successfully demonstrate that uncomplicated preferential EBLVR requires less time in the operating theatre, less use of critical care facilities and results in a significantly shorter stay in hospital than RATS LVRS in comparable groups.

However, somewhat surprisingly, we have found that only 4 in every 10 patients undergoing EBLVR have an uneventful outcome. Of the remainder approximately half will develop a post-procedural pneumothorax and half will require revisional bronchoscopy. When the outcome from EBLVR is complicated then the use of operating theatre time and hospital beds is similar to LVRS.

Our rate of revisional bronchoscopy is not unusually high and indeed is almost identical to that reported by Roodenburg et al.[6] The most common indications of their revisional bronchoscopy include loss of initial treatment effects for 43%, and 53% were found to have granulation tissue during the procedures.[19] This is reflected in our similar findings that the majority requiring revisional bronchoscopy lost the initial benefit of EBLVR which was mainly due to valvular obstruction. As we could not identify any predictive factors for the need of revisional bronchoscopy we suggest that clinicians should maintain a high level of vigilance in follow-up after EBLVR and have a low threshold for a "second-look" bronchoscopy if the clinical outcome is unsatisfactory. We have not found that a valvular problem can necessarily be seen on imaging. The outcome of revision is largely successful justifying the process. However, there remains a small minority who need to proceed to salvage LVRS.

Our rate of post EBLV-SP is higher than other reported series.[13,14] This may be attributed to our selection of patients without clear anatomical heterogeneity on CT but clear underperfused targets lobes on SPECT. This hypothesis is supported by our finding that post EBLVR-SP was associated with the absolute severity of emphysema in the ipsilateral non-target lobe and its similarity in severity to the target lobe.

On the development of SP, we did not remove the valves as suggested by experts' opinion (which comprised non-surgical pulmonologists) in the field.[19] Instead, rather than consider these as examples of "traumatic" pneumothorax as has

Table 9 30-Day or 90-Day Mortality

Mortality	RATS LVRS (N=83)	Uncomplicated EBV (N=37)	EBV with SP (N=28)	EBV with Redo Procedures (N=29)
30-Day	4.82%	8.1%	7.14%	0%
90-Day	6.02%	8.1%	10.7%	0%

Abbreviations: RATS, indicates robot-assisted thoracoscopic surgery; LVRS, lung volume reduction surgery; EBLVR, endobronchial valve lung volume reduction; SP, spontaneous pneumothorax.

been suggested, we chose to manage the complication as we would for any secondary SP from underlying emphysema. If PAL persisted over 7 days, we proceeded to VATS bullectomy and pleurodesis. Not only is the removal of EBV associated with COPD exacerbation[20] but the patient is returned to their original state of hyperinflation (and in need of a further LVR procedure). However, they have a potentially greater source of recurrent SP which remains untreated. The reluctance in many to recommend surgery for post EBLV-SP may reflect either the lack of on-site surgical opinion in many pulmonology centres performing EBLV, or the misapprehension that EBLVR is suited to those at excessively high-risk for LVRS.

We here report our experience since switching exclusively from biportal or triportal VATS to RATS LVRS. We have not focused on any comparison between these minimally invasive surgical methods. We reserve the use of VATS in these patients for the treatment of post-EBLVR SP. The perceived advantages of RATS over VATS for LVRS include the benefit of a capnothorax to improve exposure in the presence of air trapping in the operated lung; the use of NIR thoracoscopy and intra-operative ICG to better identify target areas of poor perfusion, and the benefits of "intelligent" surgical staplers. The most advanced new energy powered staplers, such as SureForm, eliminate the manual firing force and possibly enable more precise resection. Zervos et al have demonstrated that robotic surgical staplers are associated with reduced risk of AL and overall complications.[21] In addition, the incidence of PAL was significantly lower in the powered stapler group than in the manual stapler group.[22] Rathinam et al previously suggested that overall median hospital stay for LVRS was 13 days,[23] but our median hospital stay is now only 8 days. This may be explained by the improved performance from robotic surgical staplers.

The intra-operative use of ICG to identify emphysematous areas has limited evidence.[24] It has been reported to identify bullae in the treatment of SP in non-diffuse emphysema.[25,26] The definition of target areas is less obvious in diffuse emphysema, but it may lead to placing the staple lines through more well-perfused tissue leading to reduced AL.

As we have not randomised allocation of treatment modalities it could be argued that since some in the LVRS group were not suitable for EBLVR due to CV, their COPD could be more severe, or their emphysema scores were higher perpetuating post-operative AL and use of hospital bed days. The series also begins with our initial experience with RATS LVRS, although we had extensive prior experience in EBLVR. Therefore, the results may have been confounded by a learning curve effect in RATS LVRS.

The CELEB trial had relatively limited recruitment and was powered only for non-inferiority, thus there is a need for a larger prospective, possibly blinded trial, to compare EBLVR and RATS LVRS. We also hope to be able to undertake a more detailed economic analysis of the relative cost-effectiveness of the two treatments to improve the validity of the comparison. Further research could be suggested to develop a more accurate predictive tools to acknowledge and indicate that future prospective trial involving prophylactic drainage is proposed.

Conclusion

The widely held assumption that EBLVR offers a quicker and simpler alternative to LVRS should be challenged. The attraction of reduced use of theatre capacity and hospital bed resources should be balanced against the need for readmission and reoperation. If EBLVR is uncomplicated then it does indeed use fewer hospital resources. Whilst some complications ie post-procedural pneumothorax can be predicted and at risk patients counselled, the need for revision of EBLVR is unpredictable. The realisation of the limitations of EBLVR should be considered together with advances in LVRS from the use of robotic technology in the consent process for volume reduction.

Abbreviations

AL, Air Leak; ASA, American Society of Anesthesiologists; BLVR, Bronchoscopic Lung Volume Reduction; BMI, Body Mass Index; COPD, Chronic Obstructive Pulmonary Disease; CV, Collateral Ventilation; CRS, Care Record Service; DLCO, Carbon Monoxide Diffusion Capacity; EBLVR, Endobronchial Lung Volume Reduction; EBV, Endobronchial Valve; FEV1, Forced Expiratory Volume In One Second; FVC, Forced Vital Capacity; HDU, High Dependency Unit; HU, Hounsfield Units; ICG, Indocyanine Green; ITU, Intensive Care Unit; KCo, Carbon monoxide transfer coefficient; LOS, Length of Stay; LVRS, Lung Volume Reduction Surgery; MDT, Multidisciplinary Team; MRC, Medical Research Council; NETT, National Emphysema Treatment Trial; NIR, Near-Infrared; NHS, National Health Service; QCT, Quantitative Computed Tomography; RATS, Robot-Assisted Thoracoscopic Surgery; RV, Residual

Volume; VATS, Video-Assisted Thoracic Surgery; SD, Standard Deviation; SP, Spontaneous Pneumothorax; SPECT, Single-Photon Emission Computed Tomography; TLC, Total Lung Capacity.

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