Review Article

Pulmonary hemodynamics and lung surgery: a narrative review

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Contributions: (I) Conception and design: EJ Couture; (II) Administrative support: EJ Couture; (III) Provision of study materials or patients: None; (IV) Collection and assembly of data: None; (V) Data analysis and interpretation: None; (VI) Manuscript writing: Both authors; (VII) Final approval of manuscript: Both authors.

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Background and Objective: Lung cancer represents the leading cause of death from cancer. In suitable patients, lung resection surgery provides the highest chance of cure and thus it is one of the most commonly performed thoracic surgeries. Lung resection surgeries, including lobectomy and pneumonectomy are associated with high rates of cardiopulmonary complications. These complications may cause long-term morbidity which can be unrelated to the degree of lung function reduction. In particular, these sequelae could be due to cardiac impairment. These complications must be taken into consideration in the management of patients. The aim of the presented narrative review is to revisit the anatomy, the physiologic considerations of the right ventricle and pulmonary artery unit as well as the pre-operative hemodynamic and functional evaluation to understand the impact of one-lung ventilation and lung resection on pulmonary hemodynamics.

Methods: An extended review of the literature through PudMed was conducted using the keyword related to pulmonary hemodynamics, right ventricular function, lung resection and preoperative cardiovascular evaluation. Publications in English and French, published before October 29th 2021, were considered.

Key Content and Findings: Relative reduction in right ventricular function happens following lung resection due to increased pulmonary vascular resistance and reduced lung compliance. Several components of the peri-operative care including pre-operative preparation, epidural analgesia and one-lung ventilation can influence cardiovascular performance after lung resection surgery. The surgical approach can also have an influence as patients that underwent video-assisted thoracoscopic surgery (VATS) generally had higher right heart systolic function compared to thoracotomy patients.

Conclusions: Several components that are part of the peri-operative care of patient undergoing lung surgery can influence cardiovascular physiology.

Keywords: Right ventricular function; one-lung ventilation; hemodynamic; risk stratification

Received: 29 June 2021; Accepted: 23 June 2022; Published online: 18 July 2022.
doi: 10.21037/ccts-21-33
View this article at: https://dx.doi.org/10.21037/ccts-21-33

Introduction

Lung cancer represents the leading cause of death from cancer. The best chance of cure in suitable patients is through lung resection surgery which represent one of the most frequently performed thoracic surgery. Implications of lung resection surgery such as lobectomy and pneumonectomy, include a high rate of cardiopulmonary complications (1). These complications may cause long-term morbidity that is not necessarily related to the degree of lung function reduction (2,3). In fact, it may be a result of cardiac impairment (4,5). These complications must be taken into consideration in the management of these vulnerable patients.

This review will discuss anatomic and physiologic considerations of the pulmonary vascular unit.

Table 1 The search strategy summary

Items	Specification
Date of Search	October 29th, 2021
Databases and other sources searched	PubMed
Search terms used	Pulmonary artery pressure, ventriculo-arterial coupling, right ventricular function, lung resection, preoperative cardiovascular evaluation
Timeframe	Before October 29th, 2021
Inclusion and exclusion criteria	Publications in English and French were considered
Selection process (who conducted the selection, whether it was conducted independently, how consensus was obtained, etc.)	The selection process was conducted by the authors

Intraoperative factors affecting the right ventricular function will be presented. The impact of lung resection, surgical approach, epidural analgesia, fluid therapy, and one-lung ventilation on the right ventricular function will be explored. Finally, the role of pre-operative hemodynamic and functional evaluation will be examined with a focus on risk stratification. We present this article in accordance with the Narrative Review reporting checklist (available at: https://ccts.amegroups.com/article/view/10.21037/ccts-21-33/rc).

Methods

An extended review of the literature through PudMed was conducted using keywords related to pulmonary hemodynamics including "pulmonary artery pressure" and "ventriculo-arterial coupling" and "right ventricular function" in conjunction with "lung resection" and "preoperative cardiovascular evaluation". Publications in English and French, published before October 29th 2021, were considered (*Table 1*). The extracted literature has been evaluated in order to identify important anatomic and physiologic considerations related to the effects of lung resection on pulmonary hemodynamics. A special interest has also been placed on the preoperative evaluation specific to lung resection surgery.

Anatomy of the pulmonary vascular unit

The lung's arterial vasculature is composed of two parallel systems: the pulmonary circulation and the bronchial circulation. The pulmonary circulation is comprised of main pulmonary artery and its branches that deliver the mixed systemic venous blood to the alveolar capillaries in order to promote gas exchange. This capillary network is a large and low resistance reservoir for the entire cardiac output and is propagated by the right ventricle (6).

The bronchial arteries mainly originate from the descending thoracic aorta between the T5 and T6 level. The ostia of the right and left bronchial arteries are generally located on the anteromedial and anterolateral aspect of the thoracic aorta. They provide oxygenated blood to the bronchial tree (7). Approximately 1% to 4% of cardiac output is distributed to the bronchial artery blood flow (8). Bronchial arteries also assume a vital role in airway immune defense, fluid balance and metabolic functions of the lung by providing nutritional support to the airway structures. In addition, bronchial arteries are a constant source of heat and moisture, effectively warming and humidifying the inspired air. Bronchial arteries are sacrificed during the lung transplantation process. This leads to persistent hypoxia in the transplanted lung, which may be the cause of chronic allograft dysfunction (9). Most of the bronchial arteriolar blood drains into the bronchial venous system which drains into pulmonary veins. Bronchial veins are located around segmental and subsegmental bronchial and will empty in the azygos and hemiazygos systems (6). A small portion of the bronchial venous drainage thus mixes with the pulmonary venous drainage resulting in a small physiological shunt (10).

The pulmonary vasculature can maintain low pulmonary blood pressures despite the high flow. This physiologic phenomenon is due to the relatively high compliance of the thin-walled pulmonary artery with far fewer arterial vascular smooth muscle cells compared to systemic arteries of similar size. This highly compliant pulmonary arterial system can accommodate an average of 3.2 L/min/m^2 blood flow at rest to more than 6 times that blood flow during exercise (11). The pulmonary vascular resistance is 1/10th to 1/8th that of

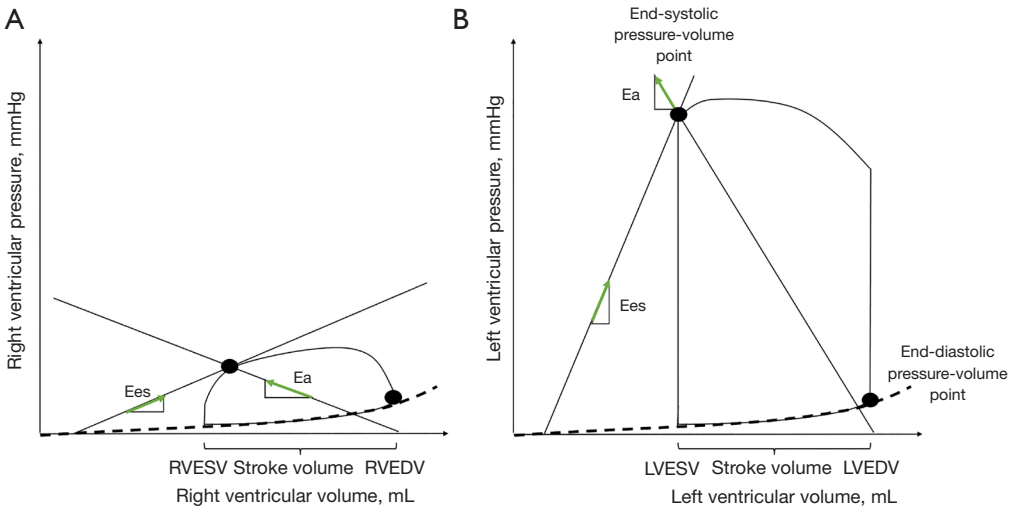


Figure 1 Ventricular pressure-volume loop. Hemodynamic analysis from (A) right and (B) left ventricular pressure-volume loop. The slope of the end-systolic pressure-volume relation is defined by the ventricular elastance (E_{es}) whereas the slope joining the end-systolic and end-diastolic pressure-volume point describes arterial elastance (E_a). Note the more trapezoidal or irregular shape of the right pressure-volume loop compared to the more sharply defined rectangular shaped left ventricular pressure-volume loop. Compared with the left ventricular pressure-volume loop, the right ventricular pressure-volume loop exhibits a much lower end-systolic pressure, as well as less-defined isovolumic relaxation and contraction periods. The right ventriculo-arterial coupling is obtained by the E_{es}/E_a ratio. Cardiac efficiency or normal ventriculo-arterial coupling would be achieved when E_{es}/E_a =1 and maximizes at E_{es}/E_a =2 meaning that the right ventricular contractility is able to overcome its afterload. A gradual decoupling would reflect an E_{es}/E_a <0.5 meaning that the right ventricular contractility is not enough to overcome its afterload. This decoupling situation can be secondary to increase in right ventricular afterload (E_a) or a decrease in right ventricular contractility (E_{es}). E_a, arterial elastance; E_{es}, right ventricular elastance; LVEDV, left ventricular end-diastolic volume; LVESV, left ventricular end-systolic volume; RVEDV, right ventricular end-diastolic volume; RVESV, right ventricular end-systolic volume.

the systemic vascular resistance, which helps enable the right ventricle to match the left ventricular output (12-14). The high vascular compliance and low vascular resistance of the pulmonary arterial system explains how the right ventricle is capable to accommodate volume (preload) and performs best under low afterload conditions compared to the left ventricle that works in a highly pressurized system (*Figure 1*).

Physiology of the pulmonary vascular unit

The high compliance of the pulmonary arterial system allows the right ventricle to work within a lower pressure range than the systemic circulation allows for the left ventricle. The high compliance of the right ventricle & pulmonary artery system is defined by the capacity of the pulmonary artery to accommodate a large blood volume with minimal change in pressure (15). Approximately 20% of the compliance of the pulmonary arterial system is assumed by the large and easily distendable proximal arteries whereas the remaining compliance is made up by distal pulmonary vessels as small as 1 mm in diameter that can distend and accommodate volume, which is distinct from the systemic circulation (15,16). On the other end, the small and distal vessels in the lung are recognized as the largest contributor of the force opposing its ejection, namely, the pulmonary vascular resistance (PVR). This distal capillary pulmonary vascular resistance can be quantified through Hagen-Poiseuille's Law: ($R = n\ L/r^4$) where "n" is the viscosity of the blood, largely influenced by the hematocrit, "L" is the length of the vessel and "r" is its radius. PVR is mainly generated in the small arteries due to its exponential relationship with blood vessel radius. Hence, increase in alveolar and pleural pressure will be transmitted to the distal vascular structures impacting vascular resistance from compression.

The pulmonary vascular resistance is increased by hypoxia, acidosis, hypercarbia, hypothermia, high hematocrit, high airway pressures as well as anatomic factors such as pulmonary emboli, primary pulmonary hypertension, or left heart conditions such as mitral valve stenosis or regurgitation, and systolic or diastolic left

ventricular dysfunction (17). Many factors influencing these determinants during and after lung resection surgery will be reviewed in the next section.

Hemodynamics monitoring during lung resection surgery

It is recommended to use intra-arterial line for pressure monitoring during thoracic surgery essentially due to the risk of sudden change in hemodynamics, hemoglobin, and blood gas concentration (18). Despite the absence of studies specific to thoracic surgery patients, studies in the general surgical population have demonstrated an association between intra-operative hypotension and major adverse cardiac or cerebrovascular events after non-cardiac surgery (19).

Advanced hemodynamic monitoring can be achieved using various methods including arterial pulse contour analysis and esophageal Doppler to guide fluid and vasoactive medication in patients at risk of intra-operative hemodynamic instability (18,20,21). However, pulse pressure and stroke volume variation have been found to be inaccurate to predict fluid responsiveness in thoracotomy and video-assisted thoracoscopic surgery (VATS) (22,23). This might be due to various reasons including: (I) the positive pressure ventilation being transmitted to the atmosphere through the chest wall opening, (II) the change in heart-lung interaction from the nonventilated lung not being able to produce intra-thoracic cycling pressure change, and (III) the shunt flow in the nonventilated lung not contributing to the stroke volume and pulse pressure variation, and (IV) the surgical manipulation directly affecting heart-lung interaction from mechanical compression of mediastinal structures (22). Central venous catheters are not routinely inserted in patients undergoing lung resection surgery for hemodynamic monitoring purposes. Pulmonary artery catheters or transesophageal echocardiography may be used in very selected patients at risk of developing right ventricular dysfunction secondary to pulmonary hypertension during one-lung ventilation. When using transesophageal echocardiography, the clinician must keep in mind the possible difficulties related to position of the patient, the risk of trauma to oropharyngeal and esophageal structures and possible subsequent dysphagia (24).

Definition of right ventricular dysfunction associated with non-cardiac thoracic surgery

There is no common definition of right ventricular dysfunction in the context of thoracic surgery. Generally, right ventricular dysfunction is commonly used to describe abnormal right ventricular function per echocardiographic or hemodynamic evaluation without resulting end-organ injury. In contrast, acute right ventricular failure is generally defined as a state of rapidly progressive systemic congestion due to impaired right ventricular filling or diminished forward flow (25). The International Right Heart Failure Foundation Scientific Working Group defines right heart failure as a clinical syndrome that can be due to an alteration of structure and/or function of the right heart circulatory system that leads to sub-optimal delivery of blood flow to the pulmonary circulation and/or elevated venous pressures at rest or with exercise (26). The definition used by the sixth World Symposium on Pulmonary Hypertension used to guide medical management, extracorporeal life support, and lung transplantation in patients with right-sided heart failure due to pulmonary hypertension includes a grade of severity characterized by secondary organ dysfunction of the liver, kidneys, or gut (27). Finally, the Interagency Registry for Mechanically Assisted Circulatory Support (INTERMACS) registry defines right ventricular failure as an elevated central venous pressure of more than 16 mm Hg with clinical manifestation including end-organ dysfunction (28). Due to the presence of various definitions based on different parameters, it is difficult to estimate the exact incidence of right ventricular dysfunction associated with thoracic surgery.

Hemodynamic changes and right ventricular function associated with lung resection surgery

In the next section the effects of (I) lung resection, (II) surgical approach, (III) fluid administration, (IV) epidural analgesia, and (V) one lung ventilation will be reviewed.

Effect of lung resection

Several studies described a 15% to 25% relative reduction in right ventricular ejection fraction following lung resection (29-34). Patients undergoing a greater decline in right ventricular function are more likely to experience postoperative complications (32-34). Among these patients, late postoperative cardio-pulmonary symptoms were related to impaired intraoperative right ventricular function (31).

The primary mechanism of reduced right ventricular function after lung resection surgery is thought to be related to increased pulmonary vascular resistance (31,32,35). Further, the use of one-lung ventilation and pulmonary

artery clamping has been associated with an increase in pulmonary vascular resistance. Despite being abrupt during surgery, these changes are generally not sustained long after surgery with a return to normal in less than 24 h after surgery (29,30,35).

The type of lung resection, whether being a lobectomy or a pneumonectomy, can influence resultant hemodynamic changes. Compared to preoperative values, both surgical approaches influence postoperative hemodynamics by increasing heart rate, mean pulmonary artery pressure, pulmonary capillary wedge pressure, and pulmonary vascular resistance as well as decreasing right ventricular ejection fraction. It was reported that patients undergoing pneumonectomy had higher mean pulmonary artery pressures, pulmonary vascular resistance, and pulmonary capillary wedge pressures compared to patients undergoing lobectomy. The patients who underwent pneumonectomy had a higher degree of right ventricular dilation, a higher incidence of post-operative arrhythmias, and a greater reduction in right ventricular ejection fraction than lobectomy patients. This suggests that the amount of parenchymal resection may be proportional to the subsequent increase in right ventricular afterload and degree of right ventricular systolic dysfunction (36).

Effect of surgical approach

Technological evolution of the surgical approach has resulted in faster post-operative patient recovery. In addition to a shorter length of stay, VATS is associated with a lower incidence of major complications including atrial fibrillation, atelectasis, prolonged air leak, acute kidney injury, and pneumonia when compared to a thoracotomy approach (37). Robot-assisted thoracic surgical lobectomy does not appear to confer added benefit with regards to mortality and morbidity when compared to VATS (38,39).

Despite the benefits of VATS over thoracotomy, the effect of the surgical approach on the post-operative right ventricular function is not so clear. A first study by Mikami *et al.* showed that 24 h after surgery, lung cancer patients that underwent VATS had higher right ventricular ejection fraction, cardiac and stroke volume index compared to thoracotomy patients. In fact, it is thought that the larger damage to the chest wall by extensive surgical incision, the amount of surgical manipulations in addition to the extent of lung resection could explain the larger increase in pulmonary vascular resistance after a thoracotomy leading to reduced right ventricular performance (40). This suggests that the VATS approach might be protective and allow for a compensatory hyperdynamic phase throughout the first postoperative day which could contribute to a faster recovery from the intervention (40). However, their results were not replicated by Yamagishi *et al.* In fact, this group compared VATS with muscle-sparing thoracotomy and found that at 36 h perioperatively, the VATS group had a greater reduction in the mean pulmonary artery pressure, pulmonary capillary wedge pressure and total pulmonary resistance index compared to the thoracotomy group. Despite this benefit in term of afterload reduction, there were no significant differences between the two groups in right ventricular performance assessed by continuous cardiac output monitoring system from pulmonary artery catheter (41). It is difficult to draw definitive conclusions from these small studies. Right ventricular performance is affected by the extend of lung resection. Thus, it can be assumed that extensive lung resection will be associated with more lung parenchymal injury and pulmonary vasospasm from surgical interventions leading to more pronounced hemodynamic variation. These changes in pulmonary vascular resistance and right ventricular performance are more related to the extent of lung resection instead of the inherent surgical approach chosen to perform lung resection (40,41).

Effect of fluid administration

Fluid overload is being recognized as a major preventable intra-operative risk factor for acute lung injury after thoracic surgery (42). Moreover, a 5 % positive cumulative fluid balance (cumulative fluid input minus output) in liters × 100/hospital admission weight (kg) during and up to 24 h after lung cancer surgery has been associated with a higher rate of 30-day unplanned re-admission (43). This has led to a more restrictive approach where the balance between lung complication and end-organ hypoperfusion may be difficult to find. In fact, the incidence of acute kidney injury is reported to be between 5% and 7% in lung resection surgery and is associated with an increased rate of re-intubation, prolonged mechanical ventilation, intensive care unit stay, hospital stay and higher mortality (44,45). This highlights the importance of judicious fluid administration to improve clinical outcome and consequently reduce resource utilization.

Ideal and optimal fluid management stand close to the near-zero fluid balance rather than being restricted or liberal; the former inducing complication related to hypoperfusion, the latter inducing complication related

to tissue edema and right heart dysfunction (18). A recent retrospective cohort study divided patients undergoing open thoracotomy into three groups: low (≤3 $mL \cdot kg^{-1} \cdot h^{-1}$), moderate (4–5 $mL \cdot kg^{-1} \cdot h^{-1}$) and high (≥6 $mL \cdot kg^{-1} \cdot h^{-1}$) fluid infusion rate from the beginning of the surgery to 24-h post-operative. The moderate group showed the lowest pulmonary and renal composite complication rate (46). Interestingly, the nature of lung injury after lung resection seems to be related to ventilator induced lung injury rather that increase in pulmonary capillary hydrostatic pressure. This highlights the fact that post-operative lung injury can occur even in euvolemic patients, however, it is exacerbated in hypervolemic states (47). This concept is supported by the fact that before the era of lung protective ventilation strategies, large tidal volume ventilation, alone or in combination with high intraoperative fluid administration, has been identified as an independent risk factor for continuation of mechanical ventilation for greater than 48 h after pneumonectomy (48-51). Excessive fluid administration can thus create additional strain on the right heart already affected by increase in afterload from pneumonectomy. Goal directed fluid therapy represents an opportunity to adapt fluid therapy to individuals in order to reduce post-operative complications, especially in high-risk patients (18).

Effect of epidural analgesia

The use of thoracic epidural analgesia is widely used in thoracic surgery as well as upper abdominal surgery. Thoracic epidural analgesia is associated with cardiac sympathectomy (T1 to T5) that reduces preload and partly suppresses baroreceptor reflexes that cause bradycardia and hypotension through a Bezold-Jarisch reflex (52). In fact, this physiologic response is mediated through chemical and mechanical stimulation in the setting of reduced end-systolic volumes that activate ventricular chemo- and mechanosensor. This sensor activation creates a decrease in sympathetic outflow and increase in parasympathetic tone leading to bradycardia, decrease in systemic vascular resistance and ultimately hypotension (52).

Cardiac sympathetic blockade following thoracic epidural anesthesia results in a significant reduction of load-independent indicators of left and right ventricular contractility with minimal changes of diastolic function (52,53). However, the clinical implications of that reduction in contractility are not fully elucidated. Thoracic epidural anesthesia improves myocardial oxygen balance in patients with ischemic heart disease by increasing myocardial performance and reducing the number and duration of ischemic episodes. In patients with pulmonary hypertension, this analgesic modality may limit the capacity of the right ventricle to adapt to situations of rapid increase in right ventricular afterload (52).

Effect of one-lung ventilation

One-lung ventilation increases the risk of hypoventilation and hypoxemia, hence, anesthesia management should be adapted to reduce its incidence to a minimum (51,54). Reducing the risk of hypoventilation and hypoxemia is paramount in order to decrease the risk of developing acute pulmonary hypertension and consequently, right ventricular dysfunction that could precipitate complications due to high systemic venous pressures such as bleeding and acute kidney injury. The effect of hypoxia on right ventricular performance has been explored in healthy young subjects that were exposed to low ambient oxygen concentrations (11% inspired) for up to 150 min. Compared to control subjects who were exposed to 21% inspired oxygen, subjects receiving the hypoxic gas mixture showed right ventricular dilation, reduced right ventricular systolic function, and an increase in right ventricular systolic pressure. This right ventricular systolic pressure (RVSP) increase was reversed to 50% of the maximum increase after supplementing 4-liter oxygen per minute via facemask for one minute (55). In a similar fashion, hypercapnia in acute respiratory distress syndrome (ARDS) is recognized as a predictor of acute cor pulmonale in patients receiving low tidal volume ventilation for acute respiratory distress syndrome (ARDS) (56). From a mechanical perspective, the "U-shaped" relationship between functional residual capacity and PVR renders one-lung ventilation a situation where poorly ventilated atelectatic zones and overdistended zones may both contribute to an increase in PVR and decrease right ventricular global performance (*Figure 2*).

A ventilation strategy protective of the right ventricle has been proposed by Paternot *et al.* in the context of acute respiratory distress syndrome (57). This approach aims to protect right ventricle by reducing the lung stress with reduction of tidal volumes to reduce plateau pressure (<27 cmH_2O) and driving pressure (<18 cmH_2O), and improve oxygenation (PaO_2/FiO_2 >150). It further aims to use the best positive end-expiratory pressure (PEEP) and FiO_2 combination to reverse hypoxic pulmonary vasoconstriction, and to correct hypercapnia ($PaCO_2$ <48 mmHg) by adequately increasing respiratory rate and

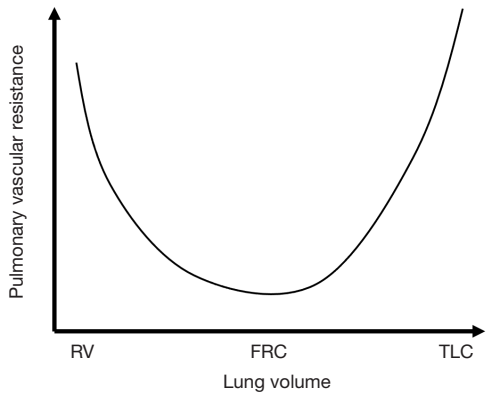


Figure 2 Relationships between pulmonary vascular resistances and lung volume. At functional residual capacity, pulmonary vascular resistances are at their lowest point. FRC, functional residual capacity; RV, residual volume; TLC, total lung capacity.

thus alveolar minute ventilation (57). These concepts have been developed and validated in acute respiratory distress syndrome patients with closed chests that received two-lung ventilation. Their applicability and benefits have not yet been evaluated in non-ARDS patients receiving one-lung ventilation.

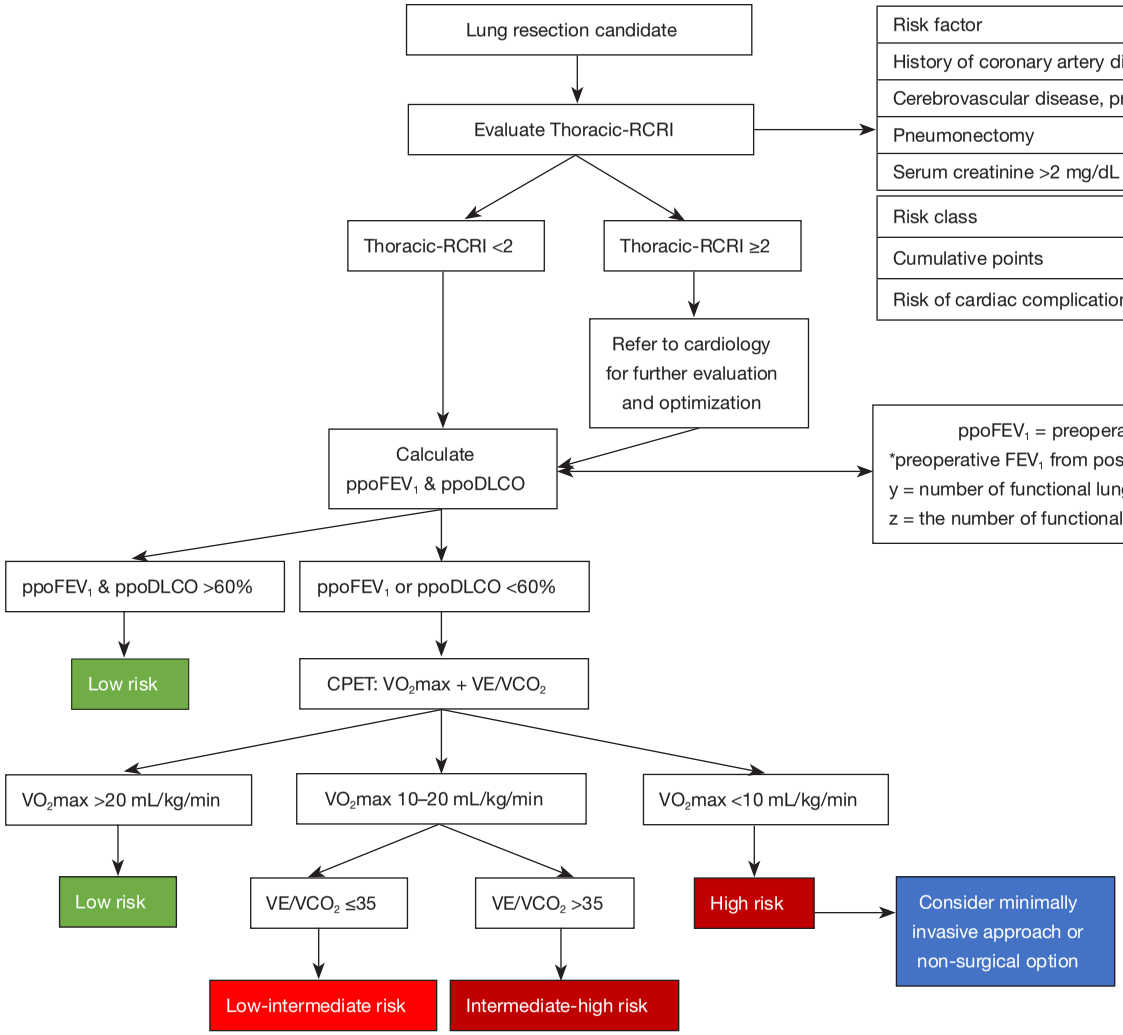
A recent prospective multicenter study showed that an open-lung approach during one-lung ventilation consisting of alveolar recruitment maneuvers, tidal volumes of 5 to 6 mL/kg predicted body weight to maintain plateau pressure of 25 cmH_2O or lower, combined with a maximum PEEP of 20 cmH_2O follow by an individualized PEEP according to the highest dynamic compliance, led to reduced driving pressures and improved pulmonary outcomes (58). A multicenter randomized trial to evaluate the effect of an open-lung approach on outcomes during one-lung ventilation is currently ongoing (PROTHOR trial; NCT 02963025). It is not known if such an approach could lead to improvement in post-operative right ventricular function. Meanwhile, a reasonable approach to perform mechanical ventilation during one-lung ventilation include the use of tidal volumes of 4 to 6 mL/kg predicted body weight, starting PEEP of 5 cmH_2O and adjustment to aim for a driving pressure <14 cmH_2O (51,59). A lung protective protective approach using lower airway pressure reduced the incidence of ventilation induced lung injury and improve right ventricular function during one-lung ventilation (60). In addition, management of mechanical ventilation should be adapted to reduce hypoxemia and hypercapnia.

Pre-operative cardio-pulmonary evaluation

Preoperative cardiovascular risk evaluation is pivotal in patients undergoing non-cardiac thoracic surgery due to the 2–3% risk of major postoperative cardiac complications within the first 30 days after surgery that account for over one third of peri-operative deaths (61,62). Moreover, these cardiac complications can worsen the intermediate and long-term prognosis of the thoracic malignancies being treated operatively (63).

Revised Cardiac Risk Index (RCRI) incorporate 6 risk factors to predict major cardiac complication after major noncardiac surgery; (I) high-risk surgery, (II) history of ischemic heart disease, (III) history of heart failure, (IV) history of cerebrovascular disease, (V) diabetes mellitus treated with insulin and (VI) preoperative serum creatinine >2.0 mg/dL (64). RCRI considers patient factors more than the risk of the operation. This may lead to excessive consultations, pre-operative testing, costs, and delays before surgery (63). Moreover, RCRI has not been a reliable predictor of cardiac events in patients undergoing lung resection or vascular surgery. For these reasons, the Thoracic-RCRI was proposed as a modification of the RCRI for patients undergoing lung resection. In fact, the Thoracic-RCRI has removed the presence of heart failure and high-risk surgery from the original RCRI. It also reduced the weight of the preoperative serum creatinine >2.0 mg/dL in the risk calculation (61,62,65-69). The American College of Chest Physicians recommends that patients with a RCRI >2 or Thoracic-RCRI >1.5 undergo a formal cardiology evaluation (70). Also, it is recommended that patients scheduled to undergo lung resection have a cardiology evaluation, if they have a cardiac condition requiring medication, recent diagnosis of active heart disease, or limited exercise capacity (inability to climb 2 flights of stairs) (71). It must be kept in mind that the majority of the risk prediction tools in lung resection surgery do not include right ventricular function or pulmonary hypertension as a variable in their algorithm.

Cardiopulmonary stress testing should be performed to assess functional capability and refine the patient's risk (*Figure 3*) (68,70). It has been shown that pre-operative right ventricular ejection fraction (RVEF) assessed by thermodilution, at rest and at exercise, could be useful to identify patients at risk of post-operative complications. In fact, reduction of RVEF during exercise has been shown to be associated with post-operative complications in a larger proportion than patients with increased RVEF at



Risk factor	Points
History of coronary artery disease or previous ischemic heart disease	1.5
Cerebrovascular disease, previous stroke or transient ischemic attack	1.5
Pneumonectomy	1.5
Serum creatinine >2 mg/dL	1

Risk class	A	B	C	D
Cumulative points	0	1-1.5	2-2.5	>2.5
Risk of cardiac complications (%)	1.5	5.8	19	23

$ppoFEV_1$ = preoperative FEV_1 × (1-y/z)
*preoperative FEV_1 from postbronchodilator
y = number of functional lung segments to be removed
z = the number of functional segments

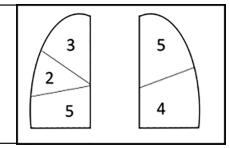


Figure 3 Proposed functional evaluation prior to lung resection. Adapted from (68), distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/). Pre-operative evaluation starts with cardiac evaluation based on the Thoracic RCRI. Patient presenting a Thoracic-RCRI ≥2 should be referred for further cardiovascular evaluation and optimization prior to surgery. In patient with Thoracic-RCRI <2, $ppoFEV_1$ and ppoDLCO should be calculated based on number of functional lung segments to be removed. Patients with $ppoFEV_1$ and ppoDLCO >60% have a low risk of complication. Patients with $ppoFEV_1$ or ppoDLCO <60% should undergo CPET to evaluate VO_2max and VE/VCO_2. Patients with VO_2max >20 mL/kg/min have a low risk of complication where as VO_2max <10 mL/kg/min is associated with a high risk of complication and should be offered minimally invasive approach or non-surgical option to minimize the risk of complication. VE/VCO_2 should be used in patient with VO_2max between 10 to 20 mL/kg/min to further precise risk. Patient having VE/VCO_2 ≤35 are classified as having a low-intermediate risk while patients with VE/VCO_2 >35 are classified as having an intermediate-high risk. CPET, cardiopulmonary exercise testing; DLCO, carbon monoxide lung diffusion capacity; FEV_1, forced expiratory volume in one second; ppo, predicted post-operative; RCRI, revised cardiac risk index; VE/VCO_2, minute ventilation to carbon dioxide output slope; VO_2max, maximal oxygen consumption.

exercise (35). The best pre-operative echocardiographic marker associated with reduction in post-operative right ventricular systolic function has been shown to be the right ventricular peak longitudinal strain of the right ventricular lateral wall (72). This metric is a marker of mechanical deformation of the ventricle and has proven to be very sensitive to detect changes in systolic function before reduction in ejection fraction is various pathological states (73). Lung resection surgery is associated with impaired post-operative right ventricular function as well as right ventricular to pulmonary artery uncoupling that appears in the early post-operative phase and can last several weeks after surgery without concomitant changes in the left ventricular ejection fraction (74) (*Figure 1*). The clinical impact of these specific long-lasting changes in right ventricular function are not well known. A strong association has also been shown between the reduced RVEF assessed at post-operative day 2 and length of intensive care unit stay (74). Despite these findings, there is no consensus on how to preoperatively identify patients at risk of symptomatic right ventricular dysfunction following thoracic surgery.

Conclusions

In summary, relative reduction in right ventricular function occurs following lung resection due to increased pulmonary vascular resistance and reduced lung compliance. The surgical approach can have an influence as patients that underwent VATS generally had better right heart systolic function compared to thoracotomy patients. Several components of the peri-operative care including pre-operative preparation, epidural analgesia and one-lung ventilation can be optimized in order to reduce the burden of cardiovascular complication after lung resection surgery.

Acknowledgments

Funding: None.

Footnote

Provenance and Peer Review: This article was commissioned by the Guest Editors (Jean Bussieres and George Rakovich) for the series "Recent Advances in Perioperative Care in Thoracic Surgery and Anesthesia" published in *Current Challenges in Thoracic Surgery*. The article has undergone external peer review.

Reporting Checklist: The authors have completed the Narrative Review reporting checklist. Available at: https://ccts.amegroups.com/article/view/10.21037/ccts-21-33/rc

Peer Review File: Available at: https://ccts.amegroups.com/article/view/10.21037/ccts-21-33/prf

Conflicts of Interest: Both authors have completed the ICMJE uniform disclosure form (available at: https://ccts.amegroups.com/article/view/10.21037/ccts-21-33/coif). The series "Recent Advances in Perioperative Care in Thoracic Surgery and Anesthesia" was commissioned by the editorial office without any funding or sponsorship. The authors have no other conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects for the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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doi: 10.21037/ccts-21-33
Cite this article as: Couture EJ, Nabzdyk CG. Pulmonary hemodynamics and lung surgery: a narrative review. Curr Chall Thorac Surg 2023;5:39.

