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Impact of Left Heart Bypass on Arterial Oxygenation During One-Lung Ventilation for Thoracic Aortic Surgery

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Objective: The aim of this study was to reveal the mechanism of improved arterial oxygenation by measuring the changes in oxygenation before and after initiation of left heart bypass (LHB) during one-lung ventilation (OLV) for thoracic aortic surgery.
Design: Prospective, observational study.
Setting: Single-institution, private hospital.
Participants: The study comprised 50 patients who underwent aortic surgery via a left thoracotomy approach with LHB circulatory support.
Interventions: Patients were ventilated using pure oxygen during OLV, and the ventilator setting was left unchanged during the measurement period.
Measurements and Main Results: The measurement of partial pressure of arterial oxygen (PaO_2) was made at the following 4 time points: 2 minutes after heparin infusion (point 1 [P1]), 2 minutes after inflow cannula insertion through the left pulmonary vein (P2), immediately before LHB initiation (P3), and 10 minutes after LHB initiation (P4). The mean ± standard deviation (mmHg) of PaO_2 measurements at the P1, P2, P3, and P4 time points were 244 ± 121, 250 ± 123, 419 ± 122, and 430 ± 109, respectively, with significant increases between P1 and P3, P1 and P4, P2 and P3, and P2 and P4 ($p < 0.0001$, respectively). No significant increase in PaO_2 was seen between P1 and P2 or between P3 and P4.
Conclusions: The improved arterial oxygenation during OLV in patients who underwent thoracic aortic surgery using LHB can be attributed to the insertion of an inflow cannula via the left pulmonary vein into the left atrium before LHB.

Key Words: left heart bypass; one-lung ventilation; oxygenation; inflow cannula; pulmonary blood flow

SURGICAL REPAIR OF the descending thoracic aorta or thoracoabdominal aorta after an aortic aneurysm requires a left thoracotomy with one-lung ventilation (OLV) in the lateral decubitus position; this is the standard procedure.[1–4] In addition, it is performed commonly under various extracorporeal circulations, including partial cardiopulmonary bypass (CPB), full CPB with deep hypothermic circulatory arrest, and left heart bypass (LHB).[3–5] Among these extracorporeal circulatory supports, LHB generally lacks an oxygenator. Therefore, maintenance of oxygenation is important during OLV with the patient under LHB. In particular, the safety and efficacy of LHB remain controversial when it is used as extracorporeal circulatory support in patients with preoperative pulmonary risks.[6–8] Some studies have suggested the use of CPB or an oxygenator during LHB to achieve better oxygenation in patients with impaired pulmonary function, such as those with chronic obstructive pulmonary disease (COPD).[6,7] However, only 2 studies have reported that LHB improved

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arterial oxygenation during OLV.[8,9] Because the change in oxygenation during LHB and the mechanism of its improvement have not been elucidated fully, such questions should be evaluated in more detail to prevent unexpected hypoxia during LHB.

In most cases of LHB, the left pulmonary vein is the proximal cannulation site, whereas distal cannulation may be accomplished via the descending aorta or femoral artery.[10] The authors have found empirically that arterial oxygenation improved during these cannulation procedures even before the initiation of LHB. On the basis of these findings, the authors hypothesized that the insertion of an inflow cannula through the left upper pulmonary vein (LUPV) contributes to the improvement of arterial oxygenation during OLV; the objective of this study was to reveal the mechanism of this improved arterial oxygenation by measuring the changes in oxygenation before and after the initiation of LHB.

Materials and Methods

This observational study was conducted with approval from the Ethics Committee of Kawasaki Saiwai Hospital, and patients provided written, informed consent for study participation. In total, 50 patients who underwent aortic surgery via a left thoracotomy approach with LHB circulatory support were included in this study. Those who did not consent to study participation and in whom adequate oxygenation could not be maintained (percutaneous oxygen saturation $< 90\%$) during OLV, despite correct position of the endobronchial tube and alveolar recruitment, were excluded and treated with two-lung ventilation.

In the operating room, standard monitoring devices, including electrocardiography, noninvasive blood pressure measurement, pulse oximetry, and body temperature monitoring, were performed for the patients without premedication. After insertion of a right radial arterial catheter for hemodynamic monitoring and analysis of the arterial blood gas, general anesthesia was induced using thiopental, propofol or midazolam, fentanyl, and rocuronium to facilitate tracheal intubation. A left-sided, double-lumen endobronchial tube (Portex Blue Line; Smiths Medical, St Paul, MN) was inserted, and its correct placement was confirmed using a flexible fiberoptic bronchoscope. After induction of anesthesia, a transesophageal echocardiography (TEE) probe was inserted. A pulmonary artery catheter was inserted through the right internal jugular vein, and the position of the catheter tip was confirmed using TEE so that it was placed inside the main pulmonary artery. In addition, intracardiac shunts (patent foramen ovale) were ruled out using TEE. Anesthesia was maintained with sevoflurane, propofol, and remifentanil. Epidural anesthesia was not used because of heparinization. The patient was placed in the right lateral decubitus position, and OLV subsequently was established.

After administration of heparin, an outflow cannula with an appropriate diameter was placed in the descending aorta, abdominal aorta, or femoral artery. A 24-Fr inflow cannula then was inserted from the LUPV into the left atrium, followed by the initiation of LHB. The inflow cannula was secured in a pursestring fashion around the insertion point. The LHB flow index was targeted to 1.5 to about 2.0 L/min/m^2. The LHB circuit included the membrane oxygenator, which is equipped with an integrated heat exchanger to rewarm patients (Fig 1). Because mild-to-moderate hypothermia during LHB is advantageous for spinal cord protection, the heat exchanger was used only at the end of LHB for rewarming. The oxygenator was used for pH control at rewarming. Patients were ventilated using pure oxygen, and ventilator settings (ie, volume-controlled ventilation or pressure-controlled ventilation, with or without positive end-expiratory pressure, respiratory rate, inspiration-to-expiration ratio, and end-tidal carbon dioxide), were left to the discretion of the attending anesthesiologist. In addition, the ventilator setting was left unchanged during the measurement period, specifically from the time of heparin administration until 10 minutes after the initiation of LHB.

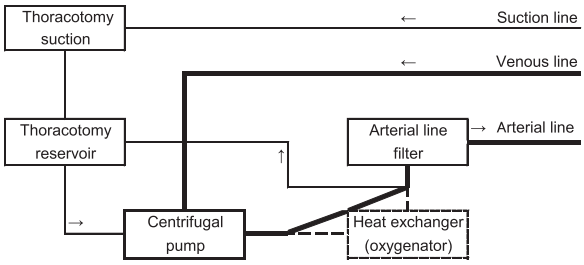

Fig 1. LHB circuit, which consists of a centrifugal pump with a reservoir for rapid transfusion and a membrane oxygenator equipped with an integrated heat exchanger for rewarming patients. The heat exchanger was used only at the end of LHB for rewarming. The oxygenator was used for pH control at rewarming.

The measurement of potential of hydrogen (pH), partial pressure of arterial oxygen (PaO_2), and partial pressure of arterial carbon dioxide ($PaCO_2$) was repeated at the following 4 time points while the patient was being ventilated using pure oxygen: 2 minutes after heparin administration (point 1 [P1]), 2 minute after inflow cannula insertion (P2), immediately before LHB initiation (P3), and 10 minutes after LHB initiation (P4). Because the LHB circuit did not use the membrane oxygenator at the start of LHB, the oxygenator never biased measurements of arterial blood gas tensions during this study. The time from the initiation of OLV until heparin administration (T1) was recorded to eliminate any possible effects of hypoxic pulmonary vasoconstriction (HPV) due to changes in PaO_2 during the measurement period. The time from inflow cannula insertion to LHB initiation (T2) and the time from P1 to P4 (T3) also were recorded. The cardiac index (CI), as determined using a pulmonary artery catheter, also was recorded at the P1 and P3 time points. The primary outcome measure was the comparison of the PaO_2 measurements at P1, P2, P3, and P4.

On the basis of results from the authors' pilot study involving 26 patients, it was estimated that the mean PaO_2 (mmHg) measurements at P1, P2, P3, and P4 were 220, 255, 388, and 403, respectively, and that the standard deviation (SD) was 140 mmHg. A power analysis demonstrated that data

Table 1
Patient Demographics

Age, mean (range), yr	65 (31-86)
Sex (M/F)	33/8
Height, mean (SD), cm	165 (14)
Weight, mean (SD), kg	66 (15)
Diagnosis (n)	
Distal aortic arch aneurysm	2
Descending aorta aneurysm	17
Thoracoabdominal aorta Aneurysm	22
COPD (n)	4
Coronary artery disease (n)	7
%VC < 80% (n)	8
FEV1.0% < 70% (n)	6
Tobacco use (n)	33

Abbreviations: %VC, percent vital capacity; COPD, chronic obstructive pulmonary disease; F, female; FEV1.0%, forced expiratory volume in 1 second; M, Male; SD, standard deviation.

for 37 patients were required to undergo a one-way analysis of variance at a level of significance of 0.05 with a statistical power of 0.8. Assuming for an approximately 20% dropout rate and missing data, 50 patients were enrolled into the study. For statistical analysis, a Tukey's honestly significant difference test was used for the post-hoc comparison of pH, PaO_2, and $PaCO_2$ measurements, and Student's *t*-test was used for the comparison of CI, with a significance level of $p < 0.05$. All analyses were performed using JMP 10 software (SAS Institute Inc, Cary, NC).

Results

In total, 41 patients were included in the final statistical analyses after 9 patients were excluded. Patient demographics and characteristics of excluded patients are summarized in Tables 1 and 2. Two patients underwent distal aortic arch replacement, 17 underwent descending thoracic aorta replacement, and 22 underwent thoracoabdominal aorta replacement. Preoperative cardiopulmonary complications included COPD in 4 and ischemic heart disease in 7 patients. For intraoperative analgesia, remifentanil was administered to all patients. Anesthesia was maintained using sevoflurane in 3 patients, propofol in 1 patient, and sevoflurane and propofol in 37 patients.

The mean ± standard deviation (SD) (mmHg) of PaO_2 measurements at the P1, P2, P3, and P4 time points were 244 ± 121, 250 ± 123, 419 ± 122, and 430 ± 109, respectively, with significant increases between P1 and P3 ($p < 0.0001$), P1 and P4 ($p < 0.0001$), P2 and P3 ($p < 0.0001$), and P2 and P4 ($p < 0.0001$). There was no significant change in PaO_2 levels between P1 and P2 ($p = 0.99$) or between P3 and P4 ($p = 0.98$). With respect to pH and $PaCO_2$, no significant difference was found ($p = 0.96$ and $p = 0.15$, respectively) between any 2 time points (Fig 2 and Table 3). The mean ± SD ($L/min/m^2$) of CI at P1 and P3 were 2.1 ± 0.6 and 2.1 ± 0.6, respectively, with no significant difference between the values ($p = 0.95$). The medians (range) for T1, T2, and T3 were 124 (51-238), 6 (3-32), and 27 (22-61) minutes, respectively (Fig 3 and Table 4).

Table 2
Excluded Patients

Required two-lung ventilation before initiation of LHB	1
Reinsertion of inflow cannula	1
Membrane oxygenator device was used mistakenly at the initiation of LHB	1
PAC could not be inserted	1
CI was not measured due to malfunction of a continuous cardiac output monitor	1
Fraction of inspired oxygen not set at 100%	4

Abbreviations: CI, cardiac index; LHB, left heart bypass; PAC, pulmonary artery catheter.

Discussion

Arterial oxygenation during LHB without an oxygenator depends on complicated interactions involving hemodynamic changes and OLV. The pulmonary blood flow of the dependent lung (ie, the right lung) is increased by the effect of gravity, HPV, and atelectasis of the left lung during OLV in the right lateral decubitus position.

Several clinical studies and reviews have described the influence of gravity on oxygenation and pulmonary blood flow distribution during OLV.[11–14] In a recent study, Lee et al[12] assessed the pulmonary venous flow using TEE and demonstrated that the lateral decubitus position itself increased the pulmonary blood flow of the dependent lung via the gravitational effect. The pulmonary blood flow increased 10 minutes after the body position change from supine to a lateral decubitus position.

HPV in the collapsed lung is the most important factor that affects pulmonary blood flow distribution during OLV. One study conducted on healthy, adult volunteers in the supine position without general anesthesia suggested that HPV comprises the following 2 phases: phase 1, which starts a few seconds after hypoxic exposure and reaches the peak pulmonary vascular resistance in 15 minutes, and phase 2, which starts approximately 40 minutes after the hypoxic exposure and slowly reaches the peak 120 minutes after the exposure.[15]

Lung collapse of the nondependent lung also plays an important role in pulmonary blood flow distribution. In an animal study, lung atelectasis resulted in a significant reduction in the pulmonary blood flow of the atelectatic lung at 15 and 30 minutes. An additional significant decrease occurred at 60 minutes, and the pulmonary blood flow remained unchanged at subsequent 120-, 180-, and 240-minute time points.[16] This suggested that the pulmonary blood flow shift due to the atelectasis of the nondependent lung was completed at 60 minutes after initiation of lung collapse.

In the study presented here, PaO_2 at 30 to 60 minutes after the initiation of OLV also was measured to eliminate the effects of gravity, HPV, and atelectasis. The mean ± SD of measurement time after the initiation of OLV was 47 ± 11 minutes. The mean ± SD of PaO_2 at that time was 215 ± 104 mmHg, and there was no significant difference from PaO_2 at 2 minutes

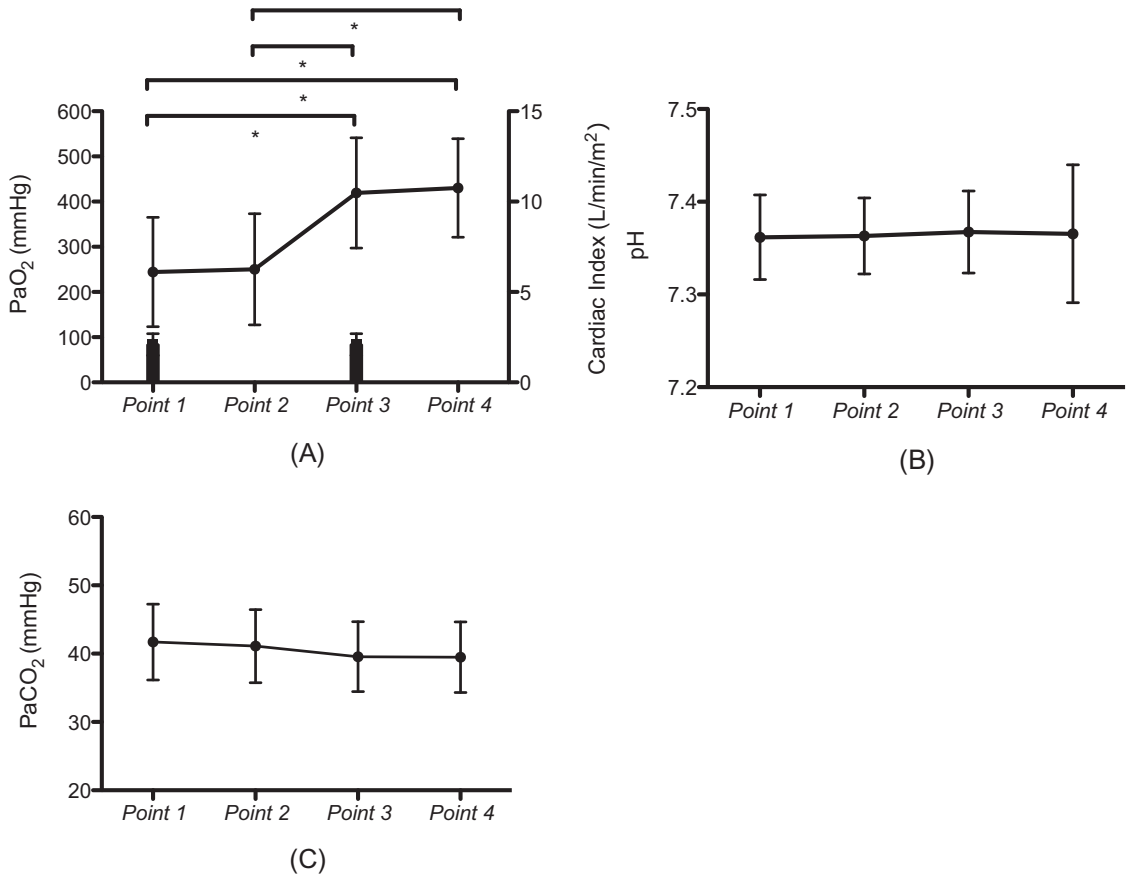

Fig 2. Primary outcome measure. Each panel represents the changes in PaO_2 (fraction of inspired oxygen 1.0) and cardiac index (A), pH (B), and $PaCO_2$ (C). Comparisons were performed using one-way repeated measures analysis of variance followed by Tukey's post-hoc test between any 2 time points. The *closed circle* represents the mean at each time point of the measurements. *Error bars* represent the standard deviation. Statistical significance is represented by $p < 0.05$.

after heparin administration (P1) (Student's *t*-test, $p = 0.26$). Moreover, the time from the initiation of OLV to heparin administration (T1) was 51 to 238 minutes, suggesting that the gravitational effect had subsided, HPV had entered phase 2 (ie, gradual phase), and the pulmonary blood flow distribution caused by lung atelectasis was complete before heparin administration (P1). Although it was unclear whether the 2 phases of HPV occur under anesthesia, it was certain that the observed changes in PaO_2 at inflow cannula insertion and LHB initiation were neither due to nor biased by gravity, HPV, or lung collapse.

The common causes of hypoxemia during mechanical ventilation include alveolar hypoventilation, ventilation/perfusion mismatch, pulmonary shunt, and diffusion impairment.[17] Therefore, in the event of impaired oxygenation during OLV, increased PaO_2 can be achieved by correcting these 4 factors. However, because no change was made to the ventilation or lung conditions just before LHB initiation in this study, it was unlikely that improvements in alveolar hypoventilation and diffusion impairment were responsible for the rapid increase in PaO_2. It is more reasonable to attribute this increase to the changes in ventilation/perfusion mismatch and the pulmonary shunt caused by the surgical procedures or extracorporeal circulation. The improved oxygenation occurred just before

Table 3
Primary Outcome Measures

	P1	P2	P3	P4
PaO_2 (mmHg)	244 ± 121	250 ± 123	419 ± 122	430 ± 109
pH	7.36 ± 0.05	7.36 ± 0.04	7.37 ± 0.04	7.37 ± 0.07
$PaCO_2$ (mmHg)	41.7 ± 5.6	41.1 ± 5.3	39.6 ± 5.1	39.5 ± 5.2
CI (L/min/m^2)	2.1 ± 0.6	–	2.1 ± 0.6	–

Abbreviation: CI, cardiac index.

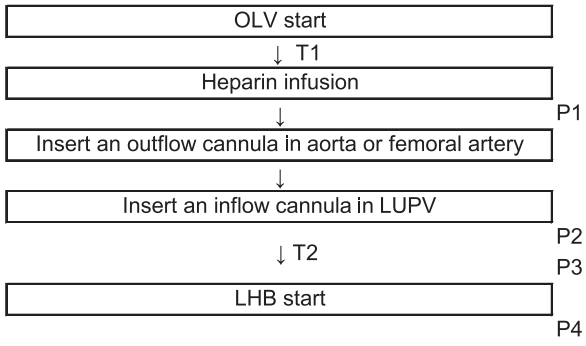

Fig 3. Study flowchart. Time points are expressed as 2 minutes after heparin administration (point 1 [P1]), 2 minutes after inflow cannula insertion (P2), immediately before LHB initiation (P3), and 10 minutes after LHB initiation (P4). T1 is the time from the initiation of OLV to heparin administration. T2 is the time from inflow cannula insertion to LHB initiation.

Table 4
Time Periods for P1 to P4, T1, and T2

	Time Duration (min)
P1-P2	12 (9-40)
P2-P3	4 (1-30)
P3-P4	12 (9-24)
P1-P4 (T3)	26 (19-51)
T1	124 (51-238)
T2	6 (3-32)

NOTE. Values are expressed as median (range).

LHB initiation; therefore, this phenomenon is unlikely to be associated with the changes in the volume and distribution of systemic and pulmonary blood flow provided by the extracorporeal circulation. Naturally, no changes in the cardiac output were observed at this time point. Eliminating these possibilities provides the reasonable explanation that the observed increase in PaO_2 was due to improvements in ventilation/perfusion mismatch and the pulmonary shunt elicited by the surgical procedure of inserting an inflow cannula via the LUPV. In this study, the authors observed improved oxygenation in the blood sample taken from the radial artery not at 2 minutes after the inflow cannula insertion (P2), but immediately before initiation of LHB (P3). The authors speculate that it took several minutes for the pulmonary blood flow to shift and, thus, improve oxygenation.

The position of the pulmonary artery catheter tip was lodged inside the main pulmonary artery to more consistently observe cardiac outputs across patients during surgery. In addition, the cardiac output, which is equal to pulmonary blood flow, did not change due to the insertion of the inflow cannula. Therefore, a redistribution of the pulmonary blood flow is the most reasonable explanation for the improvement of ventilation/perfusion mismatch and, thus, oxygenation. More specifically, the authors speculate that inflow cannula insertion, a physical factor, led to increased left lung vascular resistance via a particular mechanism, a decrease in poorly oxygenated blood that returned from the left lung, and then a redirection of blood flow to the highly oxygenated dependent lung (ie, right lung), resulting in a marked improvement in oxygenation.

The authors' speculation is consistent with a previous study,[8] in which TEE demonstrated that the increase in the right pulmonary blood flow was associated with improved oxygenation during LHB initiation. In that study, Yuki et al noted that neither the right pulmonary blood flow nor oxygenation increased before LHB initiation, but both were observed to increase after LHB initiation. However, the authors of that study did not specify whether the pre-LHB data were obtained before or after the inflow cannula insertion. If that study's data presented as obtained immediately before LHB initiation actually were obtained before inflow cannula insertion, their data are consistent with the data in the study presented here. Moreover, if the data reported by Yuki et al and the data described in the study presented here have captured the same phenomenon, it can be concluded that increased PaO_2 during LHB is attributed to increased right pulmonary blood flow caused by inflow cannula insertion into the LUPV.

In this study, not all patients exhibited improved oxygenation after inflow cannula insertion. Yuki et al[8] also reported that improved oxygenation was not achieved in 1 of 14 patients. Although the exact cause could not be demonstrated, it is possible that pulmonary blood flow shift was almost completely achieved in these patients before inflow cannula insertion. Therefore, inflow cannula insertion did not further improve the ventilation/perfusion mismatch.

In the study presented here, sevoflurane and propofol were used as hypnotic agents at various concentrations and doses. Furthermore, these agents were used at various initiation times because anesthetic management was left to the discretion of the attending anesthesiologist. Generally, sevoflurane inhibits HPV and propofol does not.[18,19] However, in clinical studies, sevoflurane and propofol had a similar effect on oxygenation during OLV.[20,21] Therefore, the authors concluded that anesthetic agents did not influence oxygenation in the study presented here.

For patients with impaired preoperative respiratory function, CPB is preferred to LHB as an extracorporeal circulation support for surgical repairs of the distal aortic arch and descending and thoracoabdominal aorta. Although partial CPB definitely preserves oxygenation during OLV and the use of deep hypothermic circulatory arrest provides a bloodless surgical field, these approaches are associated with an increased risk of lung hemorrhage and respiratory impairment in the postbypass period.[5] The changes in PaO_2 of 4 patients included in this study with a preoperative diagnosis of COPD are shown in Table 5. These data indicate that arterial oxygenation is improved during LHB in patients with decreased pulmonary function, and thus LHB may be applied for these patients during OLV.

The authors acknowledge several limitations in this study. One of these was that ventilatory settings were not protocolized and were left to the discretion of the attending anesthesiologist. Because Pardos et al[22] demonstrated that ventilatory settings during OLV did not affect arterial oxygenation during surgery and the early postoperative period and the ventilator settings were kept unchanged during the measurement period in the study presented here, the changes in oxygenation after the insertion of an inflow cannula and the initiation of LHB were not influenced by ventilator settings.

The elucidation of the mechanism by which LHB leads to improved oxygenation, along with the assurance of safe intraoperative management, will facilitate the application of

Table 5
Changes in PaO_2 (mmHg) of Patients With a Preoperative Diagnosis of COPD

	P1	P2	P3	P4
Patient 5	206	171	418	402
Patient 9	243	241	331	450
Patient 38	393	356	465	427
Patient 39	78	56	427	490

Abbreviation: COPD, chronic obstructive pulmonary disease.

LHB in patients with decreased pulmonary function. This will result in an improved prognosis of patients undergoing surgical repairs of the distal aortic arch and the descending and thoracoabdominal aorta that require a left thoracotomy.

Conclusion

In conclusion, the results of this study suggested that the improved arterial oxygenation during OLV in patients who underwent aortic repair surgery using LHB could be attributed to the insertion of an inflow cannula via the LUPV into the left atrium before LHB. Thus, the mechanical involvement of LHB may have an important effect on the oxygenation during aortic surgery.

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