Hypoxemia During One-Lung Ventilation for Robot-Assisted Coronary Artery Bypass Graft Surgery

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Background. Robot-assisted coronary artery bypass grafting requires continuous one-lung ventilation (OLV) to evacuate the thoracic cavity. Whether this ventilatory mode subjects patients to serious hypoxemia remains underinvestigated.

Methods. From 2005 to 2010, all patients receiving robot-assisted coronary artery bypass graft surgery using OLV with active capnothorax for internal mammary artery harvesting and then passive pneumothorax for minithoracotomy direct-vision coronary bypass graft surgery were included. Patients’ variables of oxygenation were monitored and compared throughout the whole surgical period. Persistent oxygen desaturation (arterial oxygen pressure <70 mm Hg) refractory to primary managements was defined as a hypoxemic event, and predictors of such events were identified by multivariate regression analysis.

Results. A total of 255 consecutive patients were enrolled. Average oxygen saturation decreased modestly during the first stage of OLV with active capnothorax, causing hypoxemic events in 9 patients (4.3%) leading to death in 2 (0.8%), whereas it dropped drastically in the second stage of OLV with passive pneumothorax, resulting in hypoxemic events in 32 patients (12.6%) and death in 1 (0.4%). Multivariate regression analysis identified high pulmonary vascular resistance and low left ventricular ejection fraction as predictors of hypoxemia during internal mammary artery takedown, whereas prolonged procedure and chronic obstructive pulmonary disease were identified as predictors during minithoracotomy bypass grafting.

Conclusions. Robot-assisted two-stage coronary artery bypass surgery employing OLV could be complicated by serious hypoxemia especially at the minithoracotomy grafting stage and in patients with specific risk factors. Thus, when managing such patients, invasive monitoring and aggressive treatment of arterial desaturation are mandatory to ensure the patient’s safety and procedural smoothness.

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a minithoracotomy under direct vision in an off-pump mode, so that the key step of grafting anastomosis can be completed more easily [9]. Nonetheless, these robotic-manual hybrid surgical procedures necessitate continuous one-lung ventilation (OLV) to prevent blockage of the surgical field by an inflated lung, thereby rendering oxygen desaturation a potential complication that may lead to hemodynamic instability [10, 11] and consequently poorer neurologic and cardiac outcome [12, 13].

Given the potentially grave impact of oxygen desaturation on the prognosis of patients receiving OLV-demanding CABG [10–13], this study explored the incidences, manifestations and predictive variables of arterial desaturation in patients undergoing OLV for robot-assisted IMA harvesting and minithoracotomy direct-vision CABG (MIDCABG). The findings of this study shed light on the influence of OLV on systemic arterial oxygenation at distinct stages of the less invasive robot-assisted coronary artery bypass surgery, and may be of value to surgeons for prevention and management of such a critical complication to ultimately improve surgical outcomes.

Patients and Methods

Patients

From November 2005 to May 2010, all patients with stable coronary artery disease undergoing elective robot-assisted CABG were enrolled. Clinical data of these patients were collected from medical records taken during the perioperative and entire in-hospital courses. Treatment protocols in this tertiary referral center require that all ventilatory and hemodynamic variables be recorded in a special chart throughout the whole course of anesthesia. Adverse events during the surgery, especially transient and persistent arterial oxygen desaturation, should be described in detail on this chart.

Anesthesia and OLV

Cardiac rhythm, arterial pulse oxygen saturation (SpO₂) and arterial blood pressure of patients were continuously monitored with electrocardiography, pulse oxymetry and intraartificial manometry throughout the entire perioperative period. Pulmonary artery was catheterized through the right internal jugular vein. Left ventricular wall motion was continuously assessed by transesophageal echocardiography. Anesthesia was induced with fentanyl (2 μg/kg), midazolam (40 to 70 μg/kg), or propofol (1.5 to 2.5 mg/kg), and succinylcholine (1.2 mg/kg), rocuronium (0.8 mg/kg), atracurium (0.6 mg/kg), or cisatracurium (0.16 mg/kg). Trachea was intubated with a 32F to 37F double-lumen endobronchial tube (Bronchocath; Mallickrodt, Athlone, Ireland) for OLV. The correct position of the endotracheal tube was confirmed by fiberoptic bronchoscopy, and endobronchial secretion was suctioned every 30 minutes.

Arterial partial pressure of oxygen (PaO₂) and partial pressure of carbon dioxide (PaCO₂) were periodically measured by arterial blood gas analysis at baseline with or without O₂ mask, at induction of anesthesia with double-lung ventilation (DLV), at OLV during the robot-assisted IMA harvesting stage when carbon dioxide (CO₂) was insufflated into the chest cavity to expand the working space, at OLV during the MIDCABG stage when a small thoracotomy was made and created a passive pneumothorax, at recovery of DLV after coronary graft anastomosis procedure was completed, and at any time when SpO₂ monitored by pulse oximetry dropped below 95%. Ventilatory determinants, including fraction of inspired oxygen (FiO₂), tidal volume, respiratory rate, peak airway pressure, and use of positive end-expiratory pressure (PEEP) were recorded at the same time points as above. Hemodynamic indexes obtained from pulmonary artery catheterization were measured at initiation of anesthesia and right after completion of beating-heart coronary artery graft anastomosis, as described below.

Robot-Assisted Coronary Artery Bypass Graft Surgery

All robot-assisted coronary artery surgeries were conducted without incident by the same experienced operator and consisted of two consecutive stages, namely, IMA takedown followed by minithoracotomy bypass grafting. For robot-assisted IMA harvesting, patients were routinely placed in supine position with the left lung collapsed by OLV and working space expanded by CO₂ insufflation. Intercostal ports were created to allow access for camera and robotic instruments into the thoracic cavity. IMA (mostly the left one) was then harvested robotically under endoscopic guidance and prepared as the arterial graft. To perform anastomosis of this graft to the native coronary vessel, CO₂ insufflation was stopped and a minithoracotomy was created at an appropriate intercostal location overlying the target coronary artery. The IMA graft was then sutured either directly to the target coronary vessel or to a radial artery U-graft, which was then anastomosed to multiple coronary arteries through the minithoracotomy under direct vision. The intercostal ports and the minithoracotomy were thereafter closed unless pleural oozing continued, which would require a chest tube left at the chest access site for drainage. The OLV was then converted to DLV, and

Abbreviations and Acronyms

- CABG = coronary artery bypass graft surgery
- DLV = double-lung ventilation
- ECMO = extracorporeal membrane oxygenation
- FiO₂ = fraction of inspired oxygen
- IMA = internal mammary artery
- MIDCABG = minithoracotomy direct-vision coronary artery bypass graft surgery
- OLV = one-lung ventilation
- PaCO₂ = arterial partial pressure of carbon dioxide
- PaO₂ = arterial partial pressure of oxygen
- PEEP = positive end-expiratory pressure
- PVR = pulmonary vascular resistance
- SpO₂ = arterial pulse oxygen saturation

- FiO₂ = fraction of inspired oxygen
- IMA = internal mammary artery
- MIDCABG = minithoracotomy direct-vision coronary artery bypass graft surgery
- OLV = one-lung ventilation
- PaCO₂ = arterial partial pressure of carbon dioxide
- PaO₂ = arterial partial pressure of oxygen
- PEEP = positive end-expiratory pressure
- PVR = pulmonary vascular resistance
- SpO₂ = arterial pulse oxygen saturation
patients were sent to the postoperative room and subsequently to the intensive care unit for postprocedural care.

**Definition and Management of a Hypoxemic Event**
During the whole OLV period, FiO2 was routinely administered at 60% to maintain SpO2 at around 100%. Oxygen desaturation was defined as a drop in SpO2 to below 95% and was managed with immediate increase of FiO2 to 100%, addition of 5 to 8 cm H2O PEEP, vacuum suction of intrabronchial sputum, and correction of the position of the endobronchial double-lumen tube by fiberoptic bronchoscopy. A hypoxemic event was defined as a PaO2 value persistently below 70 mm Hg despite the application of the aforementioned management. In the event of hypoxemia, coronary surgery was suspended at once to allow transient DLV to correct arterial oxygen levels. If hypoxemia could not be reversed or occurred for more than three times after reinduction of OLV, extracorporeal membrane oxygenation (ECMO) was implemented to maintain adequate arterial oxygen saturation for the index surgery, or the surgical mode was thoroughly converted to conventional open-chest on-pump CABG, largely according to the discretion of the cardiac surgeon.

**Statistical Analysis**
Continuous variables were expressed as mean or median ± SD. Differences in arterial oxygenation indexes (SpO2, PaO2), arterial CO2 content (PaCO2), and peak airway pressure among consecutive timepoints of anesthesia were compared by the general linear model. Normally distributed continuous data between patients with and without hypoxemic events during distinct surgical stages were compared by unpaired Student’s t test, while nonparametric continuous data were compared by Mann-Whitney U test. Categorical variables were compared by χ2 analysis with Fischer’s exact correction. Univariate followed by multivariate logistic regression analysis was used to identify independent correlates of hypoxemic events. Variables were tested in a forward conditioned multivariate logistic regression model if their univariate p values were less than 0.20. Statistical significance was defined as p less than 0.05. The odds ratios and their 95% confidence intervals from the logistic regression analyses were used as estimates of relative risk. All analyses were performed using SPSS software version 10.1 (SPSS, Chicago, IL).

**Results**

**Patient Characteristics**
A total of 255 consecutive patients undergoing robot-assisted CABG were enrolled. Demographic data of these patients are listed in Table 1. Most of these patients had multivessel disease, and the duration of OLV was 114 ± 41 minutes for IMA harvesting and 470 ± 49 minutes for MIDCABG.

**Arterial Oxygen, Arterial CO2, and Peak Airway Pressure During OLV for Serial Stages of Surgery**
When DLV was transitioned to OLV with active capnotherax for robot-assisted IMA harvesting, mean PaO2 dropped from 198 mm Hg to 142 mm Hg (versus baseline DLV stage, p < 0.05), and mean oxygen saturation decreased from 99% to 98% (versus DLV, p < 0.05). These two indexes of oxygenation declined even further to 130 mm Hg and 97% at MIDCABG stage in which OLV with passive pneumothorax was employed (versus baseline

<table>
<thead>
<tr>
<th>Table 1. Demographic Characteristics and Comorbid Illnesses of Patients Undergoing Robot-Assisted Coronary Artery Bypass Surgery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristics</td>
</tr>
<tr>
<td>Age, years (range)/male (%)</td>
</tr>
<tr>
<td>Height, cm/weight, kg (range)</td>
</tr>
<tr>
<td>Body mass index (range)</td>
</tr>
<tr>
<td>Hypertension (%)/diabetes mellitus (%)</td>
</tr>
<tr>
<td>Smoking (%)/COPD (%)</td>
</tr>
<tr>
<td>Old cerebral stroke (%)/uremia (%)</td>
</tr>
<tr>
<td>LVEF, % (range)</td>
</tr>
<tr>
<td>Cardiac index, L/min/m2 (range)</td>
</tr>
<tr>
<td>PAm pressure, mm Hg (range)</td>
</tr>
<tr>
<td>PVR index, dyne · s · cm−5 · m−2 (range)</td>
</tr>
<tr>
<td>SVR index, dyne · s · cm−5 · m−2 (range)</td>
</tr>
<tr>
<td>Duration of anesthesia, min (range)</td>
</tr>
<tr>
<td>Duration OLV for IMA takedown, min (range)</td>
</tr>
<tr>
<td>Duration OLV for MIDCABG, min (range)</td>
</tr>
<tr>
<td>CAD: LM/SVD/DVD/TVD</td>
</tr>
<tr>
<td>Number of coronary grafts: 1/2/3/4/5</td>
</tr>
</tbody>
</table>

CAD = coronary artery disease; COPD = chronic obstructive pulmonary disease; DVD = double-vessel disease; IMA = internal mammary artery; LM = left main; LVEF = left ventricular ejection fraction; MIDCABG = minithorotomy direct-vision coronary artery bypass graft; OLV = one-lung ventilation; PAm = mean pulmonary artery pressure; PVR = pulmonary vascular resistance; SVD = single-vessel disease; SVR = systemic vascular resistance; TVD = triple-vessel disease.
Table 2. Gas Exchange and Ventilatory Measurements at Different Stages of Surgery

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Baseline</th>
<th>Anesthetic Induction, DLV</th>
<th>IMA Takedown, OLV</th>
<th>MIDCABG, OLV</th>
<th>End of Surgery, DLV</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{PaO}_2 ), mm Hg</td>
<td>124 ± 102</td>
<td>198 ± 127</td>
<td>142 ± 79*</td>
<td>130 ± 76*</td>
<td>282 ± 120</td>
</tr>
<tr>
<td>( \text{PaCO}_2 ), mm Hg</td>
<td>37 ± 5</td>
<td>39 ± 6</td>
<td>41 ± 6*</td>
<td>39 ± 6*</td>
<td>37 ± 6</td>
</tr>
<tr>
<td>( \text{SaO}_2 ), %</td>
<td>98 ± 2</td>
<td>99 ± 2</td>
<td>98 ± 7*</td>
<td>97 ± 4**</td>
<td>99 ± 2</td>
</tr>
<tr>
<td>PAW, mm Hg</td>
<td>...</td>
<td>30 ± 6</td>
<td>32 ± 5*</td>
<td>32 ± 4</td>
<td>30 ± 5</td>
</tr>
</tbody>
</table>

\* Versus double-lung ventilation (DLV) after induction, \( p < 0.05 \); \*\* versus one-lung ventilation (OLV) during internal mammary artery (IMA) takedown, \( p < 0.05 \).

MIDCABG = mini-invasive direct-vision coronary artery bypass graft surgery; \( \text{PaCO}_2 \) = arterial carbon oxide pressure; \( \text{PaO}_2 \) = arterial oxygen pressure; \( \text{SaO}_2 \) = arterial oxygen saturation.

DLV and versus IMA takedown, \( p < 0.05 \) for both). The \( \text{PaCO}_2 \), however, increased only slightly from 39 to 41 mm Hg (versus baseline DLV, \( p < 0.05 \)) at IMA takedown, although \( \text{CO}_2 \) was insufflated to hemithorax, and returned to 39 mm Hg at the MIDCABG stage when no more \( \text{CO}_2 \) was insufflated (versus DLV, \( p = \text{nonsignificant} \)). Peak airway pressure increased mildly from 30 to 32 mm Hg (versus DLV, \( p < 0.05 \)) during initiation of OLV and remained at similar levels throughout the IMA harvesting and MIDCABG stages (Table 2).

Hypoxic Events During Robot-Assisted IMA Harvesting

Although most episodes of arterial desaturation during robot-assisted IMA harvesting could be safely resolved by administration of pure O\(_2\), application of PEEP, aggressive suction of sputum, and bronchoscopic adjustment of tracheal tube position, there were still 11 patients who had serious persistent hypoxemia necessitating discontinuation of surgery and reinstallation of DLV. The incidence of persistent hypoxemia during this surgical stage was 4.3% (11 of 255; Table 3). In 9 of the 11 patients, IMA takedown was resumed under OLV after oxygen saturation was restored. The other 2 subjects (overall incidence 0.8%) required application of ECMO to back up the surgical proceedings, but still died of persistent pulmonary edema, respiratory failure, and ventricular fibrillation 1 and 2 days after the whole surgical procedure (Table 3).

Hypoxic Events During MIDCABG

Of the remaining 253 patients in whom IMA was successfully taken down and OLV was shifted from active capnotherax to passive pneumothorax for MIDCABG, 32 patients (12.6%) had a hypoxic event despite the primary management, including 6 patients who had ever succumbed to hypoxemia during IMA takedown and the other 26 new subjects who had hypoxemia exclusively at this stage. The incidence of hypoxic events during MIDCABG (32 of 253, or 12.6%) was markedly higher than that (4.3%) during robot-assisted IMA harvesting (Table 3). Among the 32 patients who had hypoxemia, 29 (including the 6 subjects who also had hypoxemia at the IMA takedown stage) regained adequate oxygen saturation after transient DLV and were able to receive subsequent bypass grafting under OLV, whereas the remaining 3 patients needed ECMO to correct hypoxemia or hemodynamic instability to support ensuing surgical procedures, with 1 of them (overall incidence 0.4%) eventually dying suddenly of ventricular fibrillation in the early postoperative period (Table 3).

Predictors of Hypoxic Events During Serial Stages of Robot-Assisted CABG

The demographic and ventilatory characteristics, including body mass index and pulmonary function indexes, were largely similar between patients who tolerated and did not tolerate the surgical procedures. However, the 11 patients who encountered hypoxemia during the first OLV stage for IMA harvesting had lower left ventricular ejection fraction (median 39% ± 12% versus 58% ± 12%, \( p = 0.007 \)) and higher pulmonary vascular resistance (PVR index) (median 313 ± 216 versus 185 ± 139 dyne · s · cm\(^{-5} \) · m\(^{-2} \), \( p = 0.044 \)), and the 32 subjects who had hypoxemia during the second OLV stage for mini-thoracotomy grafting had a higher prevalence of chronic obstructive pulmonary disease (28% versus 10%, \( p = 0.009 \)) as compared subjects without hypoxic events. Multivariate logistic regression analysis confirmed that low left ventricular ejection fraction (<40%) and high PVR (PVR index ≥250 dyne · s · cm\(^{-5} \) · m\(^{-2} \)) were independent predictors of hypoxemia during robot-assisted IMA harvesting (Table 4), whereas chronic obstructive pulmonary disease and long duration of surgical procedures were

Table 3. Incidence and Outcomes of Hypoxic Events During Internal Mammary Artery Harvesting and Mini-Invasive Direct-Vision Coronary Artery Bypass Graft Surgery Using Different Modes of One-Lung Ventilation

<table>
<thead>
<tr>
<th>Hypoxic Event</th>
<th>During IMA harvesting</th>
<th>During MIDCABG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case number/incidence (%)</td>
<td>11/4.3</td>
<td>32*/12.6</td>
</tr>
<tr>
<td>Outcome</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surgery resumed (%)</td>
<td>9 (82)</td>
<td>29* (91)</td>
</tr>
<tr>
<td>Conversion to ECMO-supported surgery (%)</td>
<td>2 (18)</td>
<td>3 (9)</td>
</tr>
<tr>
<td>Death, overall incidence (%)</td>
<td>2* (0.8)</td>
<td>1* (0.4)</td>
</tr>
</tbody>
</table>

\* Including 6 patients who also had and survived hypoxemia at the internal mammary artery (IMA) harvesting stage. \*\* Causes of death detailed in the text.

ECMO = extracorporeal membrane oxygenation; MIDCABG = mini-invasive direct-vision coronary artery bypass graft surgery.
independent predictors of hypoxemia during MIDCABG (Table 5).

Comment

Robot-assisted coronary artery bypass surgery dramatically transforms a major, open-chest, on-pump cardiac operation to a less invasive, minithoracotomy, off-pump procedure and has equivalent efficiency for myocardial revascularization [4, 14]. However, the mandatory requirement of prolonged OLV for completion of this surgery without the backup of extracorporeal circulation remains a challenge due to the possibility of inadequate oxygenation during the surgery [15, 16]. This study investigating the impact of OLV on arterial oxygen saturation in patients receiving two-stage robot-assisted coronary artery bypass surgery demonstrated that the two indispensable modes of OLV involving either closed-chest capnothorax or minithoracotomy passive pneumothorax may cause persistent hypoxemia in a considerable portion of patients and even seriously compromise the perioperative outcome. These findings illustrate the potential hazard of hypoxemia in patients undergoing the relatively less invasive robot-assisted coronary bypass surgery, and highlight the need for precaution as well as timely management in the event of this potentially disastrous complication to protect patients’ periprocedural safety.

Oxygen Desaturation and Hypoxemia During Robot-Assisted IMA Harvesting

At the robotic IMA harvesting stage, the average PaO2 dropped markedly after initiation of OLV with active CO2 insufflation, whereas the average PaCO2 elevated only marginally. These findings indicated that expulsion of CO2 by one single lung was still sufficient, but oxygenation was inadequate. The incidence of hypoxemia (4.3%) in our patients was remarkably lower than that reported in studies with smaller numbers of patients who underwent capnothorax-associated OLV-facilitated video-assisted thoracoscopic surgery for pleurectomy, pleural biopsy, or pulmonary wedge resection, with rates ranging from 27% (7 of 22 patients) if hypoxemia was defined as PaO2 less than 70 mm Hg [17] to 40% (4 of 10 patients) if hypoxemia was defined as SpO2 less than 91% [18], possibly reflecting the effectiveness of the primary managements we applied, which might not have been vigorously performed in the aforementioned studies. The relatively low incidence of severe hypoxia in our patients might also be attributable to unilateral capnothorax, which actively collapses the pulmonary lobes adjacent to the surgical field, decreases perfusion to this nonventilated pulmonary region, and in turn reduces intrapulmonary shunting [10, 15]. Nevertheless, the increased intrathoracic pressure could unfavorably increase right ventricular afterload, decrease right ventricle refilling, and may ultimately jeopardize right ventricle function, thereby reducing cardiac performance in patients with preexisting high PVR, which hence served as an independent predictor for occurrence of intraoperative hypoxemia. Moreover, active CO2 insufflation exerts positive intrathoracic pressure, which mechanically compresses the left ventricle as well as the coronary arteries [18] causing left ventricular diastolic and even systolic dysfunction. This hemodynamic consequence may rationally explain why low baseline left ventricular ejection fraction accounted for the other predictor of intraprocedural hypoxemia. This action of capnothorax on heart function has been demonstrated by earlier research showing significant wall motion abnormalities of both right and left ventricles in patients undergoing capnothorax-facilitated telerobotic endoscopic surgery [8]. The balance between benefit and harm of capnothorax on patients undergoing robot-assisted coronary bypass surgery therefore requires individualized evaluation.

Oxygen Desaturation and Hypoxemia During MIDCABG

At the second surgical stage for MIDCABG, OLV was introduced along with passive pneumothorax instead of closed-chest active capnothorax, and arterial oxygen saturation further dropped with a parallel increase in the incidence of hypoxic events, indicating that passive pneumothorax has a more deleterious effect on arterial saturation compared to active capnothorax. These findings suggest the role of intrapulmonary shunting in the pathogenesis of hypoxemia at this surgical stage with passive pneumothorax, as only shunt-related hypoxemia was uncorrectable by increase of FiO2. Thus, the benefit of release of capnothorax on amelioration of PVR and improvement of cardiac function did not outweigh the

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Table 4. Logistic Regression Analysis of Risk Factors for Hypoxemia During Robot-Assisted Internal Mammary Artery Harvesting (First-Stage One-Lung Ventilation)

<table>
<thead>
<tr>
<th>Variables in the Model</th>
<th>OR</th>
<th>95% CI</th>
<th>p Value Univariate</th>
<th>p Value Multivariate</th>
</tr>
</thead>
<tbody>
<tr>
<td>LVEF &lt;40%</td>
<td>6.227</td>
<td>1.744–22.236</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>PVRI &gt;250 dyne · s · cm⁻⁵ · m⁻²</td>
<td>5.650</td>
<td>1.541–20.714</td>
<td>0.010</td>
<td>0.009</td>
</tr>
</tbody>
</table>

CI = confidence interval; LVEF = left ventricular ejection fraction; OR = odds ratio; PVRI = pulmonary vascular resistance index.

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Table 5. Logistic Regression Analysis of Risk Factors for Hypoxemia During Mini-Invasive Direct-Vision Coronary Artery Bypass Graft Surgery (Second-Stage One-Lung Ventilation)

<table>
<thead>
<tr>
<th>Variables in the Model</th>
<th>OR</th>
<th>95% CI</th>
<th>p Value Univariate</th>
<th>p Value Multivariate</th>
</tr>
</thead>
<tbody>
<tr>
<td>COPD</td>
<td>3.403</td>
<td>1.322–8.759</td>
<td>0.007</td>
<td>0.011</td>
</tr>
<tr>
<td>Duration of OLV</td>
<td>1.012</td>
<td>1.005–1.019</td>
<td>0.001</td>
<td>0.001</td>
</tr>
</tbody>
</table>

CI = confidence interval; COPD = chronic obstructive pulmonary disease; OLV = one-lung ventilation; OR = odds ratio.
Harm it caused by aggravating intrapulmonary shunting across the ipsilateral, nonventilated lung. The 12.2% incidence of refractory hypoxemia (defined as PaO₂ <70 mm Hg) during MIDCABG in our patients was higher than that in previous studies, which reported rates of low SaO₂ (<90%) in only 4% to 10% of patients who underwent various pulmonary surgical operations [16, 19].

The higher incidence in our study may be related to the distinct characteristics of our patients. First, patients in other studies were mostly placed in the lateral decubitus position for contralateral pulmonary surgery, and this position could achieve better ventilation-perfusion matching and minimize intrapulmonary shunting. In contrast, patients in our study were placed in the supine position so that both the ventilated and the nonventilated lungs were perfused evenly, producing substantial shunting in the nonventilated lung. Second, the average duration of OLV was only 30 minutes in other patient populations mainly for pulmonary surgery, but was much longer in our patients (470 minutes) undergoing the more difficult bypass grafting. Third, all of our patients had significant coronary artery stenosis and needed to be subjected to mechanical fixation of a part of the left ventricle for bypass grafting. In fact, as the right lung is volumetrically larger than the left, the overall incidence of hypoxemia in our patients should have been mitigated by the mode of right-side OLV that was applied almost exclusively in our patients, which offered better oxygenation than left-side OLV [19]. Finally, because intrapulmonary shunting was elevated during passive pneumothorax, the health of the only ventilated lung became an even more important determinant of arterial oxygenation [20]. That may explain why patients with preexisting chronic obstructive pulmonary disease tended to have hypoxemia, as a solitary and unhealthy lung is insufficient for maintaining adequate arterial oxygenation. Our finding that long duration of MIDCABG also predicts hypoxemia emphasizes the need for simplification and abbreviation of the surgical procedures to avoid serious hypoxic events, or to convert the surgical plan to other approaches not requiring OLV in some patients for whom time-consuming operations are anticipated.

In conclusion, OLV for robot-assisted CABG provides greater thoracic space for versatile operation of surgical instruments yet impairs arterial O₂ saturation modestly at the active capnotherapy stage for IMAs harvesting and drastically at the passive pneumothorax stage for bypass grafting. Although most episodes of hypoxemia can be reversed by primary managements, a considerable proportion of patients may have persistent hypoxemia requiring cessation of surgery and reinstallation of DLV, or even implementation of ECMO for circulatory support, resulting in postoperative mortality in some cases. These findings illustrate the potential risk of serious hypoxemia in patients undergoing different modes of OLV for robot-assisted CABG, and may be of value to clinicians for the prevention and management of this potentially fatal complication during this less invasive coronary bypass surgery.

References