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Perioperative ventilatory strategies in cardiac surgery

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Recent data promote the utilization of prophylactic protective ventilation even in patients without acute respiratory distress syndrome (ARDS), and especially after cardiac surgery. The implementation of specific perioperative ventilatory strategies in patients undergoing cardiac surgery can improve both respiratory and extra-pulmonary outcomes. Protective ventilation is not limited to tidal volume reduction. The major components of ventilatory management include assist-controlled mechanical ventilation with low tidal volumes (6–8 mL kg^{-1} of predicted body weight) associated with higher positive end-expiratory pressure (PEEP), limitation of fraction of inspired oxygen (FiO_2), ventilation maintenance during cardiopulmonary bypass, and finally recruitment maneuvers. In order for such strategies to be fully effective, they should be integrated into a multimodal approach beginning from the induction and continuing over the postoperative period.

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Introduction

Despite its beneficial technological advances, cardiac surgery with or without extracorporeal circulation (ECC) still causes substantial respiratory morbidity, leading to prolonged intensive care and hospital length of stay [1]. Several mechanisms are potentially involved and include ischemia–reperfusion phenomena, ventilation disorders or overload-related lung injury due to transfusion or early respiratory mechanics impairment [1–4]. Systemic inflammation due to ECC and aggressive high tidal volume ventilation can cause non-cardiogenic pulmonary edema or other organ failure [5–7]. Perioperative pulmonary morbidity related to these dysfunctions may manifest itself in different ways, from simple atelectasis to acute respiratory distress syndrome (ARDS) [1,2]. To be effectively contained, ischemia–reperfusion lesions necessitate no disruption in pulmonary artery blood flow, which can be achieved with specific ECC methods but further complicates the proceedings [3,4]. Conversely, adequate ventilatory strategies could prevent various lung injuries, such as atelectasis, which lead to intra-pulmonary shunt and are the leading cause of postoperative hypoxemia [5]. The implementation of protective perioperative ventilation especially with reduced tidal volumes and fraction of inspired oxygen (FiO_2) as well as increased respiratory rate and positive end-expiratory pressure (PEEP) levels may improve patients' outcomes following cardiac surgery with cardiopulmonary bypass [6–12].

A brief history of mechanical ventilation in the operating room: from high volumes and zero end-expiratory pressure to low volume with positive end-expiratory pressure

The main objectives of mechanical ventilation during cardiac surgery, outside the bypass period, are to ensure adequate oxygenation along with adequate carbon dioxide removal and to avoid postoperative pulmonary complications. Although apparently straightforward, these goals (oxygenation and CO_2 removal) are based on principles described in the early 1960s by Bendixen et al. [13] who showed that the use of high tidal volume ventilation during surgery led to the prevention of atelectasis and respiratory acidosis and also reduction of per-operative desaturation. This concept markedly influenced perioperative ventilatory management and this work is still cited in recent reference books [14] but is now questionned. It should be noted that data on perioperative atelectasis presented by Bendixen et al. [13] were obtained with zero end-expiratory pressure (ZEEP) and with high FiO_2 levels. At that time, some publications even suggested a possible interest in perioperative use of physiological sighs. Since the 1980s, the use of these sighs, which were 1.5–3 times as large as the already huge tidal volume and applied 6–10 times per hour was frequent. It is no longer part of the ventilatory strategy, although recruitment maneuvers are recommended during the protective ventilation strategy for some authors [15]. For several decades and until recently, the ventilatory management during surgery has associated high tidal volumes without positive expiratory pressure, high FiO_2, and low respiratory rates.

Currently, a modern approach for ventilation management with protective ventilation should not only take into account tidal volume reduction, but also carefully adjust other important ventilatory parameters, with higher PEEP, higher respiratory rates, and lower FiO_2. This progressive evolution has been influenced by studies on ARDS and by technological improvement of anesthesia ventilators.

Since the initial description of ARDS by Ashbaugh in 1967 [16], animal experimentations [17] followed by several randomized controlled studies in humans [18,19] demonstrated in the late 1990s the negative effects of high tidal volumes in ARDS patients.

There arose a new concern regarding the effects of high tidal volumes in patients without ARDS. Over the 2000s, several studies demonstrated that beneficial effects of low tidal volume ventilation could be present even in non-ARDS context and especially during high-risk surgeries [20,21]. The notion of “iatrogenic” ARDS was described by Gajic et al. [22,23] through two observational studies conducted in patients without pulmonary lesions at admission and among whom an association between the occurrence of acute lung injury (ALI) or ARDS and the use of high tidal volumes had been found, as well as with blood transfusions or pneumonia at admission.

Numerous studies have evidenced the benefits of lung protective ventilation during thoracic, abdominal, and cardiac surgery [21]. More recently, a French multicentric randomized controlled trial,

the *IMPROVE study*, demonstrated significant pulmonary and extrapulmonary benefits of lung protective ventilation (tidal volumes of 6–8 mL kg^{-1} of predicted body weight, PEEP of 6–8 cmH_2O, and perioperative recruitment maneuvers every 30 min) as compared with traditional ventilation (tidal volumes of 10–12 mL kg^{-1} of predicted body weight, PEEP of 0 cm H_2O, and no recruitment maneuver) during long-lasting major abdominal surgery [15]. In patients undergoing cardiac surgery, there are now several studies that demonstrate benefits of tidal volume reduction [6–8,24–27] (Table 1). Patients frequently receive blood products during cardiac surgery [28] and ECC induces systemic inflammation that may be further increased by conventional ventilation or decreased with protective ventilation [7]. We have recently shown that the use of high tidal volumes (>12 mL kg^{-1} of predicted body weight) after cardiac surgery was associated with organ failure, prolonged mechanical ventilation, and prolonged intensive care unit (ICU) stay. In this study, women and obese patients (body mass index >30 kg m^{-2}) were at risk of receiving injurious ventilation [6]. As highlighted in the editorial of this paper, patient's "size does matter" when the tidal volume is set, and the tidal volume should be calculated based on predicted body weight and not based on actual weight [29]. One must keep this notion in mind, as the proportion of obese patients is dramatically increasing, with an incidence of 40% in the United States in 2013, and, although less important, an increasing incidence in other countries as well [30].

What should be behind "protective ventilation" nowadays?

Protective ventilation consists not only in reducing tidal volumes but also in modifying several other ventilatory settings. Recent knowledge on this topic should lead in the upcoming years to major changes in our daily perioperative practice.

Table 1
Impact of the ventilatory strategy during cardiac surgery.

Author (reference) (Year) Study design	Type of surgery (n)	TV – PEEP mL/kg cmH_2O	Main results Impact of protective ventilation
Cardiac surgeries			
Chaney [24]	CABG	TV 12 – PEEP 5	Respiratory mechanics less altered
(2000)	25	TV 6 – PEEP 5	↗ oxygenation
RCT			
Koner [25]	CABG	TV 10 – PEEP 0	No difference for inflammatory cytokines
(2004)	44	TV 6 – PEEP 0	levels
RCT			↗ oxygenation with PEEP
Wrigge [27]	CABG	TV 6 – PEEP 10	↘ TNF in BAL
(2005)	44	TV 12 – PEEP 7	
RCT		TV 6 – PEEP 9	
Reis Miranda [26]	CABG	TV 6–8 – PEEP 5	More rapid ↘ of pro-inflammatory cytokines
(2005)	62	TV 4–6 – PEEP 10	
RCT			
Zupancich [7]	CABG	TV 10–12 (ABW) – PEEP 2–3	More important ↘ of pro-inflammatory
(2005)	40	TV 8 (ABW) – PEEP 10	cytokines
RCT			
Sundar [8]	CABG, Valves	TV 10 - PEEP >5	Less intubated patients after 6 h
(2011)	149	TV 6 – PEEP >5	Moins de réintubations
RCT			
Lellouche [6]	CABG, Valves	TV < 10 vs. 10–12 vs. >12	↗ organ dysfunction
(2011)	3434		↗ ICU length of stay
Observational			with high (>12) and traditional (10–20) TV

Abbreviations: RCT = randomized controlled trial. CABG = coronary artery bypass graft. MV = mechanical ventilation. BAL = broncho-alveolar lavage. TNF = tumor necrosis factor. TV = tidal volume. PEEP = positive end-expiratory pressure. ICU = intensive care unit. ABW = actual body weight.

Tidal volume

Tidal volumes delivered by mechanical ventilation should be reduced and no longer be calculated as a function of patient's real body weight but rather of its predicted body weight [29]. Many investigations have focused on using an optimal tidal volume since the very beginning of mechanical ventilation. Bendixen et al. emphasized in 1963 the benefits of high tidal volume ventilation in prevention of atelectasis [13]. This study has had for many years a significant influence on ventilatory settings in the daily clinical practices. However, in ARDS patients, actual trends suggest that tidal volume should not exceed 6–8 mL kg^{-1} of the predicted body weight, and that plateau airway pressure should be kept below 30 cmH_2O [31]. In non-ARDS patients, several recent data also demonstrated detrimental effects of high tidal volumes (defined as volumes >10 mL kg^{-1} of the predicted body weight) [6,32,33]. Thus, one can therefore state that protective ventilation in ARDS patients refers to tidal volumes ranging from 6 to 8 mL kg^{-1} of the predicted body weight, and that protective, prophylactic, or even preventive ventilation in non-ARDS patients refers to tidal volumes below 10 mL kg^{-1} of the predicted body weight. Nevertheless, some authors suggest that it is essential to maintain plateau airway pressure less than 28–30 cmH_2O in ARDS patients and more recently, it has been suggested that limiting driving pressure in patients may be beneficial [34]. In fact, the widespread use of protective ventilation strategy in patients without ARDS is still an ongoing debate [35,36], but there is growing evidence favoring its use in all mechanically ventilated patients [33]. In the specific setting of cardiac surgery, there is a strong rationale for using protective ventilation. Pathophysiologically, there is a systemic inflammation due to ECC, which can be accentuated by using high tidal volumes after surgery, or reduced by implementing protective ventilation [7]. Blood product transfusion in these patients may in turn lead to non-cardiogenic pulmonary edema [28]. Sundar et al. randomized 149 elective cardiac surgery patients to receive a tidal volume of either 6 or 10 mL/kg PBW. In this study, PEEP levels were the same in both groups. Patients receiving lower tidal volumes were more likely to be extubated at 6 h post surgery. Moreover, fewer patients with low tidal volumes required re-intubation [8].

Recently, Lellouche et al. [6] examined 3434 consecutive bypass, valve, or combined procedures and the immediate postoperative tidal volumes used. The analysis showed that the use of tidal volumes >12 mL kg^{-1} of the predicted body weight during the postoperative period of cardiac surgery was associated with prolonged mechanical ventilation (lasting more than 24 h), vasoplegia, and renal failure. In this study, high tidal volumes were also identified as independent risk factors for multiple organ failure and prolonged ICU stay after cardiac surgery [6]. Women and obese patients (body mass index >30 kg m^{-2}) were more at risk of receiving injurious ventilation [6,29]. Tidal volume reduction can be implemented with charts to optimize this setting (Table 2). Recent ventilators will likely monitor VT kg^{-1} of the predicted body weight rather than tidal volume alone that is less significant and advanced modes may also automatically implement protective mechanical ventilation with automated tidal volume reduction [37].

As previously mentioned, protective ventilation consists not only in reducing tidal volume but also in adjusting other important settings such as respiratory rate, PEEP, and FiO_2.

Respiratory rate

When tidal volume is reduced, the maintenance of adequate alveolar ventilation, to ensure sufficient carbon dioxide clearance, necessitates either an increase in respiratory rate or a decrease in the instrumental dead space. The implementation of lung protective ventilation with an increase in respiratory rate above 20 breaths min^{-1} remains challenging, especially in ARDS patients [19]. Indeed, habits may sometimes be difficult to overcome. In order to avoid the occurrence of auto-PEEP and its associated detrimental hemodynamic effects, the use of high tidal volumes has been, in numerous centers, traditionally associated with respiratory rates <20 breaths min^{-1} (and frequently close to 10 breaths min^{-1}) [38]. It has been shown in ARDS patients that the increase in respiratory rate could be limited, as long as acceptable levels of hypercapnia and acidosis are tolerated. This so-called notion of permissive hypercapnia is well known in the field of ARDS management since the works of Hickling [39]. Nevertheless, in the perioperative period of cardiac surgery, hypercapnia may turn out to require

Table 2
Example of chart to implement tidal volume reduction (from 6 to 9 mL/kg of predicted body weight) based on gender and patient's height.

Height (cm)	PBW(Kg)	TV 6 mL/kg	TV 7 mL/kg	TV 8 mL/kg	TV 9 mL/kg
Women					
145	39	233	271	310	349
147	41	244	284	325	365
149	42	254	297	339	382
151	44	265	310	354	398
153	46	276	322	368	414
155	48	287	335	383	431
157	50	298	348	397	447
159	52	309	361	412	464
161	53	320	373	427	480
163	55	331	386	441	496
165	57	342	399	456	513
167	59	353	412	470	529
169	61	364	424	485	545
171	62	375	437	499	562
173	64	385	450	514	578
175	66	396	462	529	595
177	68	407	475	543	611
179	70	418	488	558	627
181	72	429	501	572	644
183	73	440	513	587	660
185	75	451	526	601	676
187	77	462	539	616	693
189	79	473	552	630	709
191	81	484	564	645	726
193	82	495	577	660	742
195	84	506	590	674	758
197	86	517	603	689	775
199	88	527	615	703	791
201	90	538	628	718	808
Men					
145	43	260	303	346	389
147	45	271	316	361	406
149	47	281	328	375	422
151	49	292	341	390	439
153	51	303	354	404	455
155	52	314	367	419	471
157	54	325	379	433	488
159	56	336	392	448	504
161	58	347	405	463	520
163	60	358	418	477	537
165	61	369	430	492	553
167	63	380	443	506	570
169	65	391	456	521	586
171	67	402	468	535	602
173	69	412	481	550	619
175	71	423	494	565	635
177	72	434	507	579	651
179	74	445	519	594	668
181	76	456	532	608	684
183	78	467	545	623	701
185	80	478	558	637	717
187	81	489	570	652	733
189	83	500	583	666	750
191	85	511	596	681	766
193	87	522	609	696	783
195	89	533	621	710	799
197	91	544	634	725	815
199	92	554	647	739	832
201	94	565	660	754	848

Abbreviations: PBW = predicted body weight. TV = tidal volume.

more consideration with respect to its hemodynamic effects. Hypercapnia can significantly increase cerebral blood flow; on the contrary, hypocapnia can reduce that same flow. Pulmonary circulation is also closely tied to CO_2 variations. Hypercapnia can increase pulmonary vascular tone, which can adversely affect the pre-existing pulmonary hypertension, especially in the presence of preoperative or transient postoperative right ventricular failure. Finally, to prevent undesirable hypercapnia, one can also reduce apparatus dead space by switching from a large to small volume heat and moisture exchanger, or to a heater humidifier [40,41].

All these data provide evidence that in cardiac surgery, perioperative reduction of tidal volume must be associated with an increase in respiratory rate in order to avoid hypercapnia-related detrimental effects. However, in this particular context, the need for respiratory rate to be increased can be moderate due to frequent hypothermia at the end of the surgical procedure, which is very likely to reduce CO_2 production. Therefore, a respiratory rate <20 breaths min^{-1} often allows gas exchange to remain within an acceptable range until patient's awakening [8]. It is very unusual for auto-PEEP to occur within these respiratory rate levels, except for some cases of major bronchospasm.

Positive end-expiratory pressure

PEEP consists in maintaining positive residual airway pressure during the expiratory phase in order to keep alveoli open and to increase alveoli-to-capillary gas exchange duration. It aims at preventing end-expiratory alveolar collapse and occurrence of atelectasis. PEEP is usually set between 5 and 20 cmH_2O. Interestingly, in the first paper describing ARDS, the key role of PEEP in improving blood oxygenation and even patient's outcome was already underlined [16]. It has been shown in ARDS patients that an increase in PEEP by 3 cmH_2O above basal level prevents progressive alveolar derecruitment observed when using low tidal volumes [42]. Numerous randomized controlled trials have compared different PEEP levels [42–46]. However, outside the ARDS field, only few studies sought to determine what would be the best PEEP level. Large observational studies have shown that the absence of PEEP was associated with an increase in mortality rate [47]. Moreover, it has also been demonstrated that the absence of PEEP could increase the incidence of ventilator-associated pneumonia [48].

Major studies which evaluated protective ventilation used lower tidal volumes and higher PEEP levels in comparison with conventional ventilation. In Serpa Neto meta-analysis, the mean PEEP levels were 6.4 ± 2.4 cmH_2O in patients with protective ventilation and 3.4 ± 2.8 cmH_2O in patients with conventional mechanical ventilation ($P = 0.01$) [33]. Although the optimal PEEP level is still under debate, several data suggest the utilization of PEEP with low tidal volume ventilation [15,49,50]. In the context of abdominal surgery, a PEEP level between 6 and 8 cmH_2O was used in the protective ventilation strategy, in conjunction with low tidal volumes and recruitment maneuvers, within the IMPROVE study that demonstrated benefits with this strategy in comparison with traditional mechanical ventilation (no PEEP, 10–12 mL/kg of tidal volume and no recruitment maneuvers) [15]. Interestingly, two levels of PEEP (0–2 vs. 12 cmH_2O) associated with reduced tidal volumes and recruitment maneuvers were compared in 900 patients undergoing abdominal surgery [51]. There was no difference between these strategies in terms of postoperative pulmonary complications; however, more number of patients in the high PEEP group required vasoactive drugs (62 vs. 51%, $P = 0.0016$), while those in the low PEEP group required rescue strategy for desaturation (8 vs. 2%, $P = 0.0008$). An evaluation of the impact on ventilator parameters was conducted in a large database analysis of 29,343 patients undergoing general anesthesia for surgeries excluding cardiac, thoracic, and liver transplant [50]. The authors found that in this cohort of patients managed with low levels of PEEP (4 [2.2–5], median [25–75]), the utilization of low tidal volumes (below 8 mL/kg of the predicted body weight) was associated with increased mortality. This suggests that low PEEP levels should not be associated with low tidal volumes, as previously suggested by Bendixen's study. Indeed, in this study, low or no PEEP was used, even if this was not directly discussed in this paper [13]. In protective ventilation during cardiac surgery, it is likely that a certain level of PEEP is necessary to reduce the risk of atelectasis due to low volume ventilation. Several studies have since demonstrated that PEEP reduced the incidence of postoperative atelectasis and improved respiratory function

particularly in obese patients [52]. Few studies have evaluated the impact of PEEP in patients who underwent cardiac surgery.

Zupancich et al. showed decrease of systemic and pulmonary inflammatory biomarkers after cardiac surgery with protective ventilation (lower tidal volumes and higher levels of PEEP) in comparison with traditional ventilation. During protective and traditional ventilation, the mean level of PEEP was, respectively, 9.1 ± 3.5 and 2.1 ± 2.2 cmH_2, $P < 0.001$ [7].

Dongelmans compared in a retrospective analysis of two randomized controlled studies two PEEP levels (5 and 10 cmH_2O) after cardiac surgery. A total of 121 patients were analyzed and compliance as well as oxygenation improved with higher levels of PEEP without significant difference in inotrope requirements. Interestingly, less number of patients required oxygen administration after ICU discharge in the group ventilated with higher levels of PEEP. In this analysis in patients with higher levels of PEEP, the time to extubation was increased, 16.9 ± 6.1 versus 10.5 ± 5.0 h ($P < 0.001$) [53].

Borges et al. included 136 patients ventilated with low tidal volumes after coronary artery bypass graft (CABG) surgery and compared three groups of patients with PEEP of 5, 8, and 10 cmH_2O. At PEEP level of 10 cmH_2O, compliance and oxygenation significantly improved with higher levels of PEEP. PaO_2/FiO_2 ratio was, respectively, 270 ± 90, 279 ± 71, and 328 ± 85 mmHg for the three groups, and the rate of hypoxemia ($PaO_2/FiO_2 < 300$ mmHg) significantly reduced with increase in PEEP. The authors have not reported the hemodynamic impact of higher levels of PEEP in this study [9].

With regard to non-ARDS protective ventilation in other populations, studies report the use of much higher levels of PEEP as compared with conventional ventilation [6,15,33]. No precise recommendation is available for the best PEEP level in this particular context as well. In the postoperative period of cardiac surgery, we found that even at a PEEP level of 5 cmH_2O, the reduction of tidal volume could lead to progressive hypoxemia, probably due to atelectasis (unpublished data). When tidal volume is reduced, atelectasis can probably be prevented by application of PEEP levels slightly above 5 cmH_2O (8–12 cmH_2O), especially in obese patients with reduced thoracic compliance. Some authors suggest that transpulmonary pressure can provide useful information to accurately set the PEEP level, by monitoring pleural and esophageal pressures [54,55]. However, transpulmonary pressure measurement may not be easily carried out routinely in the intraoperative setting and may be only used in selected patients with severe shunt. Alternatively, other authors proposed to titrate the PEEP level to improve oxygenation during one-lung ventilation, by a PEEP decrement trial to obtain maximal dynamic compliance in patients [56]. A recent study conducted in ARDS patients suggested that PEEP levels were similar when determined with transpulmonary pressure or decrement trial [57].

Fraction of inspired oxygen (FiO_2)

This setting is generally adjusted in an empirical approach to achieve satisfactory oxygenation. Some authors showed that deep-rooted habits still do provide fertile ground to hyperoxia [58]. Indeed, it seems difficult for some clinicians to reduce FiO_2 below 0.40. And yet, there is not any benefit in keeping patient's PaO_2 above 100 mmHg. Much to the contrary, hyperoxemia can cause coronary vasospasm and reduction of cerebral blood flow [11,12,59]. Moreover, high FiO_2 levels (>0.60) can contribute to the development of denitrogenation atelectasis, and thus progressive derecruitment. FiO_2 above 60% may increase reabsorption atelectasis, but the effect is even more significant above 80% [60].

This has been demonstrated five decades ago [61], and recently confirmed in ARDS patients [62].

In the study by Bendixen on the impact of tidal volumes on perioperative atelectasis [13], it should be noted that patients received very high levels of FiO_2, which have probably led to atelectasis of more severe forms. In obese patients, if associated with low tidal volumes and insufficient PEEP, high levels of FiO_2 can cause excessive gas exchange impairment.

In the context of cardiac surgery, effects of abnormal PaO_2 levels on coronary and carotid arteries can have substantial impact. It is usually recommended to maintain pulse oxygen saturation (SpO_2) values above 92% in order to ensure that the arterial oxygen saturation (SaO_2) value is greater than 90% [63]. An upper limit should also be recommended to avoid hyperoxemia, as there is so far no argument in cardiac surgery to support the use of SpO_2 values greater than 96%.

Potential benefits of hyperoxia include reduction of surgical site infection [64] or postoperative nausea [65]. However, other studies did not demonstrate such effects and recent meta-analysis showed no or very limited benefits [66,67]. To note, there was no study evaluating these potential benefits after cardiac surgery.

Recruitment maneuvers

For some authors, recruitment maneuvers are an integral part of ARDS management [18]. Nevertheless, several questions remain unanswered with regard to their interest, effectiveness, and the best way they should be performed [68]. Some studies found numerous complications, especially in not fully sedated patients [69], and reported effects of recruitment maneuvers actually show some discrepancies within the available literature. Toth et al. showed that recruitment maneuvers (45 cmH_2O for 40 s) could provoke transient reduction in cardiac output, while mean arterial pressure remained unchanged [70]. Nonetheless, other studies reported a significant drop in the mean arterial blood pressure, using similar maneuvers. Several techniques have been described, either applying CPAP of 40–45 cmH_2O or increasing PEEP to the desired level. In a recent study conducted by Futier et al. [15], which evidenced the benefits of lung protective ventilation during major abdominal surgery, the protocol included recruitment maneuvers that consisted in applying 30 cmH_2O for 30 s every 30 min. In cardiac surgery, few data are available, but recruitment maneuvers should be considered carefully and associated with cautious patient monitoring during the procedure, with pressure levels that should more likely be lower. Maneuver should be discontinued when arterial blood pressure drops. Thus, special attention should be paid to patients with hypovolemia or exhibiting significant volume dependence (such as patients with ventricular hypertrophy). However, recruitment maneuvers in cardiac surgery may in some cases be required, especially immediately following ECC period, in order to re-open un-ventilated or low-ventilated lung areas, or after shifting the patient to ICU and even more, if an obese patient is shifted without ventilator support. Unfortunately, few data are available with regard to perioperative management of this specific population in cardiac surgery.

Reis Miranda et al. showed that an open lung strategy including recruitment maneuvers (40 cmH_2O for 15 s) applied in patients undergoing cardiac surgery reduced inflammatory cytokines, especially when this strategy was utilized early, immediately after intubation. However, recruitment maneuvers were part of a bundle of care (lower tidal volume, higher levels of PEEP, maintenance of small tidal volumes during cardiopulmonary bypass), and hence it is not possible to draw conclusions on the impact of the recruitment maneuvers per se. Hemodynamic tolerance was not reported in this study [26], but some data in a study conducted by the same group with the same methodology showed that fluid balance was higher in early open lung strategy (conventional ventilation: 91 mL/h; early open lung strategy, 255 mL/h), even if the difference was not statistically significant [71]. Minkovich et al. showed that recruitment maneuvers (35 cmH_2O for 15 min after CBP and 30 cmH_2O for 5 s upon arrival at ICU) moderately improved oxygenation until ICU discharge, without other impact on outcome [72].

Taken together, all these elements lead to the fact that protective ventilation cannot be restricted to isolated reduction of tidal volume. We recommend that other measures are associated with tidal volume reduction, including the application of a moderate level of PEEP (8–12 cmH_2O), increase in respiratory rate (with apparatus dead space reduction when needed), limiting FiO_2 level, and careful use of recruitment maneuvers. These ventilation guidelines should be implemented all along the perioperative period and also in the postoperative period. They might ideally be subject to standardized written protocols, and eventually be carried on with fully automated ventilators [37].

Ventilatory strategies during cardiopulmonary bypass

Physiopathological considerations

Although lung perfusion has traditionally been categorized into pulmonary and bronchial circulations, with functional and feeding duties, respectively, it is now well described that intrapulmonary shunts can markedly interfere with their respective contributions to each of these two roles. Moreover, oxygen present in the alveoli can passively diffuse and contribute to lung tissue

oxygenation; however, the oxygen proportion involved in this function remains unknown. During cardiopulmonary bypass, blood flow to lungs due to venous drainage is associated with a 50% reduction in bronchial blood flow and results in ischemic lesions [73]. Lung ischemia–reperfusion phenomena occurring during cardiac bypass surgery causes not only local inflammatory reaction but also systemic inflammation, which contributes to postoperative lung injury. In the absence of ventilation during ECC period, the lung is likely to collapse, and thus the aforementioned hypothetical lung oxygenation by passive diffusion of alveolar oxygen is no longer possible. This collapse additionally worsens an already impaired bronchial circulation architecture, increases ischemia phenomena, and leads to atelectasis [73]. The latter conditions are observed in the very beginning of the surgical procedure [5].

Ventilation maintenance during cardiopulmonary bypass

Ventilation maintenance prevents alveolar collapse, atelectasis, and therefore hypoxemia. However, between the two main ventilatory modes described in the available literature, no conclusive evidence exists that one leads to better outcomes than the other. In a randomized study, Berry et al. [74] compared the effects of disconnection of lungs from the breathing system during bypass cardiac surgery when continuous positive airway pressure (CPAP) ventilation is applied at two levels of FiO_2 (0.21 and 1.0). If beneficial effects were observed in the first 30 min following ECC, they were no longer noticeable 4 h later. The increase in CPAP level to 10 cmH_2O with a FiO_2 of 0.21 seems to be more significant, with substantial effects during the 48 h following ECC [75]. Ventilation can also be implemented with low volume and low-frequency assist-controlled modes [76–78]. As compared with no ventilation, Ng et al. showed in a randomized study that volume assist-controlled mechanical ventilation (5 mL kg^{-1}) led to better thoraco-pulmonary compliance and reduced interleukin release [78]. In an original work that must be highlighted, Loer et al. [76] compared the pulmonary vein content from right and left lungs, while only one lung was ventilated during cardiopulmonary bypass. They found a significant increase in oxygenation in the pulmonary vein from the ventilated lung, while thromboxane level remained lower. A recent study compared the chemokine levels after continued ventilation (15 patients) and no ventilation (15 patients) during CABG surgery [79]. The chemokine levels in the continuous ventilation group were significantly lower and oxygenation was higher [79,80].

Ventilatory modes during cardiopulmonary bypass

Several studies compared CPAP to assist-controlled ventilation [81,82]. In porcine models, Imura et al. found better oxygen tension and alveolar arterial oxygen gradient with assist-controlled ventilation as compared with CPAP [81]. On the contrary, using a similar approach in humans, Zabeeda et al. found that CPAP with 5 cmH_2O resulted in better outcomes [82]. However, the improved oxygenation in this study was only found within the 5 min following cardiopulmonary bypass, which is obviously of low clinical relevance. Available literature is actually too scarce to conclude on the best ventilatory mode to use, but whatever the setting, maintaining ventilation during cardiopulmonary bypass may be beneficial.

Fraction of inspired oxygen during cardiopulmonary bypass

As tissue oxygenation may be related to the oxygen present in the alveoli as previously mentioned, increase in alveolar oxygen content seems relevant. This could explain the negative results of ventilatory strategies with FiO_2 of 0.21 [81,82]. Conversely, high FiO_2 levels increase pulmonary oxygen toxicity [83]. For instance, Pizov et al. found a significant increase in TNF-alpha release when perioperative ventilation was performed with FiO_2 values of 1.0 [84]. It can be therefore recommended to limit FiO_2 in a range of values from 0.4 to 0.5, as it has already been advocated by some authors [78]. As discussed above, it is now well demonstrated that hyperoxia is deleterious, with relevant impact in patients, who have undergone cardiac surgery, such as coronary vasospasm and decrease in cerebral blood flow [11,12,59].

Recruitment maneuvers during cardiopulmonary bypass

In an experimental study performed in pigs, Magnusson et al. reported that vital capacity maneuver (40 cmH_2O for 15 s) performed before termination of the cardiopulmonary bypass was effective in reducing the incidence of atelectasis, as assessed by computed tomography [85]. These results have been confirmed by two randomized clinical studies evaluating the maneuver's efficiency by assessing intrapulmonary shunt, alveolar arterial oxygen gradient, or oxygen tension [72,86]. Surprisingly, in these two studies, the ventilator was disconnected during the bypass period. It should be emphasized that in order to improve its efficiency, this maneuver should also be repeated after connecting the patient to the ICU ventilator [72]. This maneuver should obviously be performed with caution, especially in case of mammary artery bridge, which can be stretched during this expansion.

Multimodal approach

As explained above, ventilatory strategy during cardiopulmonary bypass surgery is of crucial importance. Nevertheless, this can be optimal only if associated with complementary measures implemented both before and after the extracorporeal circulation period. Therefore, during anesthetic induction, controlled pressure ventilation using facemask will be preferentially performed [87]. Detailed ventilatory instructions have been given in the first part of this chapter. The utilization of a “fast-track” management with reduced dosage of sedation and analgesia leading to early extubation was promoted more than 20 years ago [88] and several studies have confirmed the superiority of this strategy which is now the standard of care [89,90]. Interestingly, although there are several studies demonstrating the benefits of noninvasive ventilation (NIV) after abdominal surgery [91] or thoracic surgery [92], there is no study that clearly demonstrates benefits of this technique on outcome after cardiac surgery. Some studies showed an improvement of the respiratory function, a reduction of atelectasis, and improvement of oxygenation parameters [93–95]; however, none demonstrated an improvement of other important outcomes such as reintubation rate, length of stay, or mortality. Most of the patients included in these studies were not very old and had few risk factors of reintubation. Thus, the choice of the population may explain these negative results. There is probably a rationale to use NIV in selected populations after cardiac surgery. Indeed, it was shown that old patients with heart failure and obese and chronic obstructive pulmonary disease (COPD) patients (populations frequently encountered in cardiac surgery unit) could benefit from prophylactic NIV [96–98]. A large randomized controlled study including 500 patients with scheduled cardiac surgery has evaluated nasal CPAP at 10 cmH_2O for at least 6 h after extubation [99]. Patients who received nasal CPAP for 6 h had improved oxygenation and reduced pulmonary complications and readmission rate. More recently, it was shown that a less invasive and better tolerated technique such as high-flow oxygen therapy used as a prophylactic or curative treatment was as efficient as NIV to prevent or treat respiratory failure after cardiac surgery [100].

A specific management of respiratory supports, especially of mechanical ventilation before, during, and after cardiac surgery, may reduce pulmonary complications and improve outcomes.

Conclusion

In cardiac surgery, postoperative pulmonary morbidity has multifactorial etiologies, and identifying the precise mechanisms involved remains challenging. Although it is difficult to avoid bypass-induced lung ischemia, lung lesions induced either by the surgery itself or by the ECC can be prevented by the implementation of adequate ventilatory strategies. After the surgery, the implementation of prophylactic protective ventilation is beneficial. This strategy combines tidal volume reduction, utilization of PEEP, limitation of FiO_2 levels, and a slightly increased respiratory rate. For the latter to be effective, they must be integrated into a multimodal approach, beginning from the anesthetic induction and continued all along the patient's hospital stay.

Practice points

- Protective mechanical ventilation strategies and tidal volume reduction should be applied in patients immediately after cardiac surgery.
- Women, obese and small patients are at risk of receiving high tidal volumes.
- Predicted body weight rather than actual weight must be used.
- Tidal volumes of 6–8 mL/kg of predicted body weight should be used.
- Protective mechanical ventilation is not only tidal volume reduction. Higher positive end-expiratory pressure, higher respiratory rate, and titrated FiO_2 (with low and high SpO_2 target) should be used in association with tidal volume reduction.

Research agenda

- We need data on the clinical practices for mechanical ventilation strategies and settings during and after cardiac surgeries and the degree of heterogeneity of these practices.
- There are preliminary data to promote ventilatory strategies combining ventilation maintenance, protective ventilation utilization, and FiO_2 titration during cardiac surgery, but randomized trials to demonstrate the clinical impact of these strategies are still lacking.
- We need some data on the clinical impact of very high PaO_2 on coronary blood flow and cerebral blood flow reduction. Physiological data demonstrate a potentially significant impact but there is no clear recommendation to titrate oxygen levels.
- No or very low levels of PEEP in association with low tidal volumes may promote atelectasis especially in obese patients but the optimal level of PEEP required is not well defined. Physiological studies to evaluate the respiratory and hemodynamic impact of different PEEP levels in association with tidal volume reduction are needed
- We need to demonstrate with large and well-conducted randomized controlled studies if automated modes of mechanical ventilation that implement protective ventilation are useful after cardiac surgery.
- We need additional data on postoperative respiratory supports: oxygen titration, need for prophylactic NIV or prophylactic high-flow oxygen therapy in this population and in specific populations at risk of postoperative respiratory complications.

Conflict of interest statement

The program of research on automated mechanical ventilation was funded by the Canadian Foundation for Innovation (Leaders funds), and the Co-founder of a company that develops devices for automated oxygen and respiratory supports (Oxynov.inc).

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