Gas Exchange and Pulmonary Hemodynamics During Lung Resection in Patients at Increased Risk*

Relationship With Preoperative Exercise Testing

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Study objectives: **To evaluate the intraoperative evolution of patients with COPD during lung resection and to test whether exercise testing could be helpful in the prediction of the intraoperative course.**
Design: **Prospective study.**
Setting: **University teaching hospital.**
Patients: **Forty patients (mean [± SD] age, 65 ± 9 years) with COPD (*ie*, FEV_1, 55 ± 11% of predicted) and resectable lung neoplasms.**
Interventions: **Preoperatively, pulmonary function testing, quantitative lung perfusion scanning, and exercise performance testing were administered. Intraoperatively, pulmonary, hemodynamic, and blood gas measurements were performed at five stages, including periods of two-lung ventilation (TLV) and periods of one-lung ventilation (OLV).**
Results: **During OLV, compared with TLV, the PaO_2/fraction of inspired oxygen (FIO_2) ratio decreased from 458 ± 120 to 248 ± 131 mm Hg ($p < 0.05$), whereas pulmonary artery pressure (PAP) increased from 18 ± 5 to 23 ± 5 mm Hg ($p < 0.05$). Cardiac output ($\dot{Q}t$) also increased from 4.0 ± 1.2 to 5.1 ± 1.9 L/min ($p < 0.05$), yielding to a higher mixed venous PO_2. Both PaO_2 and $\dot{Q}t$ during OLV were significantly lower in patients who had undergone right thoracotomies compared with those who had undergone left thoracotomies. The PaO_2/FIO_2 ratio during OLV correlated with the PaO_2 during exercise ($r = 0.39$; $p = 0.01$) and with the perfusion of the non-neoplastic lung ($r = 0.44$; $p = 0.005$).**
Conclusions: **In COPD patients, OLV leads to a significant derangement of gas exchange, which is more pronounced in right thoracotomies. Preoperative measurement of PaO_2 during exercise and the distribution of perfusion by lung scan might be useful to identify those patients who are at the greatest risk of abnormal gas exchange during lung resections.** ***(CHEST 2001; 120:852–859)***

Key words: anesthesia; exercise testing; lung neoplasm; obstructive lung disease; one-lung ventilation

Abbreviations: BSL = baseline (stage 1); BSL-P = closed chest, supine position, two-lung ventilation (stage 5); DLCO = diffusing capacity of the lung for carbon monoxide; FIO_2 = fraction of inspired oxygen; LD = closed chest, lateral decubitus position, and two-lung ventilation (stage 2); OLV = one-lung ventilation; OLV-BR = open chest, lateral decubitus position, one-lung ventilation, before pulmonary resection, without clamping pulmonary vessels (stage 3); OLV-PR = open chest, lateral decubitus position, one-lung ventilation, postpulmonary resection (stage 4); $P(A-a)O_2$ = alveolar-arterial oxygen pressure difference; PAP = mean pulmonary artery pressure; PCWP = pulmonary capillary wedge pressure; Pplat = plateau airway pressure; PPN = predicted postpneumonectomy; $P\bar{v}O_2$ = mixed venous PO_2; PVR = pulmonary vascular resistance; $\dot{Q}t$ = cardiac output; $\dot{Q}va/\dot{Q}t$ = venous admixture; $\dot{V}/\dot{Q}$ = ventilation-perfusion; $\dot{V}E$ = minute ventilation; $\dot{V}O_2$peak = oxygen uptake at peak exercise; VT = tidal volume; Wpeak = peak workload

Surgery remains the treatment of choice for patients with resectable lung cancer. However, a significant proportion of patients undergoing lung resections have the associated condition COPD,[1] which increases the risk of perioperative complications and death.[2] New techniques in anesthesiology and critical care have enabled patients with COPD to have better outcomes following lung resections. Nowadays, patients with limited lung function, who would have been denied surgery according to the criteria proposed in the past,[2] may undergo pulmonary resection with a low mortality rate.[3]

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Exercise testing is a useful tool in the evaluation of high-risk thoracotomy candidates,[4,5] since it assesses the cardiopulmonary reserve that may be needed to survive the stress of surgery and its potential complications.[6] Our group has shown previously that gas-exchange measurements during exercise may help to identify patients with a higher risk of mortality among those with impaired lung function.[7] Although potentially hazardous, the intraoperative period of lung resection in COPD patients has received little attention in the past. The potential of exercise testing in the prediction of intraoperative hemodynamic and gas-exchange abnormalities has not been addressed yet. In this regard, it is interesting to note that exercise testing has proven to be useful in the prediction of patients who will require cardiopulmonary bypass procedures during single-lung transplantation.[8]

Lung resection requires one-lung ventilation (OLV) and pulmonary artery clamping, procedures that may produce profound hemodynamic and gas-exchange abnormalities. Presumably, these changes are more pronounced in patients with COPD, since they are at a greater ventilatory and hemodynamic disadvantage. Considering the present tendency to offer surgery to patients with greater lung function impairment,[3] a higher incidence of intraoperative gas-exchange and hemodynamic abnormalities might be expected, resulting in a more difficult anesthetic management. In this regard, preoperative tests that could identify those patients who are at greater risk of intraoperative complications could be very helpful. Accordingly, the present study was addressed to evaluate the intraoperative evolution of COPD patients during lung resection, and to test whether preoperative measurements, specifically exercise testing, could be helpful in the prediction of the intraoperative course.

Materials and Methods

Patients

Forty patients with moderate-to-severe airflow obstruction (Table 1), and who subsequently underwent lung resections because of the presence of pulmonary neoplasms, were prospectively examined. Twenty patients had been included in a previous study[7] on the relationship between preoperative assessment and postoperative complications. All patients were at an increased risk for lung resection as defined by a predicted postpneumonectomy (PPN) FEV_1 of < 40% of predicted values and/or a PPN value for the diffusing capacity of the lung for carbon monoxide (DLCO) of < 40% of that predicted.[9] Characteristics of the patients are shown in Table 1. The study was approved by the Ethical Committee of Hospital Clínic, and informed consent was obtained from each participant.

Table 1—*General Characteristics, Lung Function, and Incremental Exercise Data**

Characteristics	Values
Age, yr	65 ± 9
Gender, No.	
Male	38
Female	2
FVC, % predicted	77 ± 13
FEV_1	
L	1.63 ± 0.47
% predicted	55 ± 11
FEV_1/FVC, %	52 ± 12
RV, % predicted	153 ± 41
TLC, % predicted	101 ± 15
RV/TLC, %	53 ± 9
DLCO, % predicted	73 ± 22
Perfusion of non-neoplastic lung, %	56 ± 11
PPN FEV_1	
L	0.97 ± 0.31
% predicted	32 ± 8
PPN DLCO, % predicted	41 ± 13
Wpeak	
W	80 ± 28
% predicted	62 ± 19
$\dot{V}O_2$peak	
mL/min	1,081 ± 292
mL/kg/min	16.6 ± 3.9
% predicted	80 ± 24

*Results are expressed as mean ± SD unless otherwise noted. RV = residual volume; TLC = total lung capacity.

Pulmonary Function Tests

Pulmonary function measurements were made within the month prior to surgery. Forced spirometry, body plethysmography, and single-breath DLCO were measured (Pulmonary Function System 1070; Medical Graphics; St. Paul, MN). Results were expressed as a percentage of the predicted values from our own equations.[10–12] Both the PPN FEV_1 and the PPN DLCO were calculated on the basis of quantitative perfusion pulmonary scintigraphy, as described by Markos and coworkers.[13]

Exercise Testing

Initially, prior to catheterization, all patients performed an incremental (*ie*, 20 W/min), symptom-limited exercise test on a cycle ergometer (Ergotest; Jäeger; Würzburg, Germany) to determine the peak workload (Wpeak) that they could tolerate and the level of oxygen uptake at peak exercise ($\dot{V}O_2$peak). Subsequently, all patients had an arterial catheter (Seldicath; Plastimed; Saint-Leu-La-Forêt, France) inserted into the radial artery for blood gas measurements. In 14 patients, a triple-lumen Swan-Ganz catheter (Edwards Laboratories; Santa Ana, CA) was also placed into the pulmonary artery under pressure-wave monitoring (model M1166A; Hewlett-Packard; Boeblingen, Germany) for hemodynamic and mixed venous blood gas measurements. No differences in general characteristics and pulmonary function data existed between this subset of patients and the remaining ones.

After a resting period of 60 min, all patients performed a second exercise test. Patients with only systemic artery catheterization followed a second incremental work-rate protocol, with gas-exchange measurements performed at peak exercise. Due to the difficulties in performing complete hemodynamic measurements at peak exercise, in the 14 patients with pulmonary artery catheterization, gas-exchange and hemodynamic measurements were performed at the end of a 4-min period of a constant work-rate equivalent to 60% of the Wpeak. The values used for predicted exercise measurements were those of Jones et al.[14] Measurements of pulmonary artery pressure (PAP) were made at the end of expiration. Alveolar-arterial oxygen pressure difference (P[A-a]O_2) and pulmonary vascular resistance (PVR) were calculated using standard formulas.

Anesthetic Management

Before the induction of anesthesia, patients were premedicated with midazolam (0.5 to 1 mg), and an arterial catheter (Seldicath; Plastimed) was inserted into the radial artery for blood gas and systemic arterial pressure measurements. Arterial oxygen saturation was continuously monitored throughout the intervention by means of pulse oximetry (model M1020A; Hewlett-Packard). A thoracic epidural catheter was inserted (between T8 and T9) for postoperative analgesia. General anesthesia was induced with propofol (1.5 mg/kg), fentanyl (10 μg/kg), lidocaine (1.5 mg/kg), and vecuronium (0.1 mg/kg). An additional fentanyl IV bolus (150 μg) was administered if necessary. Patients were intubated with a Robertshaw double-lumen endotracheal tube (Broncho-Cath; Mallinckrodt Medical; Dublin, Ireland), its correct position being confirmed by fiberoptic bronchoscopy. A triple-lumen Swan-Ganz catheter (Edwards Laboratories; Santa Ana, CA) was introduced through the right jugular vein into the pulmonary artery of the non-neoplastic (dependent) lung for hemodynamic and gas-exchange measurements (model 54S; Hewlett-Packard; Palo Alto, CA), its position being confirmed by fluoroscopy. Patients received ventilation using a standard volumetric ventilator (model VT/3; Temel; Valencia, Spain). The initial ventilator settings were the following: tidal volume (VT), 10 to 12 mL/kg; respiratory rate, 10 to 12 breaths/min; and inspiratory-to-expiratory (I:E) ratio, 1:2. During OLV, as per the study protocol, minute ventilation ($\dot{V}E$) was not modified, although VT was reduced to avoid an excessive increase in airway pressure, and hence the respiratory frequency was increased in order to maintain $PaCO_2$ at approximately 35 mm Hg. Patients were studied at a fraction of inspired oxygen (FIO_2) concentration of 0.70, a level that was kept constant throughout the study. Ventilatory parameters (*ie*, inspiratory and expiratory flows, airway pressure, and flow/volume or pressure/volume loops) were continuously monitored (Capnomac Ultima monitor; Datex; Helsinki, Finland).

Modifications of the Standard Protocol

When pulmonary hypertension (*ie*, mean PAP, > 25 mm Hg) developed during the procedure, one of the following treatments was initiated, as decided by the attending anesthesiologist: nitroglycerin plus dopamine; milrinone; or inhaled nitric oxide.

A fall in arterial oxygen saturation of > 10% from baseline was treated with continuous positive airway pressure or high-frequency jet ventilation applied to the non-dependent lung. If the latter measures failed to improve hypoxemia, FIO_2 was increased to 1.0.

Intraoperative Measurements

Intraoperative measurements were taken at the following consecutive stages:

1. Closed chest, supine position, and two-lung ventilation (TLV) (baseline [BSL]);
2. Closed chest, lateral decubitus position, and TLV (LD);
3. Open chest, lateral decubitus position, OLV, before pulmonary resection, without clamping pulmonary vessels (OLV-BR);
4. Open chest, lateral decubitus position, OLV, postpulmonary resection (OLV-PR); and
5. Closed chest, supine position, and TLV (OLV of the remaining lung in the 16 patients who required pneumonectomy) [BSL-P].

Special care was taken to guarantee stable conditions for several minutes before each set of measurements. At each stage, the following measurements were performed: pulmonary and systemic hemodynamics; cardiac output ($\dot{Q}t$); arterial and mixed venous respiratory gas measurements; $\dot{V}E$; VT; and plateau airway pressure (Pplat). Venous admixture ($\dot{Q}va/\dot{Q}t$) was calculated using the standard formula.

Statistical Analysis

The results are presented as the mean ± SD. Student's *t* test was used to compare gas-exchange and hemodynamic variables at rest and during exercise. The χ^2 test was used for categoric variables. Repeated-measures analysis of variance was used to analyze the evolution of gas-exchange, ventilatory, and hemodynamic variables during the surgical procedure. The Pearson correlation coefficient was used to explore the relationship between preoperative and intraoperative variables, and multiple linear regression was additionally performed when appropriate. A p value < 0.05 was considered to be significant in all cases.

Results

Patients had moderate-to-severe airflow obstruction, gas trapping, and mildly to moderately decreased DLCO values (Table 1). The predicted PPN FEV_1 was severely reduced, averaging 32 ± 8% of predicted. The following surgical interventions were performed: pneumonectomies, 16; lobectomies, 15; bilobectomies, 5; and wedge resections, 4. Twenty-four thoracotomies were right-sided, and 16 were left-sided.

Exercise Study

Exercise capacity, as measured by Wpeak and $\dot{V}O_2$peak, was mildly to moderately impaired (Table 1). Blood gas and hemodynamic measurements at rest and during exercise are shown in Table 2. During exercise, gas exchange worsened mildly, as shown by the increase of both P(A-a)O_2 and $PaCO_2$. In the subset of patients who underwent right-heart catheterization, the PAP at rest was within normal limits and increased significantly during exercise. Yet, PVR decreased moderately during exercise. No differences in gas exchange, which was measured at rest and during exercise, were shown between this subset of patients and the remaining patients.

Intraoperative Measurements

As expected, the PaO_2/FIO_2 ratio decreased significantly during OLV, with a return toward baseline

Table 2—*Gas Exchange and Pulmonary Hemodynamics at Rest and During Exercise**

Variables	Rest	Exercise
Pa_{O_2}, mm Hg	77 ± 9	76 ± 12
Pa_{CO_2}, mm Hg	38 ± 4	39 ± 5†
$P(A\text{-}a)O_2$, mm Hg	30 ± 9	36 ± 12†
$P\bar{v}_{O_2}$, mm Hg‡	37 ± 5	29 ± 3†
PAP, mm Hg‡	19 ± 6	41 ± 11†
PCWP, mm Hg‡	6 ± 4	20 ± 12†
$\dot{Q}t$, L/min‡	6.3 ± 1.9	11.5 ± 2.3†
PVR, dyne · s · cm^{-5}‡	170 ± 39	146 ± 52†

*Results are expressed as mean ± SD.
†$p < 0.05$ compared with resting conditions.
‡n = 14.

values after the reinstitution of TLV (Table 3). Pa_{CO_2} showed a tendency to increase during OLV, an increase that was significant after resection (OLV-PR), although it remained within the normal range in the majority of patients throughout the whole surgical procedure. Mixed venous P_{O_2} ($P\bar{v}_{O_2}$) increased when the patient was placed in the lateral decubitus position and remained at a similar level throughout the intervention. The $\dot{Q}va/\dot{Q}t$ increased markedly during OLV, with a return toward baseline values after the reinstitution of TLV (Table 3). The increase in $\dot{Q}va/\dot{Q}t$ was significantly correlated with the fall in Pa_{O_2}/F_{IO_2} ratio (r = -0.72; p = 0.01). Furthermore, during OLV, $\dot{Q}va/\dot{Q}t$ was significantly correlated with PAP (r = 0.61; $p < 0.0001$).

$\dot{V}_E$ was kept constant during the intervention. Despite the fact that V_T was reduced from 9.7 to 6.8 mL/kg during OLV (Table 3), Pplat significantly increased in this condition.

The mean PAP increased moderately during surgery, reaching the highest values during OLV. The mean $\dot{Q}t$ also increased significantly during OLV, and PVR remained essentially unchanged during the procedure, thereby indicating that the rise in PAP resulted mainly from the increase in $\dot{Q}t$ rather than from greater vascular tone. Indeed, the increase in PAP correlated with the change in $\dot{Q}t$ during OLV (stage 3) (r = 0.33; p = 0.04). Pulmonary capillary wedge pressure (PCWP) and right atrial pressure remained unchanged throughout the intervention.

For a better understanding of the interaction between the different factors that govern gas exchange during the intervention, we analyzed separately the intraoperative course of hemodynamic and gas-exchange measurements according to the thoracotomy side (Fig 1). In patients who had undergone right thoracotomies vs left thoracotomies during OLV, the following conditions prevailed: lower Pa_{O_2}/F_{IO_2} (208 ± 114 vs 308 ± 135 mm Hg, respectively; p = 0.02); similar $\dot{Q}va/\dot{Q}t$ (32 ± 12 vs 28 ± 10%, respectively; p = 0.34); lower $\dot{Q}t$ (4.3 ± 1.4 vs 5.6 ± 1.2 L/min, respectively; p = 0.004); and lower $P\bar{v}_{O_2}$ (46 ± 6 vs 54 ± 13 mm Hg, respectively; p = 0.04).

Modifications of the Standard Protocol

Fourteen patients (35%) required intraoperative pharmacologic treatment for short-term increases in PAP during OLV at stages 3 (OLV-BR) and/or 4 (OLV-PR). Nitroglycerin plus dopamine was administered to four patients, milrinone was administered to seven, and inhaled nitric oxide was administered to three. Ten patients (25%) required continuous positive airway pressure and/or an increase in the F_{IO_2} because of persistent arterial hypoxemia. Overall, 16 patients (40%) required these special measures to treat increases in PAP and/or hypoxemia. All these interventions were performed after measurements corresponding to stage 3 had been performed.

Table 3—*Patient Variables During Thoracotomy**

Variables	BSL	LD	OLV-BR	OLV-PR	BSL-P
F_{IO_2}	0.73 ± 0.12	0.73 ± 0.10	0.78 ± 0.12†	0.79 ± 0.13†	0.75 ± 0.14
Pa_{O_2}/F_{IO_2}, mm Hg	458 ± 120	470 ± 96	248 ± 131†	322 ± 128†	424 ± 116
Pa_{CO_2}, mm Hg	34.6 ± 5.4	33.9 ± 5.2	37.2 ± 6.6	39.7 ± 11.3†	37.8 ± 7.1
$P\bar{v}_{O_2}$, mm Hg	46 ± 8	50 ± 9†	49 ± 10	50 ± 8†	51 ± 14
$\dot{Q}va/\dot{Q}t$, %	12 ± 7	13 ± 7	30 ± 11†	25 ± 10†	15 ± 7
$\dot{V}_E$, L/min	7.9 ± 1.3	7.9 ± 1.1	7.6 ± 2.8	7.7 ± 2.2	7.6 ± 1.5
V_T, mL/kg	9.7 ± 2.3	9.8 ± 2.2	6.8 ± 1.6†	7.0 ± 1.7†	8.7 ± 2.1
Pplat, cm H_2O	15.0 ± 4.6	16.5 ± 5.8†	20.4 ± 5.2†	18.6 ± 5.4†	17.9 ± 5.4†
PAP, mm Hg	17.6 ± 5.0	19.7 ± 4.5†	23.3 ± 4.8†	21.9 ± 5.3†	21.5 ± 5.4†
PCWP, mm Hg	10.1 ± 4.2	11.6 ± 4.3	12.4 ± 3.5	11.0 ± 4.2	11.2 ± 4.8
RAP, mm Hg	7.8 ± 4.2	7.3 ± 3.4	8.7 ± 3.6	7.3 ± 4.1	7.4 ± 3.8
PVR, dyne · s · cm^{-5}	158 ± 64	164 ± 65	179 ± 78	194 ± 114	187 ± 97
$\dot{Q}t$, L/min	4.0 ± 1.2	4.2 ± 1.0	5.1 ± 1.9†	4.8 ± 1.5	4.8 ± 1.3

*Results are expressed as mean ± SD. RAP = mean right arterial pressure.
†$p < 0.05$ compared with BSL.

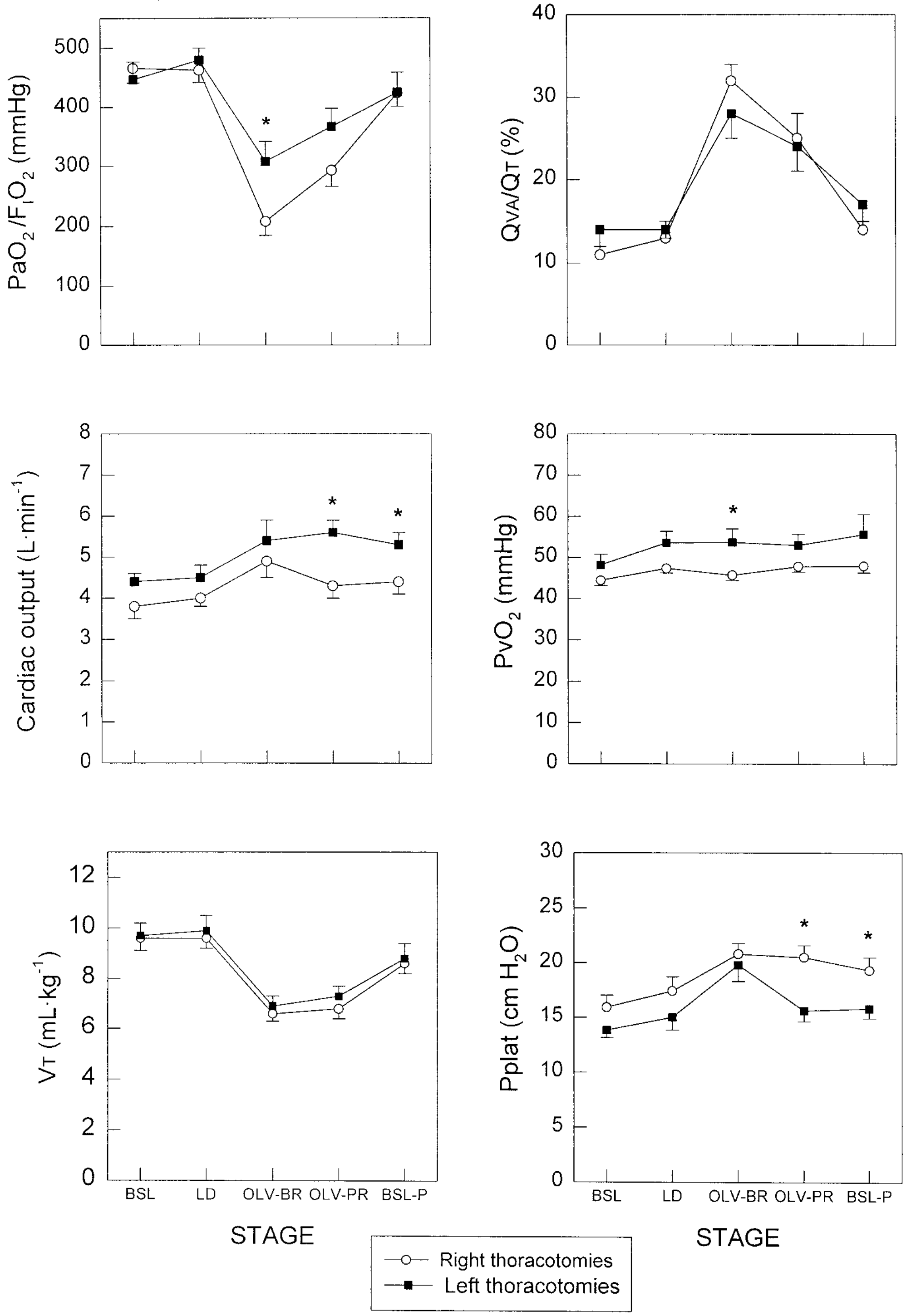

FIGURE 1. The evolution of Pa_{O_2}/FI_{O_2} ratio, $\dot{Q}va/\dot{Q}t$, $\dot{Q}t$, $P\bar{v}_{O_2}$, VT, and Pplat during lung resection in patients undergoing right thoracotomies (open circles) and left thoracotomies (closed squares). * = $p < 0.05$ for the comparison between patients undergoing right and left thoracotomies at each stage. Values are given as mean ± SE.

Accordingly, the results obtained in stage 3 were not influenced by interventions made by the anesthesiologist. Furthermore, no differences were shown between the subset of patients who required special measures and other patients in terms of the extent of lung resection, the side on which the thoracotomy was performed, preoperative lung function, or the response to exercise.

Relationships Between Preoperative and Intraoperative Measurements

The Pa_{O_2}/F_{IO_2} ratio during stage 3 (OLV-BR) correlated significantly with the perfusion of the non-neoplastic lung ($r = 0.44$; $p = 0.005$) and exercise Pa_{O_2} ($r = 0.39$; $p = 0.01$). Multiple regression analysis showed a slightly better estimation of the Pa_{O_2}/F_{IO_2} ratio during stage 3 (OLV-BR) when both the percentage of perfusion of the non-neoplastic lung and the change in Pa_{O_2} during exercise were taken together as covariates ($R^2 = 0.28$; $p = 0.003$). By contrast, the Pa_{O_2}/F_{IO_2} ratio during stage 3 (OLV-BR) did not correlate with preoperative FEV_1, DLCO, exercise capacity (*ie*, oxygen uptake level or No. of watts), or gas exchange measured at rest. The mean PAP at stage 3 (OLV-BR) correlated significantly with preoperative PAP, both at rest and during exercise (at rest, $r = 0.58$ [$p = 0.03$]; during exercise, $r = 0.57$ [$p = 0.03$]).

Discussion

The results of the present study show that patients with COPD who undergo resective lung surgery develop significant gas-exchange disturbances during OLV, which are more pronounced in patients undergoing right thoracotomies. Moreover, patients with lower Pa_{O_2} values on exertion and with reduced perfusion of their non-neoplastic lung are at the greatest risk of gas-exchange worsening during the surgical procedure.

OLV is required during resective lung surgery. Nevertheless, significant hypoxemia may develop during OLV,[15–17] mainly due to increased intrapulmonary shunting.[16,17] The severity of arterial hypoxemia during OLV may be reduced by hypoxic pulmonary vasoconstriction in the nonventilated lung,[18] a mechanism that avoids the perfusion of poorly or nonventilated lung units. A potential consequence of hypoxic pulmonary vasoconstriction is the increase of PAP. Yet, in patients without marked preoperative impairment of lung function, OLV only produces minor elevations of PAP.[19] These changes that are induced by OLV might be more pronounced in patients with COPD. First, the non-neoplastic lung is affected by diffuse abnormalities in the airways and lung parenchyma that produce ventilation-perfusion ($\dot{V}/\dot{Q}$) mismatching,[20] hence potentially precluding an adequate compensation of the fall in Pa_{O_2}. Second, hypoxic pulmonary vasoconstriction may be altered in some COPD patients,[21] promoting a greater perfusion through nonventilated lung units. Moreover, patients with COPD who undergo lung surgery show significant abnormalities in pulmonary arteries that may facilitate a greater increase in PAP.[21] Nevertheless, the magnitude of the hemodynamic and gas-exchange consequences of OLV in selected thoracotomy candidates with COPD and severely impaired pulmonary function has not been comprehensively evaluated as yet.

In our population of COPD patients, the Pa_{O_2}/F_{IO_2} ratio decreased by 210 ± 141 mm Hg after the initiation of OLV. In two patients, Pa_{O_2} fell to < 60 mm Hg, and a modification of ventilator settings was necessary in 25% of the patients. Worsening arterial oxygenation during OLV was the consequence of the development of increased intrapulmonary shunting and areas with low $\dot{V}/\dot{Q}$, as shown by a significant increase in the $\dot{Q}va/\dot{Q}t$, which is in agreement with previously reported[17,19] data in nonselected thoracotomy candidates. The increase in $\dot{Q}va/\dot{Q}t$, together with the lower V_T during OLV, likely accounted for the mild increase in Pa_{CO_2} observed during the procedure. Conceivably, the increase in $\dot{Q}va/\dot{Q}t$ during OLV was partially compensated for by the parallel increase of $P\bar{v}_{O_2}$ that resulted from the increase in $\dot{Q}t$ (assuming that oxygen uptake remained constant), thus preventing a further decrease in the Pa_{O_2}/F_{IO_2} ratio.

In a previous study[22] carried out in nonselected thoracotomy candidates, only preoperative perfusion lung scans have been found to be predictive of Pa_{O_2} during OLV. In the same study, age, sex, the side on which the operation was performed, resting Pa_{O_2} and Pa_{CO_2}, FEV_1, and lung volume measurements did not correlate with oxygenation during OLV. In our study, the results of the univariate and multivariate analysis showed that patients with greater perfusion of the non-neoplastic (dependent) lung and better oxygenation during exercise tended to have less of a derangement of gas exchange during OLV. These results reinforce the interest in arterial blood gas measurements during exercise in the preoperative evaluation of these patients, as they can provide valuable information not only on postoperative morbidity and mortality,[7,13,23] but also on intraoperative oxygenation. Accordingly, we recommend preoperative exercise testing with blood gas sampling in patients with COPD who are at high risk for lung resection (*ie*, PPN FEV_1 and/or PPN DLCO < 40% of predicted), particularly in those patients with low perfusion of the non-neoplastic lung.

In our population of COPD patients, PAP increased by 6 ± 5 mm Hg during OLV. In 14 patients (35%), the attending anesthesiologist considered it to be necessary to administer vasodilators because mean PAP was > 25 mm Hg. It should be noted, however, that the degree of pulmonary hypertension was much greater during preoperative exercise testing than during OLV (Tables 2, 3). Moreover, such an increase in PAP during OLV likely was due to the increase in $\dot{Q}t$, since PVR did not increase significantly during the intervention, thus indicating that the slope of the pressure-flow relationship did not change. Nevertheless, we cannot exclude that some increase in vascular tone in the nonventilated lung due to hypoxic vasoconstriction also could play a part in the development of pulmonary hypertension. A potential explanation for the increase in $\dot{Q}t$ could be the decrease of intrathoracic pressure that resulted from thorax aperture, which might minimize the effect of alveolar pressure on ventricular filling. This suggestion is in agreement with the previous finding of an increase in $\dot{Q}t$ following pleurotomy.[19,24] Pharmacologic interventions to treat pulmonary hypertension can be ruled out as the mechanism for the increase in $\dot{Q}t$, since its change from stage 1 to stage 3 was similar in patients who did and did not receive pharmacologic interventions ($p = 0.88$).

Taking into account the aforementioned, the sequence of events during OLV and thorax aperture with the patient in the lateral decubitus position would be as follows: the initiation of OLV with the collapse of the nondependent lung would result in an increase in $\dot{Q}va/\dot{Q}t$ with a consequent fall of PaO_2; opening the thoracic cage would allow greater left ventricular filling and, hence, would increase $\dot{Q}t$, accounting for the rise in PAP during OLV. Although the preoperative PAP was significantly correlated with the intraoperative PAP, and given the low degree of pulmonary hypertension observed during the surgical procedure, we think that the preoperative assessment of pulmonary hemodynamics does not provide valuable information for the intraoperative management of these patients. Consequently, we do not recommend right-heart catheterization in the preoperative evaluation of these patients.

The analysis of the intraoperative course according to the thoracotomy side shows that the fall in the PaO_2/FIO_2 ratio during OLV was more pronounced in right thoracotomies, when the left lung was in the dependent position (Fig 1). However, $\dot{Q}va/\dot{Q}t$ for patients during OLV was similar during right and left thoracotomies, indicating that lung collapse led to a similar degree of intrapulmonary shunting and/or $\dot{V}/\dot{Q}$ mismatching, irrespective of the side on which the thoracotomy had been performed. Interestingly, $P\bar{v}O_2$ during OLV was significantly lower in patients undergoing right thoracotomies. Such a difference in $P\bar{v}O_2$ may explain why the PaO_2/FIO_2 ratio was also lower in patients who underwent right thoracotomies, despite the fact that the magnitude of intrapulmonary shunting was similar. Presumably, the lower $P\bar{v}O_2$ in right thoracotomy patients resulted from a lower increase in $\dot{Q}t$ compared with left thoracotomy patients (Fig 1). We hypothesize that the heart might suffer greater compression by the lung, mediastinum, and abdominal content in right thoracotomies, when left hemithorax is placed down, thereby limiting the increase of $\dot{Q}t$ that takes place when opening the thoracic cage. This suggestion is supported by the finding of higher airway pressures in this position (right thoracotomies) during OLV (Fig 1). As shown in Figure 1, in our series, V_T did not differ between patients undergoing right and left thoracotomies. These findings suggest that right thoracotomies produce greater impairment of gas exchange, essentially due to the impact of higher external pressure on the heart function. Although some investigators[25] have not found differences in oxygenation between patients undergoing right and left thoracotomies who have COPD, our findings are in agreement with those of Katz and coworkers,[26] who reported a profound decrease in PaO_2 during OLV of the left lung, but not during OLV of the right lung, in the course of endoscopic transthoracic sympathectomies in a series of young patients without cardiorespiratory disease.

In summary, our results, obtained in a selected population of candidates for lung resection with moderate-to-severe COPD, show that significant worsening of pulmonary gas exchange takes place during OLV and that this worsening is more marked in patients undergoing right thoracotomies. Since gas-exchange impairment during lung resection appears to be more pronounced in patients with lower PaO_2 values during exercise and with lower perfusion of the non-neoplastic lung, we recommend exercise testing with arterial blood gas measurements in the preoperative assessment of high-risk COPD patients, particularly in those patients with less perfusion of the non-neoplastic lung, as that procedure can be of help in identifying those patients who are at the highest risk for hypoxemia during the surgical procedure. Furthermore, our results show the important role played by extrapulmonary factors in modulating PaO_2 values during OLV, especially by $\dot{Q}t$. In this respect, we consider that intraoperative monitoring of pulmonary hemodynamics and $\dot{Q}t$ might be useful in patients who are at the greatest risk of an adverse intraoperative course (*eg*, those with reduced perfusion of the non-neoplastic lung and exercise-induced hypoxemia), especially in patients undergoing right thoracotomies when the left lung will be placed in the dependent position.

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