Original Article

The predictive and prognostic value of risk factors in patients receiving hybrid coronary revascularization with postoperative pulmonary complications

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Background: The mortality rate of coronary artery disease ranks first in developed countries, and coronary revascularization therapy is an important cornerstone of its treatment. The postoperative pulmonary complications (PPCs) in patients receiving one-stop hybrid coronary revascularization (HCR) aggravate the dysfunction of multiple organs such as the heart and lungs, therefore increasing mortality. However, the risk factors are still unclear. The objective of this study was to explore the risk factors of PPCs after HCR surgery.

Methods: In this study, the perioperative data of 311 patients undergoing HCR surgery were reviewed. All patients were divided into two groups according to whether the PPCs occurred. The baseline information and surgery-related indicators in preoperative laboratory examination, intraoperative fluid management, and anesthesia management were compared between the two groups.

Results: Advanced age [odds ratio (OR): 1.065, 95% confidence interval (CI): 1.030–1.101, P<0.001], high body mass index (BMI; OR: 1.113, 95% CI: 1.011–1.225, P=0.02), history of percutaneous coronary intervention (PCI) surgery (OR: 2.831, 95% CI: 1.388–5.775, P=0.004), one-lung volume ventilation (OR: 3.804, 95% CI: 1.923–7.526, P<0.001), inhalation of high concentration oxygen (OR: 3.666, 95% CI: 1.719–7.815, P=0.001), the application of positive end-expiratory pressure (PEEP; OR: 2.567, 95% CI: 1.338–4.926, P=0.005), and long one-lung ventilation time (OR: 1.015, 95% CI: 1.006–1.023, P=0.001) may be risk factors for postoperative PPCs in patients undergoing one-stop coronary revascularization surgery. Using the above seven factors to jointly predict the risk of PPCs in patients undergoing one-stop coronary revascularization surgery, the receiver operating characteristic (ROC) curve showed an area under the curve (AUC) =0.873, 95% CI: 0.835–0.911, sensitivity: 84.81%, and specificity: 75.82%; the predictive model was shown to be effective.

Conclusions: Patients undergoing HCR surgery with advanced age, high BMI, a history of PCI surgery, one-lung volume ventilation, inhalation of high concentration oxygen, use of PEEP, and prolonged single lung ventilation are more prone to PPCs.

Keywords: One-stop hybrid coronary revascularization (one-stop HCR); postoperative pulmonary complications (PPCs); risk factor

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Introduction

Coronary artery disease is the leading global cause of mortality and coronary revascularization therapy is an important cornerstone of its treatment (1,2). Traditional coronary revascularization treatment includes coronary artery bypass graft (CABG) and percutaneous coronary intervention (PCI). The advantage of CABG is that it has a higher long-term survival rate and a lower incidence of major adverse cardiac or cerebrovascular events (MACCE) in patients with complex multivessel disease (3). The advantage of PCI is that it is used in patients with uncomplicated coronary artery disease, has a lower incidence of early stroke (4). However, CABG has the higher incidence of stroke after surgery and the higher occlusion rate of the great saphenous vein after coronary artery grafting, as well as the invasive and high-risk characteristics of cardiopulmonary bypass (5). PCI used in patients with complex coronary artery disease shows a higher incidence of MACCE and higher mortality, and has a higher incidence of repeated coronary revascularization therapy (6).

One-stop hybrid coronary revascularization (HCR) refers to the combination of two different coronary revascularization treatments including the left internal mammary artery as left anterior descending coronary artery graft (LIMA-LAD) surgical minimally invasive (microincision, off-pump) coronary artery bypass surgery and non-LAD disease vascular with PCI (7). PCI is performed immediately after bypass surgery. HCR was first reported in 1996 by Angelini *et al.* and has been applied to the revascularization of multiple coronary artery lesions (8). In clinical practice, some HCR patients experience severe dyspnea after surgery, with arterial blood gas analysis and chest imaging examination confirming the presence of acute lung injury (ALI) signs such as hypoxemia and pulmonary infection (9). The postoperative pulmonary complications (PPCs) in patients receiving HCR surgery have been shown to aggravate the dysfunction of multiple organs such as the heart and lungs, therefore increasing mortality. There is an urgent need to identify the patients at great risk of developing lung injury (10). However, the risk factors of PPCs in patients receiving HCR surgery are still unclear.

In this study, the baseline information and surgery-related indicators in preoperative laboratory examination, intraoperative fluid management, and anesthesia management were compared. The study aimed to reveal the possible risk factors for PPCs after HCR surgery. Importantly, we monitored the influence of different choices of intraoperative respiratory management on PPCs in this special technique for this particular group of patients. We present this article in accordance with the TRIPOD reporting checklist (available at https://jtd.amegroups.com/article/view/10.21037/jtd-24-422/rc).

Highlight box

Key findings

- Patients undergoing hybrid coronary revascularization (HCR) surgery with advanced age, high body mass index (BMI), a history of percutaneous coronary intervention (PCI) surgery, one-lung volume ventilation, inhalation of high concentration oxygen, use of positive end-expiratory pressure (PEEP), and prolonged single lung ventilation are more prone to postoperative pulmonary complications (PPCs).

What is known and what is new?

- PPCs are more likely to occur in patients with advanced age, high BMI, one-lung volume ventilation, and inhalation of high concentration oxygen.
- There are no studies on the risk factors for pulmonary complications after HCR surgery. In this study, Patients with a history of PCI surgery and use of PEEP were found to be more prone to PPCs, which contrasts with the results of previous studies.

What is the implication, and what should change now?

- Previous lung protection strategies may not be appropriate for HCR surgery (e.g., with or without PEEP). More attention should be paid to how to reduce PPCs in HCR patients.

Methods

Patients

This study retrospectively involved 311 patients admitted to Department of Cardiac Surgery, Beijing Chaoyang Hospital from April 2018 to April 2022. All of these patients underwent HCR surgery during their hospitalization. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The research proposal was approved by the Ethics Committee of Beijing Chaoyang Hospital (No. 2022-KE-507) and individual consent for this retrospective analysis was waived.

Inclusion and exclusion criteria

The patients diagnosed of coronary atherosclerotic heart disease receiving HCR surgery with the age of no less than

18 years old were included. The patients with preoperative pulmonary infection and missing clinical data were excluded.

Study design

The baseline information including age, sex, body mass index (BMI), smoking, alcohol consumption, diabetes, hypertension, cerebrovascular disease, and lung disease was collected. The surgery-related indicators including preoperative hemoglobin, preoperative red blood cells, preoperative triglycerides, preoperative low-density lipoprotein, preoperative creatine kinase, preoperative brain natriuretic peptide (BNP), preoperative cardiac troponin I (CTNI), intraoperative total fluid input, intraoperative fluid volume, unilateral ventilation time, unilateral inhaled oxygen concentration, unilateral pulmonary partial pressure of oxygen, unilateral lung ventilation mode, anesthesia approach, bridge recanalization oxygenation index changes, and positive end-expiratory pressure (PEEP) were recorded.

PPCs diagnosis

Melbourne Group Scale (version 2.0) was used for PPCs diagnosis (11). There were 8 criteria: (I) body temperature >38 ℃; (II) white blood cell (WBC) $>11.2\times10^9$/L or use of respiratory antibiotics; (III) doctor diagnosis pneumonia or chest infection; (IV) chest radiograph showing atelectasis or consolidation; (V) purulent sputum (yellow/green), different from preoperative; (VI) sputum pathogenic microorganism culture positive; (VII) oxygen saturation (SpO_2) <90% under air; (VIII) re-admission due to respiratory problems or stay in the intensive care unit (ICU) for >36 hours. The occurrence of ≥4 items was defined as the occurrence of PPCs.

Anesthesia procedure

All patients were under general anesthesia with double-lumen bronchial intubation, routinely deprived of water and food before surgery, and received intramuscular injection of 0.1 mg/kg morphine in the ward 30 minutes before surgery. After entering the operating room, routine oxygen inhalation, continuous electrocardiographic monitoring of vital signs, and right radial artery puncture under local anesthesia were performed to measure arterial blood pressure. Anesthesia induction was induced by intravenous midazolam 0–0.03 mg/kg, sufentanil 1.5–2 μg/kg, etomidate 0.1–0.3 mg/kg, and rocuronium 0.6 mg/kg. After induction of anesthesia, double-lumen bronchial intubation was performed and connected to an anesthesia machine, and mechanical ventilation was performed. After successful induction of anesthesia, a central venous catheter was placed through the right internal jugular vein to monitor central venous pressure. Some patients may require the placement of a floating catheter through the right internal jugular vein to monitor pulmonary arterial pressure, cardiac output, and mixed venous blood flow depending on the condition. Monitoring of oxygen saturation was monitored: if it was difficult for the patient to maintain oxygenation above 90% during one-lung ventilation during the operation, a low-flow oxygen supply was supplied to the bronchus on the surgical side to ensure the intraoperative arterial blood oxygen partial pressure level of the patient.

Anesthesia parameters

The respiratory rate was set to 12–20 times/min, the tidal volume to 6–8 mL/kg, and the inspiratory-to-breath ratio at 1:2 or 1:1.5. The PEEP was situation-dependent, ranging from 0 to 10 cmH_2O. Pressure ventilation volume depends on the patient's single lung airway pressure, and the arterial blood carbon dioxide partial pressure was maintained at 35–45 mmHg during the operation.

Anesthesia approach

There were three possible anesthesia approaches: (I) total intravenous anesthesia, only propofol was used for anesthesia maintenance. The maintenance dose was 4–12 mg/kg/h, and sufentanil was intermittently given to supplement analgesia. (II) Intravenous anesthetics combined with sevoflurane. The maintenance dose of propofol was 3–8 mg/kg/h, and the combined inhalation of 0.5–1.5% sevoflurane. (III) Intravenous anesthetic combined with desflurane. The maintenance dose of propofol was 3–8 mg/kg/h, combined with inhalation of 2–4% sevoflurane.

Statistical analysis

The data of this study were analyzed using the software SPSS 22.0 (IBM Corp., Armonk, NY, USA). Measurement data conforming to a normal distribution were expressed as mean ± standard deviation (SD). Nonnormal measurement data were expressed as medians (interquartile range). Enumeration data were expressed by rate or composition ratio. Differences between groups were determined by *t*-test, Chi-squared test, Fisher's exact test, and nonparametric test. Binary logistic regression was used for univariate and multivariate analysis. Receiver operating characteristic (ROC) curve was used for index prediction. Correlation analysis was performed by Spearman rank correlation analysis. A P value <0.05 was considered statistically significant.

Results

This study reviewed 354 patients who underwent HCR. Excluding 43 patients who were younger than 18 years of age or had preoperative pulmonary infections, the final total for this study comprised 311 patients. According to the Melbourne Group Scale (version 2.0), 158 patients were ultimately determined to have developed PPCs with an incidence of 50.8%.

Univariate analysis of patient characteristics

Patients were grouped according to the development or absence of PPCs. The univariate analysis results of patient demographics between the two groups are shown in *Table 1*, in which statistically significant differences were found in terms of age (P=0.002), BMI (P=0.007), and whether the patients were post-PCI (P<0.001). Patients of advanced age, high BMI, and with a history of PCI surgery had a higher probability of developing postoperative PPCs.

Univariate analysis of surgery-related factors in patients with/without PPCs

The results of the univariate analysis of surgical-related factors in the two groups are shown in *Table 2*, in which statistically significant differences were found in the duration of one-lung ventilation (P=0.003), the mode of one-lung ventilation (P<0.001), fraction of inhaled oxygen (FiO_2) (P<0.001), and PEEP (P=0.004). The probability of postoperative PPCs was higher in patients with prolonged one-lung ventilation, volume ventilation, and high inhalation of FiO_2, as well as in those treated with PEEP.

Univariate analysis of relevant laboratory tests in patients with/without PPCs

The results of univariate analysis of the relevant preoperative and postoperative laboratory tests of the two groups are shown in *Table 3*, with no statistically significant differences found in any parameter.

Multivariate logistic regression analysis

The results of multivariate logistic regression analysis are shown in *Table 4*, which further confirms that age [odds ratio (OR): 1.065, 95% confidence interval (CI): 1.030–1.101, P<0.001], BMI (OR: 1.113, 95% CI: 1.011–1.225, P=0.02), post-PCI (OR: 2.831, 95% CI: 1.388–5.775, P=0.004), one-lung ventilation mode (OR: 3.804, 95% CI: 1.923–7.526, P<0.001), high FiO_2 levels (OR: 3.666, 95% CI: 1.719–7.815, P=0.001), PEEP (OR: 2.567, 95% CI: 1.338–4.926, P=0.005), and duration of one-lung ventilation (OR: 1.015, 95% CI: 1.006–1.023, P=0.001) may be risk factors for the development of PPCs in patients undergoing one-stop HCR.

ROC curves for the risk prediction of PPCs in patients undergoing one-stop HCR

Age, BMI, post-PCI surgery, one-lung ventilation mode, high FiO_2 levels, PEEP, and one-lung ventilation duration were combined to predict the risk of PPCs in patients undergoing one-stop HCR. The ROC curves were effective as a prediction model, with an area under the curve (AUC) =0.873, 95% CI: 0.835–0.911, sensitivity: 84.81%, and specificity: 75.82%. The model was effective in predicting PPCs (*Figure 1*).

Discussion

Approximately 230 million people worldwide undergo surgical procedures each year. PPCs account for a large proportion of perioperative risks (12). The incidence of severe PPCs in open surgery, including thoracic surgery, can be as high as 40% (13). Hulzebos *et al.* reported an even higher incidence of PPCs (53%) in patients undergoing CABG (14).

PPCs mainly include pulmonary atelectasis, pulmonary edema, emphysema, lung infections, respiratory failure, pleural effusion, hypoxemia, acute respiratory distress syndrome (ARDS), and pulmonary embolism (15,16). The occurrence of PPCs not only increases hospitalization duration and cost but also the mortality rate of patients, with the 30-day mortality rate of patients with PPCs being as high as 39.6% (17). The main measures currently used to prevent and minimize the occurrence of PPCs include

Table 1 Results of univariate analysis of the demographics of patients with/without postoperative pulmonary complications

Demographic information	Patients without PPCs (n=153)	Patients with PPCs (n=158)	t/χ^2	P value
Gender			0.194[a]	0.65
Male	110 (71.9)	110 (69.6)		
Female	43 (28.1)	48 (30.4)		
Age (years)	62.67±9.08	65.96±9.77	–3.072[b]	0.002*
BMI (kg/m²)	25.37±2.68	26.37±3.72	–2.705[b]	0.007*
ASA			0.273[a]	0.60
3	82 (53.6)	80 (50.6)		
4	71 (46.4)	78 (49.4)		
Diabetes	63 (41.2)	52 (32.9)	2.278[a]	0.13
Hypertension	113 (73.9)	116 (73.4)	0.008[a]	0.93
Post-PCI surgery	23 (15.0)	54 (34.2)	15.293[a]	<0.001*
Cerebrovascular disease	32 (20.9)	37 (23.4)	0.282[a]	0.59
Lung disease	7 (4.6)	7 (4.4)	0.004[a]	0.95
Smoking status			4.370[a]	0.11
Non-smoker	79 (51.6)	65 (41.1)		
Former smoker	39 (25.5)	42 (26.6)		
Current smoker	35 (22.9)	51 (32.3)		
Alcohol use			2.007[a]	0.36
Non-drinker	107 (69.9)	108 (68.4)		
Former drinker	23 (15.0)	18 (11.4)		
Current drinker	23 (15.0)	32 (20.3)		
Acute myocardial infarction	37 (24.2)	31 (19.6)	0.947[a]	0.33
Atrial fibrillation	20 (13.1)	27 (17.1)	0.978[a]	0.32
Ejection fraction (%)			1.236[a]	0.26
<50	7 (4.6)	12 (7.6)		
≥50	146 (95.4)	146 (92.4)		
Pulmonary arterial hypertension	5 (3.3)	8 (5.1)	0.626[a]	0.42
Abnormal preoperative chest X-ray	80 (52.3)	75 (47.5)	0.722[a]	0.39
Postoperative VAS score	3.50±1.23	3.42±1.35	0.541[b]	0.58

Data are presented as n (%) or mean ± SD. [a], χ^2 value; [b], *t* value. *, P≤0.05. The above statistical testing using independent *t*-tests, nonparametric rank sum tests, and Chi-squared tests demonstrates a statistically significant difference between groups when P<0.05, whereas the differences between the groups were not statistically significant when P>0.05. PPC, postoperative pulmonary complication; BMI, body mass index; ASA, American Society of Anesthesiologists; PCI, percutaneous coronary intervention; VAS, visual analog scale; SD, standard deviation.

Table 2 Results of univariate analysis of surgery-related factors in patients with/without postoperative pulmonary complications

Demographic information	Patients without PPCs (n=153)	Patients with PPCs (n=158)	$t/Z/\chi^2$	P value
Anesthesia method			1.637[a]	0.44
Total intravenous	7 (4.6)	10 (6.3)		
Propofol + sevoflurane	108 (70.6)	101 (63.9)		
Propofol + desflurane	38 (24.8)	47 (29.7)		
Anesthesia duration, min	383.3±47.5	388.2±58.3	–0.811[b]	0.41
One-lung ventilation duration, min	173.6±36.8	186.5±38.8	–2.989[b]	0.003*
One-lung ventilation oxygenation index, mmHg	146.1±45.2	143.7±60.9	0.401[b]	0.68
Partial pressure of oxygen in one lung, mmHg	120.5±42.0	121.6±54.5	–0.205[b]	0.83
The mode of one-lung ventilator support			19.041[a]	<0.001*
Pressure support	65 (42.5)	31 (19.6)		
Volume support	88 (57.5)	127 (80.4)		
Contralateral high-flow oxygen therapy			3.201[a]	0.07
No	149 (97.4)	147 (93.0)		
Yes	4 (2.6)	11 (7.0)		
FiO_2, %			94.274[a]	<0.001*
60–79	26 (17.0)	34 (21.5)		
80–94	103 (67.3)	25 (15.8)		
95–100	24 (15.7)	99 (62.7)		
PEEP, cmH_2O			8.097[a]	0.004*
No	63 (41.2)	41 (25.9)		
Yes	90 (58.8)	117 (74.1)		
Total liquid input, mL	2,897.9±680.6	2,829.1±735.4	0.855[b]	0.39
Total liquid output, mL	1,200.00 (800.00, 1,600.00)	1,200.00 (900.00, 1,500.00)	–0.351[c]	0.72
Bleeding volume, mL	200.00 (200.00, 300.00)	250.00 (200.00, 400.00)	–1.507[c]	0.13

Data are presented as n (%) or mean ± SD or median (interquartile range). [a], χ^2 value; [b], *t* value; [c], Z value. *, P≤0.05. The above statistical testing using independent *t*-tests, nonparametric rank sum tests, and Chi-squared tests demonstrates a statistically significant difference between the groups when P<0.05, whereas the differences between groups were not statistically significant when P>0.05. PPC, postoperative pulmonary complication; FiO_2, fraction of inhaled oxygen; PEEP, positive end-expiratory pressure; SD, standard deviation.

preoperative and postoperative respiratory function exercises and physical exercise.

CABG and PCI are typical strategies for the treatment of coronary artery disease (18). One-stop HCR is a procedure that combines CABG and PCI and prevents their respective shortcomings. HCR can be performed by combining CABG and PCI simultaneously in a hybrid operating room (simultaneous HCR) or by performing CABG in the conventional operating room and PCI in the interventional operating room, with the 2 procedures being performed hours or days apart (staged HCR). The participants in this study were those who underwent simultaneous HCR. Simultaneous HCR was performed through a small-incision CABG, which required one-lung ventilation to complete the procedure. One-lung ventilation is prone to volume trauma, pneumatic pressure trauma, pulmonary atelectasis, and oxygen toxicity, all of which are important aspects of ventilator-induced lung injuries (19). In addition, one-lung ventilation is associated with a significant release of cellular inflammatory factors, as well as increases in

Table 3 Results of univariate factor analysis of laboratory tests of patients with/without postoperative pulmonary complications

Parameter	Patients without PPCs (n=153)	Patients with PPCs (n=158)	*t*/Z	P value
Hemoglobin, g/L	133.11±15.99	132.65±14.49	0.266[a]	0.79
Albumin, g/L	41.08±3.29	40.78±2.88	0.853[a]	0.39
HDL, mmol/L	0.93±0.22	0.92±0.20	0.549[a]	0.58
LDL, mmol/L	2.17±0.77	2.33±0.87	–1.654[a]	0.09
Triglycerides, mmol/L	1.26 [0.98, 1.93]	1.46 [1.04, 1.96]	–0.057[b]	0.95
CTNI, ng/mL	0.01 [0.00, 0.13]	0.02 [0.00, 0.29]	–0.987[b]	0.32
BNP, pg/mL	76 [24, 114]	90.5 [38, 114]	–1.606[b]	0.10
Postoperative hemoglobin, g/L	27.31±3.93	26.93±3.77	0.872[a]	0.38
Postoperative CTNI, ng/mL	0.57 [0.24, 1.94]	0.6 [0.23, 2.52]	–0.219[b]	0.82
Postoperative BNP, pg/mL	263 [116, 292.5]	284 [138.25, 298]	–0.945[b]	0.34

Data are presented as mean ± SD or median [interquartile range]. [a], *t* value; [b], Z value. The above statistical testing using independent *t*-tests and nonparametric rank sum tests demonstrates a statistically significant difference between groups when P<0.05, whereas the differences between groups were not statistically significant when P>0.05. PPC, postoperative pulmonary complication; HDL, high-density lipoprotein; LDL, low-density lipoprotein; CTNI, cardiac troponin I; BNP, B-type natriuretic peptide; SD, standard deviation.

Table 4 Results of multivariate logistic regression analysis

Parameter	B	S.E.	Wald	P	OR (95% CI)
Age	0.063	0.017	13.427	<0.001	1.065 (1.030–1.101)
BMI	0.107	0.049	4.744	0.02	1.113 (1.011–1.225)
Post-PCI surgery	1.041	0.364	8.189	0.004	2.831 (1.388–5.775)
One-lung ventilation mode	1.336	0.348	14.734	<0.001	3.804 (1.923–7.526)
FiO_2					
0.60–0.79			61.627	<0.001	1.000
0.80–0.94	–1.583	0.387	16.745	<0.001	0.205 (0.096–0.438)
0.95–1.00	1.299	0.386	11.309	0.001	3.666 (1.719–7.815)
PEEP	0.943	0.332	8.043	0.005	2.567 (1.338–4.926)
One-lung ventilation duration	0.015	0.004	11.135	0.001	1.015 (1.006–1.023)

Variables that were statistically significant in univariate analysis and those that were considered by experts in the field to have an impact on the outcome were included in the multivariate stepwise logistic regression model. Stepwise logistic regression, employing the forward logistic regression method, was used considering the covariance between the respective variables, with P<0.05 being indicative of an independent factor influencing the occurrence of PPCs. S.E., standard error; OR, odds ratio; CI, confidence interval; BMI, body mass index; PCI, percutaneous coronary intervention; FiO_2, fraction of inhaled oxygen; PEEP, positive end-expiratory pressure; PPC, postoperative pulmonary complication.

neutrophil counts and pulmonary vascular permeability. These reactions usually precede systemic inflammatory response syndrome, ARDS, pneumonia, and catabolic pathways, affecting the rate at which the patient's body recovers. Therefore, lung protection strategies during the HCR process are strongly recommended, and it is crucial to explore the risk factors for the development of PPCs after HCR.

The incidence of PPCs in patients in this study who had undergone one-stop HCR was 50.8%, a result similar to those of a previous study (14), suggesting that one-lung ventilation during HCR did not increase the incidence

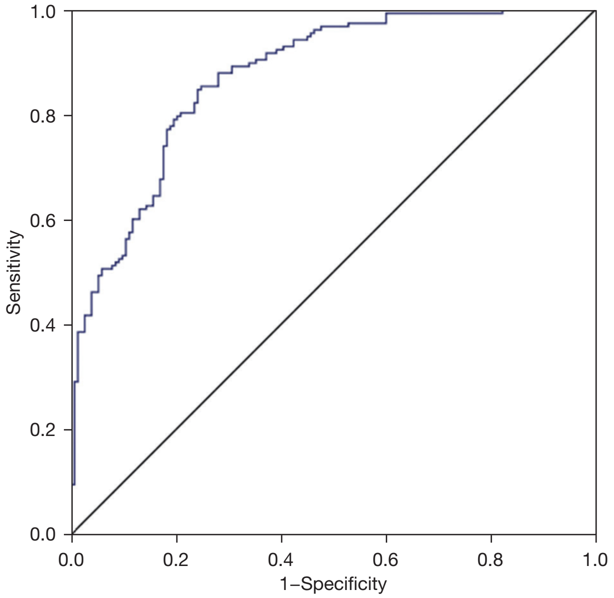

Figure 1 ROC curve combining age, BMI, post-PCI, one-lung ventilation mode, high FiO_2 levels, PEEP, and duration of one-lung ventilation to predict the risk of PPCs in patients undergoing one-stop HCR. AUC =0.873, 95% CI: 0.835–0.911; sensitivity: 84.81%; specificity: 75.82%. ROC, receiver operating characteristic; BMI, body mass index; PCI, percutaneous coronary intervention; FiO_2, fraction of inhaled oxygen; PEEP, positive end-expiratory pressure; PPC, postoperative pulmonary complication; HCR, hybrid coronary revascularization; AUC, area under the curve; CI, confidence interval.

of PPCs in cardiac patients. The results of this study showed that patients of an older age, with a higher BMI, and those who underwent post-PCI were more likely to develop PPCs. In elderly patients, the functions of various bodily organs gradually decline, the degenerative changes of respiratory organs lead to the decline of lung function, and the degradation of liver and kidney functions leads to the slow metabolism of anesthesia drugs, all of which affect respiratory function recovery in the postoperative period (20). These factors, in turn, increase the likelihood of encountering difficulties in postoperative sputum expectoration, resulting in pulmonary atelectasis or lung infections. Obese patients are also prone to PPCs due to the elevation of their diaphragm, a smaller chest volume, and reduced lung compliance (21). Furthermore, obese patients are susceptible to PPCs after a prolonged surgical procedure due to the anesthetic drug accumulating in fat cells, which slows metabolism, resulting in delayed recovery of bodily functions. Patients with coronary artery disease who undergo PCI before surgery have varying degrees of cardiac function decline, which can, in severe cases, lead to a reduction in cardiac output, obstruction of pulmonary venous return, pulmonary congestion, impairment of oxygen diffusion, effects on pulmonary ventilation functions, susceptibility to hypoxemia, and an increased risk of pulmonary infection.

In clinical practice, anesthesiologists tend to use high oxygen concentrations, which can ameliorate and prevent hypoxemia, but this choice can also induce hyperoxemia. Martin *et al.* showed impaired reactive oxygen species (ROS) production under both hyperoxia and hypoxia (22). The results of the multivariate logistic regression analysis in this study were consistent with previous findings, with the lowest incidence of PPCs in the group with moderate FiO_2 levels (0.8–0.94) and the highest incidence of PPCs in the high FiO_2 group (0.95–1). When high concentrations of oxygen are inhaled, alveolar epithelial cells are exposed to high oxygen conditions, generating large amounts of ROS, initiating intracellular transduction pathways, secreting inflammatory mediators, and disrupting the alveolar capillary barrier, all of which lead to reduced lung ventilation (23). In addition, absorption atelectasis has been associated with high FiO_2 levels. Therefore, once the airway is established, FiO_2 levels should be minimized while still meeting the body's oxygen supply needs (24). The 2019 International Expert Consensus on Lung Protective Ventilation Strategies also recommends that once a good airway has been established, FiO_2 <0.4 should be adjusted to maintain oxygen saturation at normal levels (or SpO_2 no less than 94%) and to avoid unnecessarily high FiO_2 levels (25). However, the overall oxygen concentration requirements of this study group were higher, and none of the patients included in this study had an FiO_2 level of less than 0.6, possibly because all patients participating in this study were subjected to CABG and required one-lung ventilation during the operation. As a result, this study could not substantiate the conclusions in the Consensus. In contrast to the Consensus recommendation, in this study, the incidence of PPCs was higher in the low FiO_2 concentration group (0.6–0.8) than in the moderate FiO_2 concentration group.

The results of multivariate logistic regression analysis in this study also showed that prolonged one-lung ventilation and volume-controlled ventilation (VCV) increased the incidence of PPCs. One-lung ventilation poses inherent risks to lung tissue, and longer durations lead to greater severity of lung damage. VCV maintains a set tidal volume with a constant airflow, but higher inspiratory pressures may cause coiling trauma, shear damage, and pneumatic pressure injury, resulting in lung atelectasis and oxidative stress, and ultimately mechanical ventilation-related lung injury (26,27). Pressure-controlled ventilation (PCV) is a method of mechanical ventilation aimed at achieving inspiratory pressure. However, it has the drawback that rapid changes in respiratory compliance cannot be compensated using tidal volume, potentially leading to inadequate ventilation or the delivery of inappropriate tidal volumes (28). Higher driving pressures are thought to be an important factor in PCV-induced lung injury. PROVE Network investigators confirmed that increased driving pressure is associated with an increased incidence of PPCs (29). Therefore, PCV should be a protective factor for PPCs, and the results of this study are consistent with these findings.

It has been suggested that intraoperative low-tidal volume ventilation applied alongside PEEP does not significantly reduce PPCs (30). However, Zhang *et al.* found that the use of individualized PEEP based on minimal driving pressure reduced PPCs after episiotomy (31). As a protective strategy for the lungs, the role of PEEP in assisted ventilation has been widely recognized (32,33). Recent research on intraoperative ventilation strategies has shown that 4–15 cmH_2O of PEEP improves respiratory mechanics and oxygenation, thereby reducing PPCs (34). The 2019 International Expert Consensus on Lung Protective Ventilation Strategies states that the use of airway/alveolar pressure to zero end-expiratory pressure is not recommended. Instead, the Consensus recommended an initial setting of 5 cmH_2O for PEEP (25). The results of our study showed that the incidence of PPCs was increased in patients who were treated with PEEP, which is in contrast to the findings of previous studies on lung protection strategies. The reasons for this discrepancy may be the result of two factors. The first is the patient's position; previous studies have focused on two-lung ventilation in the prone position or one-lung ventilation in the lateral position, whereas our study involved one-lung ventilation in the prone position with the left side elevated by 30°. One-lung ventilation inherently poses a higher risk of lung injury, and the position used in our study could not take advantage of the gravitational shift of blood flow to regulate the ventilation-to-blood flow ratio, a benefit associated with the purely lateral position. The second reason is that all patients in our study had heart disease, leading to an imbalance in oxygen supply and demand in the myocardium. The use of PEEP can be detrimental to circulatory stability, and hemodynamic fluctuations may lead to inadequate blood and oxygen supply to the lung tissues, thereby increasing the chance of pulmonary complications (35). Although some previous studies have shown that PEEP did not reduce PPCs, the lack of corresponding previous studies on lung protection during one-lung ventilation in the prone position resulting from HCR prevents us from validating our findings (36,37).

Conclusions

In patients undergoing HCR, PPCs were more likely to occur in those who were older, had a higher BMI, had undergone PCI, had high FiO_2 levels, had prolonged one-lung ventilation, were using VCV, or were administered PEEP. ROC curves applying the combination of these factors to predict the occurrence of PPCs in HCR surgery showed moderate predictive power. Further prospective studies will increase the strength of the evidence from this single-center retrospective study.

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Footnote

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Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The research proposal was approved by the Ethics Committee of Beijing Chaoyang Hospital (No. 2022-KE-507) and individual consent for this retrospective analysis was waived.

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