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An individualized recruitment maneuver for mechanically ventilated patients after cardiac surgery

Ryohei Serita[1], Hiroshi Morisaki[2], and Junzo Takeda[2]

[1] Department of Anesthesiology, Tokyo Dental College Ichikawa General Hospital, 5-11-13 Sugano, Ichikawa 272-8513, Japan
[2] Department of Anesthesiology, School of Medicine, Keio University, Tokyo, Japan

Abstract
Purpose. The recruitment maneuver (RM) has been shown to improve oxygenation for post-cardiopulmonary bypass (CPB) patients; however, sustained inflation of the lung gives rise to hypotension. The primary goal of our study was to evaluate the safety and efficacy of our proposed RM, defined on the basis of dynamic lung compliance (Cdyn).
Methods. Twenty-eight patients undergoing elective cardiac surgery with CPB were assigned to two treatment groups: an individualized RM group, in which a pressure equal to 15 ml × real body weight/Cdyn + positive end-expiratory pressure (PEEP) cmH_2O was applied for 15 s; and a control RM group, in which a pressure of 20 cmH_2O was applied for 25 s. Arterial blood pressure, cardiac output, pulmonary artery pressure, and heart rate (HR) were monitored. Tidal volume (Vt), and airway pressure were continuously obtained from an expiratory flow meter and pressure monitor. Blood samples were obtained and analyzed with a blood gas analyzer.
Results. The changes in HR, mean arterial pressure, mean pulmonary artery pressure, and cardiac index at the end of the RM were not significantly different between the two groups. The mean airway pressure of sustained inflation was 28.3 ± 1.3 cmH_2O in the individualized RM group. The individualized RM significantly improved the Cdyn and partial pressure arterial oxygen/inspiratory fraction of oxygen (P/F) ratio compared with values in the control RM group ($P = 0.026$ and $P = 0.012$, respectively).
Conclusion. The present study indicates that the individualized RM resulted in minimum changes of hemodynamics and brought about improvement in oxygenation and lung compliance.

Key words Recruitment maneuver · Dynamic compliance · Cardiopulmonary bypass · Cardiac surgery

Introduction

The recruitment maneuver (RM) has been shown to improve oxygenation for patients with cardiopulmonary bypass (CPB) [1]. However, sustained inflation of the lung often gives rise to a decrease in venous return and cardiac output (CO) in patients ventilated after CPB [2–6]. A previous study demonstrated that the RM using a sustained pressure technique with continuous inspiratory pressure of 40 cmH_2O for 10 s and 20 s reduced CO by more than 50%, reduced left ventricular end-diastolic area by about 45%, and reduced mean arterial pressure (MAP) by 20% in cardiac patients [6]. The hemodynamic effects of positive airway pressure will depend on the degree of lung inflation and holding time [3,4]. Furthermore, the inflation volume of the lung will contribute to lung compliance and chest wall elastance [5]. Although lung compliance varies among mechanically ventilated patients, in previous studies the level of the sustained inflation pressure used in RMs has been the same constant pressure [1,7]. The optimal pressure and duration of inflation have not been documented for RMs, so that the most effective technique for RM remains undetermined, despite many studies of acute respiratory distress syndrome (ARDS) [8].

Individualization of RM to respiratory mechanics may improve oxygenation without causing hemodynamic effects. Traditionally, static pulmonary mechanics has been used to assess lung mechanics [5]. However, recent studies have indicated that the application of dynamic respiratory mechanics in ventilated patients is more appropriate than the use of static lung mechanics [9–11]. Therefore, we have proposed the concept of an individualized RM that was defined on the basis of dynamic compliance (Cdyn), which is easily obtained from the ventilator as a bedside diagnostic tool [9–11].

The purpose of the present study was to assess the safety and efficacy of our individualized RM in patients after cardiac surgery. The primary endpoint of our study was to verify the hemodynamic effects induced by the individualized RM and to evaluate the improvement in oxygenation and Cdyn.

Address correspondence to: R. Serita
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Methods

Patients

With the approval of our institutional ethics committee and informed consent, from the patients, patients who had undergone elective cardiac surgery with CPB and received overnight mechanical ventilation were enrolled in this prospective and randomized study. Patients were admitted to the 14-bed medical and surgical intensive care unit (ICU) at a university hospital. All patients were mechanically ventilated with an 840 Ventilator System (Nellcor Puritan Bennet, Boulder, CO, USA). Patients with chronic obstructive lung disease (percent volume exhaled during the first second of a forced expiratory maneuver ($[FEV_{1.0\%}] < 70\%$), intraoperative pulmonary trauma, and hemodynamic instability (cardiac index [CI] < 2.2 $l \cdot min^{-1} \cdot m^2$ and/or arterial systolic pressure < 80 mmHg) were excluded. Patients with a pacemaker, intraaortic balloon pumping, or percutaneous cardiopulmonary support were also excluded.

Protocol

All patients were ventilated in the pressure-regulated control mode with 5 cmH_2O of positive end-expiratory pressure (PEEP). Other ventilatory parameters were set as follows: inspiratory plateau pressure (≤30 cmH_2O) was set to obtain a tidal volume (VT) of 10–12 $ml \cdot kg^{-1}$, or inspiratory plateau pressure (>30 cmH_2O) was set to obtain a VT of 6–8 $ml \cdot kg^{-1}$; respiratory rate (RR) and inspiratory fraction of oxygen ($F_{I_{O_2}}$) were set to obtain a Pa_{CO_2} of 38–42 mmHg and a Pa_{O_2} of 150–180 mmHg; inspiratory time was set at 1.0 s. A standard-size tracheal tube was used, with a 7.5-mm inner diameter (ID) for women and an 8.5-mm ID for men. A standard ventilator tubing set (Universal Ventilator Tubing Set; Hudson Respiratory Care, Durham, NC, USA) was used for the respiratory circuit. The patients were well-sedated with a continuous infusion of propofol (50–100 $mg \cdot h^{-1}$), and were observed for 3 to 4 h after intensive care unit (ICU) admission so as to ascertain hemodynamic stability, which was defined as less than 15% variation of hemodynamic parameters with no clinically relevant bleeding (<100 $ml \cdot h^{-1}$).

The VT, RR, and airway pressure were obtained from the eligible patients, and the Cdyn in each patient was calculated as VT/(end-inspiratory pressure—PEEP), breath-by-breath. Then the eligible patients were randomly assigned to two treatment groups: an individualized RM group and a control RM group. In the individualized RM group, an inflation pressure (cmH_2O) equal to 15 × real body weight/Cdyn + PEEP (previously used) was applied for 15 s. We allowed a maximum inflation pressure of up to 45 cmH_2O. In the control RM group, an inflation pressure of 20 cmH_2O was applied for 25 s; this has been reported to have minimal effects on CO and arterial pressure in cardiac surgery patients [2,4]. A table of random numbers, generated by computer software, was utilized for patients' randomization into the two groups (Fig. 1).

The baseline variables of hemodynamics and respiration were obtained before the initiation of RM, and then hemodynamic variables were measured at the end of RM. Respiratory measurements were repeated at 15, 60, and 180 min after RM. The percent change (Δ%) in the variables was calculated [(variables post-RM–the variables at baseline) × 100/ variables at baseline].

Measurements and calculations

Arterial blood pressure was monitored through a radial artery catheter (20-G Arterial Line Kit; Argon Medical, Athens, TX, USA). Cardiac output (CO) and pulmonary arterial pressure (PAP) were measured by the thermodilution method, using a continuous CO catheter (Swan-Ganz CCO mbo; Edwards Life Sciences, Irvine, CA, USA). Heart rate (HR) was monitored by an electrocardiogram.

The VT, RR, and airway pressure were continuously obtained from the expiratory flowmeter and pressure monitor of the ventilator system. Calibrations of the flowmeter and oxymeter, and correction of the respiratory circuit, were performed daily by a biomedical engineer. Respiratory variables, which were obtained from

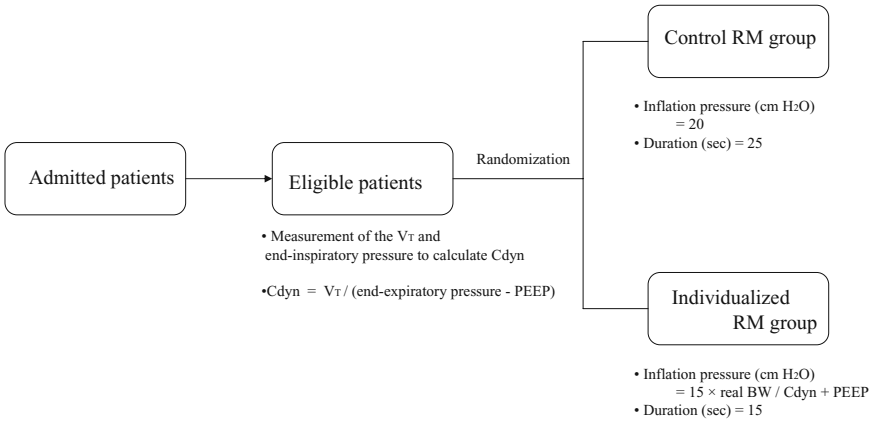

Fig. 1. Protocol for the setting of the recruitment maneuver (RM). *VT*, Tidal volume; *Cdyn*, dynamic compliance; *real BW*, real body weight; *PEEP*, positive end-expiratory pressure

the flowmeter and pressure monitor, were calculated by an average of five breaths. Arterial blood samples were analyzed with a blood gas analyzer (ABL 700; Radiometer, Copenhagen, Denmark). Dynamic compliance was calculated on a breath-by-breath basis.

Statistical analyses

All data values are expressed as means ± SEM unless otherwise described. Before starting the present study, we determined the number of subjects based on a power calculation; this showed that 28 subjects would be needed to achieve an 80% power to detect a difference of 10% in the Pa_{O_2}/FI_{O_2} (P/F) ratio, with $\alpha = 0.05$. The patient characteristics were analyzed using Student's *t*-test, the Mann-Whitney *U*-test, and the Kruskal-Wallis test for differences between the groups. The data were analyzed by two-way repeated-measures analysis-of-variance for differences between the groups, followed by the Mann-Whitney *U*-test. $P < 0.05$ was considered to be statistically significant.

Results

Thirty-nine post-CPB patients were admitted our ICU, and 11 patients were excluded (1 patient with chronic obstructive lung disease, 3 patients with intraoperative pulmonary trauma, 3 patients with hemodynamic instability, 2 patients with a pacemaker, and 2 patients with intraaortic balloon pumping). In total, 28 patients were randomly allocated to the individualized RM group ($n = 14$) or the control RM group ($n = 14$).

The patients' characteristics, including the duration of CPB, were not significantly different between the groups (Table 1). Both hemodynamic and respiratory parameters in the two groups had similar values at baseline and there were no significant differences (Table 2). No patient was ventilated with an inspiratory plateau pressure of more than 30 cmH_2O in either group. The P/F ratio in 4 of the 14 patients in the RM control group and in 6 of the 14 patients in the individualized RM group ranged between 200 and 300. There was no patient with a P/F ratio of less than 200 in either group.

Table 3 shows the percent changes in HR, MAP, mean pulmonary arterial pressure (MPAP), and cardiac index (CI) at the end of the RM. There were no significant differences between the groups. During the RM, no patient in either group was observed with hypotension (MAP < 50 mmHg), arrhythmia, or a low CI ($<2.2\ l \cdot min^{-1} \cdot m^2$). There were significant improvements in the Δ Cdyn and the Δ P/F in the individualized RM group, compared with values in the control RM group ($P = 0.026$ and $P = 0.012$, respectively; Fig. 2). The mean airway pressure of sustained inflation was 28.3 ± 1.3 (21.4–33.8) cmH_2O in the individualized RM group. In the six patients with a P/F ratio ranging between 200 and 300, this pressure was 28.6 ± 1.8 cmH_2O range, 24.2–32.9 cmH_2O. Two of the 14 patients in the control RM group were ventilated with a noninvasive positive-pressure ventilator within 24 h of extubation due to hypoxemia, whereas none of the patients in the individualized RM group needed such ventilation.

There was no correlation between the inflation pressure and the changes in hemodynamic parameters, involving the HR, MAP, MPAP, and CI, in the individualized RM group ($P > 0.1$; linear regression analysis). Also the inflation pressure was not correlated with the improvement of the P/F ratio (Fig. 3; $r^2 = 0.07$, $P = 0.18$, linear regression analysis).

Discussion

The present study indicates that the individualized RM, defined on the basis of dynamic compliance, improved pulmonary oxygenation and slightly increased lung compliance in post-CPB patients. In addition, there was no difference in hemodynamic stability between the two groups, and both groups were stable and safe. These findings suggest that our individualized RM, which is optimized for each patient's dynamic compliance, is appropriate for post-CPB patients without hemodynamic instability.

Table 1. Patients' characteristics

	Control RM group ($n = 14$)	Individualized RM group ($n = 14$)	*P* value
Age (years)	64.6 ± 3.4	66.7 ± 3.4	0.67
Height (cm)	161.8 ± 1.9	158.5 ± 2.9	0.36
Weight (kg)	62.8 ± 2.4	59.6 ± 2.6	0.38
Sex (M/F)	10/4	10/4	1
Surgery			
CABG	7	6	0.56
AVR	3	3	
MVR	1	3	
Ao graft	3	2	
Duration of CPB (min)	111.1 ± 9.4	111.1 ± 12.6	1

Values are means ± SEM
CABG, coronary artery bypass graft; AVR, aortic valve replacement; MVR, mitral valve replacement; Ao graft, aortic graft surgery; CPB, cardiopulmonary bypass

Table 2. Baseline hemodynamic and respiratory parameters

Parameter	Control RM group (n = 14)	Individualized RM group (n = 14)	P value
Heart rate (bpm)	81.1 ± 3.0	87.6 ± 3.5	0.18
Mean arterial pressure (mmHg)	73.3 ± 2.9	75.0 ± 3.1	0.70
Mean pulmonary pressure (mmHg)	15.6 ± 1.1	15.6 ± 1.6	0.98
Cardiac index ($l \cdot min^{-1} \cdot m^2$)	3.1 ± 0.2	3.5 ± 0.2	0.20
$F_{I_{O_2}}$	0.51 ± 0.02	0.50 ± 0.02	0.78
Pressure (cmH_2O)	20.7 ± 1.0	20.7 ± 1.7	1.00
Respiratory rate (bpm)	11.6 ± 0.6	12.1 ± 0.9	0.64
Tidal volume (ml)	650.4 ± 32.7	610.1 ± 28.3	0.36
Dynamic compliance ($ml \cdot cmH_2O^{-1}$)	41.5 ± 2.3	39.2 ± 2.1	0.46
Pa_{O_2} (mmHg)	163.3 ± 6.4	157.0 ± 9.3	0.58
Pa_{CO_2} (mmHg)	38.3 ± 1.9	39.9 ± 1.2	0.45
$Pa_{O_2}/F_{I_{O_2}}$	326.8 ± 18.4	313.7 ± 19.5	0.63

Values are means ± SEM
$F_{I_{O_2}}$, inspiratory fraction of oxygen; Pa_{O_2}, partial pressure of arterial oxygen; Pa_{CO_2}, partial pressure of arterial carbon dioxide

Table 3. Hemodynamic changes at the end of the RMs

Percent change in parameter	Control RM group (n = 14)	Individualized RM group (n = 14)	P value
Heart rate (%)	7.9 ± 4.8	1.8 ± 1.2	0.25
Mean arterial pressure (%)	0.3 ± 1.8	–2.7 ± 6.3	0.64
Mean pulmonary artery pressure (%)	17.3 ± 7.8	28.2 ± 13.5	0.49
Cardiac index (%)	–1.0 ± 0.7	1.0 ± 1.2	0.14

Values are means ± SEM

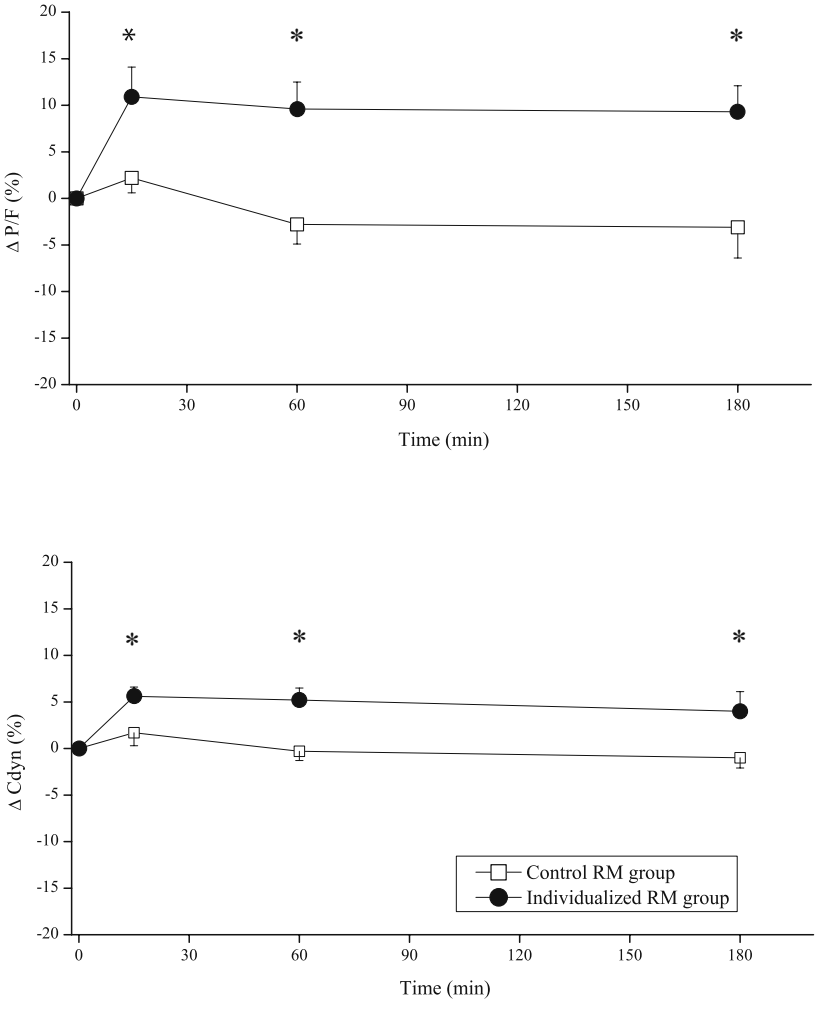

Fig. 2. Effects of control *vs* individualized recruitment maneuver (*RM*) on the percent change in partial pressure arterial oxygen/inspiratory fraction of oxygen (*P*/*F*) and dynamic compliance (*Cdyn*). Changes in both parameters decreased beyond 15 min after the control RM, whereas significant improvements were found in the individualized RM group immediately after RM, and these were preserved for 3 h. There were significant improvements in the percent changes in P/F and Cdyn in the individualized RM group compared with values in the control RM group ($P = 0.026$ and $P = 0.012$, respectively). *$P < 0.05$ vs control group, at each time point

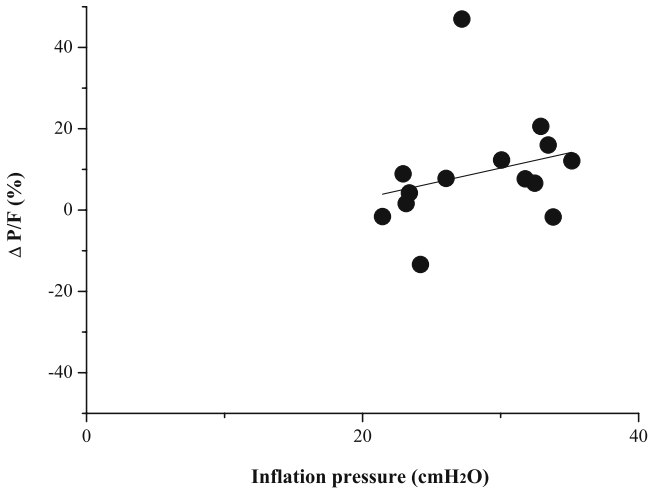

Fig. 3. The inflation pressure was not correlated with the improvement of the P/F ratio at 15 min after RM ($r^2 = 0.07$; $P = 0.18$; linear regression analysis). *P/F*, partial pressure arterial oxygen/inspiratory fraction of oxygen

The preservation of hemodynamic stability should be the first priority for the postoperative management of cardiac surgery. The RM should be used to avoid hemodynamic changes after cardiac surgery because cardiac compensation is insufficient in post-CPB patients, owing to myocardial stunning [6,12]. Indeed, in our clinical experience, a substantial decline in CO and MAP occurs in some patients. Therefore, the application of up to 20 cmH_2O continuous positive airway pressure (CPAP) for 25 s, associated with minimal and short-term changes in CO, was selected for the control procedure. It was obvious that this application was insufficient to improve pulmonary oxygenation or compliance in our pilot study.

The inflation pressure of the individualized RM was relatively higher than that of the control method (28 cmH_2O vs 20 cmH_2O); however, hemodynamic changes were similar in the two groups. The individualized RM in our study reduced MAP by only 3% and changed CI by 1% and HR by about 2%, while an RM with high inflation pressure (40 cmH_2O, 10 s or 20 s) has been reported to reduce CO by more than 50%, left ventricular end-diastolic area by about 45%, and MAP by 20% [6]. This discrepancy between the studies may be explained in terms of intrathoracic pressure (ITP) and sympathetic withdrawal [13]. Increasing airway pressure is elevated in ITP and this leads to decreased venous return and CO. Decreasing lung compliance, however, has been shown to decrease the transmission of the airway pressure to the ITP [13]. In our patients, in whom lung injury was mild to moderate, there was not much difference in ITP, even though there were about 8-cmH_2O differences in inflation pressure between the groups. On the other hand, large-volume inflation of the lung (>15 $ml \cdot kg^{-1}$) decreased HR in an animal model [14]. Lung volume in an RM with 40 cmH_2O may reach more than 15 $ml \cdot kg^{-1}$, and lead to sympathetic withdrawal in post-CPB patients. Indeed, an RM with high inflation pressure (40 cmH_2O, 20 s), as opposed to our methods, was shown to decrease HR by about 20% [6]. Therefore, an RM with high inflation pressure may contribute to hemodynamic instability.

An injured lung often shows nonhomogeneous alveolar distension and high airway pressure is needed to recruit alveoli. Previous studies have shown that, if inflation volume is constant, ITP will be equally increased, which will not reflect a change in the cardiovascular status, although the alveolar distention is not homogeneous [13,15]. In our study, inflation pressure varied, while the inflation volume of the individualized RM was theoretically constant (= 15 × real body weight). Accordingly, the individualized RM would change hemodynamic stability only slightly.

The impairment of pulmonary gas exchange after cardiac surgery contributes to the requirement for prolonged mechanical ventilation [16]. A previous study showed that the P/F ratio in patients with extubation failure was only 7% lower than that in the patients without extubation failure after cardiac surgery [17]. Another study demonstrated that the relative risk of delayed extubation was 0.935 when the P/F ratio increased by 10 [18]; in that study, the patients' P/F ratio at baseline was similar to that in our study. Determining the effect of the RM on long-term outcome after the procedure was not the purpose of our study; however, 2 of the 14 patients in the control RM group were ventilated with a noninvasive positive-pressure ventilator as a result of hypoxemia, whereas none of the patients in the individualized RM group needed such ventilation. Therefore, this slight improvement, without hemodynamic instability, could have some relevance for patients with CPB, although our individualized RM increased the P/F ratio by only about 38 from baseline.

The present study has some limitations. First, our ventilation setting of V_T was relatively high and may be unsuitable for the management of patients with acute lung injury. Pulmonary dysfunction in most patients with CPB is reported to range from subclinical functional changes to moderate lung injury [19,20]. In our patient population, lung injuries were not severe but mild, and no patient had a P/F ratio of less than 200. All patients had been ventilated with an inspiratory plateau pressure of about 20 cmH_2O. It remains controversial whether or not V_T should be reduced when the inspiratory plateau pressure is lower than 30 cmH_2O [21,22]. Therefore, we used a V_T of 10–12 ml to avoid increasing pulmonary atelectasis. Second, we did not try to obtain static pressure-volume loop values because it was our desire to simplify the individualized RM in terms

of daily management. We considered that static pressure—volume loop values did not always provide clear inflection points without neuromuscular agents and the use of these parameters was not necessarily of advantage for post-CPB patients [23]. Recent studies indicate that the application of dynamic respiratory mechanics as a diagnostic tool in ventilated patients could be more appropriate than using static pressure-volume curves [9]. Similarly, we did not correct for the influence of the tracheal tube on airway pressure, and this influence possibly modifies the measurement of dynamic lung compliance. Correction of the airway pressure could make it possible to accurately calculate the dynamic compliance of the respiratory system. By the monitoring of airway pressure in the trachea, respiratory mechanics can be assessed more accurately [24]. Third, in the present study, we chose the pressure to be 15 × real body weight/dynamic compliance + PEEP (cmH_2O), and did not investigate other pressures or hold-times. There may be another combination of pressure and hold-time which is even more effective for the improvement of oxygenation. Nevertheless, we believe that our method, based on dynamic compliance, facilitates the identification of the optimal pressure and hold-time. Finally, based on the P/F ratio, lung injuries in our patient population were not severe but mild, and no patient had a P/F ratio of less than 200. Therefore, it remains unclear whether our individualized RM would be effective for patients with ARDS.

Conclusion

In conclusion, this preliminary study suggests that an individualized RM, defined on the basis of dynamic compliance, slightly improves oxygenation and lung compliance, without hemodynamic instability, for post-CPB patients. We expect to propose a new RM concept by seeking to optimize the inflation pressure for each individual patient, but a large-scale study will be required to determine the optimal pressure and hold-time, and other parameters.

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