Original Article

Respiratory mechanics with volume-controlled auto-flow ventilation mode in cardiac surgery*

ABSTRACT

Aim: We aimed to investigate the changes in respiratory mechanics in adult patients undergoing open heart surgery (OHS) while using volume-controlled auto-flow (VCAF) ventilation mode.

Materials and Methods: After obtaining ethics committee's approval and informed consent, 30 patients (17 males and 13 females; mean age: 57.3 ± 17.0 years; mean weight; 74.9 ± 13.6 kg) scheduled for OHS were enrolled. Mechanical ventilation was carried out using VCAF mode (V_T: 5–8 mL/kg, I/E: 1/2, 10 ± 2 fr/min). Values of dynamic compliance (C_{dyn}) and resistance (R) were obtained at six time points (TPs). Normally distributed variables were analyzed with repeated measure of analysis of variance and Bonferroni tests. For abnormally distributed variables, Friedman variance analysis and Wilcoxon signed-rank tests were used. Values were expressed as mean ± standard deviation. *P* value <0.05 was considered significant.

Results: C_{dyn} (mL/mbar) and R (mbar/L/s) values were as follows – (1) before sternotomy (S): 49.9 ± 17.1 and 7.8 ± 3.6; (2) after S: 56.7 ± 18.3 and 7.1 ± 3.7; (3) after S and after sternal retractor placement: 48.7 ± 16.1 and 8.3 ± 4.4; (4) after weaning from cardiopulmonary bypass and following decannulation while retractor was in place: 49.6 ± 16.5 and 8.1 ± 4.0; (5) after retractor removal: 56.5 ± 19.6 and 7.4 ± 3.7; and (6) after sternal closure: 43.1 ± 14.2 and 9.6 ± 9.1, respectively. Significant differences were observed in C_{dyn} and R between; first and second TPs, second and third TPs, fourth and fifth TPs, and fifth and sixth TPs. Also, significant difference in C_{dyn} was found between first and sixth TPs, but it was not found in R.

Conclusion: C_{dyn} decreases, but R remains the same in cardiac surgical patients when mechanical ventilation is performed with VCAF ventilation mode. Additionally, C_{dyn} is negatively affected by the presence of sternal retractor and the sternal closure in OHS.

Key words: Cardiopulmonary bypass; dynamic compliance; open heart surgery; resistance; volume-controlled auto-flow ventilation mode

Introduction

Long-term general anesthesia, intrathoracic surgical manipulation, and cardiopulmonary bypass (CPB) may lead to significant changes in respiratory functions of patients during open heart surgery (OHS).[1,2] These changes are

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mainly related to respiratory mechanics,[3-5] lung volumes,[6] ventilation–perfusion ratio,[7] and gas exchange.[8]

Respiratory mechanics were investigated during surgeries of coronary artery bypass grafting (CABG) and aortic valve replacement in adult patients[1,3,8] and during congenital cardiac surgery in pediatric patients,[5,9] mainly using the volume-controlled (VC) ventilation mode.[1,3,4,8] However, data related to volume-controlled auto-flow (VCAF) ventilation mode were not investigated previously. This ventilation mode may have beneficial and/or protective effects on respiratory mechanics.

In this study, we aimed to investigate the changes in respiratory mechanics of adult patients undergoing OHS with CPB in which mechanical ventilation was performed using VCAF ventilation mode.

Materials and Methods

A total of 30 patients above 18 years of age who underwent elective OHS with CPB at the operating rooms of Department of Cardiovascular Surgery in Medical Faculty of Dokuz Eylül University were included in this observational study. The study protocol was approved by the Non-invasive Research Ethics Committee of the Faculty of Medicine of Dokuz Eylül University. A written informed consent was obtained from each patient. The study was conducted in accordance with the principles of the Declaration of Helsinki.

A low ejection fraction (<30%), morbid obesity, previous history of cardiac or lung surgery, preoperative use of inotropic infusion or cardiac mechanical support, and/or artificial respiratory support were the exclusion criteria of the study.

Standard monitorization including noninvasive arterial blood pressure, electrocardiogram, and peripheral oxygen saturation were obtained from all patients. Midazolam (1–2 mg) was administered intravenously when intravenous access was achieved. Standard anesthesia protocol was applied to all patients, and no additional drug was used apart from routine anesthetic drugs. After arterial cannulation, anesthesia was induced with thiopental sodium and morphine. Endotracheal intubation was performed with injection of rocuronium bromide. For maintenance of anesthesia, sevoflurane (<1.5 Minimum alveolar concentration) and morphine (0.05–0.1 mg/kg) were used. Bolus doses of rocuronium bromide (0.15–0.3 mg/kg) were injected for maintenance of muscle relaxation (Infinity Trident NMT SmartPod MS15007; no response to train-of-four stimulus).

The anesthesia machine used for artificial respiration (Drager, Zeus Infinity Empowered; Drager Medical AG & Co. KG, Germany) was automatically tested before the operation, and the compliance of the breathing circuit (Altech AL-1121; Altera Ltd., İzmir, Turkey; and Anesthesia set for Zeus MK04248 reusable) was detected during the autotest procedure and the results were recorded. Mechanical ventilation was performed using VCAF ventilation mode under auto-control closed circuit system (fresh gas flow per minute was adjusted to the lowest value according to the uptake of oxygen of the patient) [V_T: 5–8 mL/kg, I/E: 1/2, FiO_2: 0.5–1.0, PEEP: Ø, RR: 10 ± 2 fr/min (to maintain ET_{CO2} between 30 and 35 mmHg)]. The adjusted tidal volume was kept the same throughout the surgery. Mechanical ventilation was stopped during total aortic cross-clamping time of CPB and oxygen insufflation was performed (0.5–0.6 L/min).

Following median sternotomy and heparinization (ACT > 480 s), CPB was initiated by standard ascending aortic, and right atrial or bicaval cannulation according to the type of surgery. The pulsatile pump flow was adjusted to 2.4 ± 0.4 L/min/m^2, and the mean perfusion pressure was adjusted between 50 and 80 mmHg.

The type of surgical procedure, durations of surgery, CPB, and cross-clamping were recorded. Also, the patients who needed administration of inotropic agent following CPB were noted.

Data related to respiratory mechanics such as P_{ins} (inspiratory pressure, VCAF mode $P_{ins} = P_{plat}$), $PEEP_{auto}$ (end expiratory intrinsic positive pressure), C_{dyn} (dynamic compliance), and R (resistance) were recorded by monitoring anesthesia machine (Infinity C500; Drager Medical AG & Co. KG) at six time points (TPs) such as follows: before sternotomy $(S)_{(1)}$, after $S_{(2)}$, after S and after sternal retractor placement$_{(3)}$, after weaning from CPB and following decannulation while retractor was in place$_{(4)}$, after removal of retractor$_{(5)}$, and after closure of the sternum$_{(6)}$.

The anesthesia machine identified the compliance and R of the patient during passive expiratory period. During expiration, the first measurement was performed a short period after the beginning of expiration (100 ms). The second measurement was performed, when the flow fell to 25%, and the equilibrium presented below was used to calculate the values for each time period:[10]

$$P_{aw}^{(t)} + R \bullet V^{(t)} = V_{Lung}^{(t)}/C$$

Where P_{aw} = Airway pressure, R = resistance, V = flow, V_{Lung} = lung volume, C = compliance, P = pressure, and t = time.

The parameters of arterial blood gas samples (pH, PaO_2, $PaCO_2$, and SaO_2) which were taken before and after CPB were compared. At the end of the surgical procedure, the patients were transferred to the cardiovascular intensive care unit.

Statistical analysis

Statistical analysis was performed using SPSS for Windows version 15.0 (SPSS, Chicago, IL, USA). Shapiro–Wilk test was used for the distribution of the variables. For comparison of normally distributed variables of respiratory mechanics, repeated measure of analysis of variance and Bonferroni tests were used (P_{ins}, C_{dyn}), whereas Friedman variance analysis and Wilcoxon signed-rank tests were used to analyze abnormally distributed variables ($PEEP_{auto}$, R).

For comparison of arterial blood gas parameters before and after CPB, Shapiro–Wilk test was performed. Paired samples *t*-test was used for normally distributed variables (pH, PaO_2, and $PaCO_2$) and Wilcoxon signed-rank test was used for abnormally distributed variables (SaO_2). The values were expressed as mean ± standard deviation (SD) or number and percentage (%) where available. A P value <0.05 was considered statistically significant.

Results

Demographic and baseline clinical characteristics of the patients are presented in Table 1. The type of surgical procedure, durations of surgery, CPB, and cross-clamping are shown in Table 2.

Table 1: Demographic and baseline clinical characteristics of patients (*n*=30)

Sex (M/F)	17 (56.6%)/13 (43.3%)
Age (year)	57.36±17.06
Weight (kg)	74.96±13.68
Height (cm)	167.96±5.63
BMI (kg/m²)	26.50±4.41
ASA classification	
ASA II	4 (13.3%)
ASA III	26 (86.6%)
EF (%)	53.93±10.60
Comorbidities	
Cardiovascular (hypertension)	24 (80.0%)
Endocrine (diabetes mellitus)	6 (33.3%)
Respiratory	5 (16.60%)
Other	4 (13.3%)
Previous surgical procedure	18 (60.0%)
Preoperative drug use	26 (86.6%)
Cigarette smoking (±)	7 (23.3%)/23 (76.6%)

Mean±SD or % value. BMI: Body mass index; ASA: American Society of Anesthesiologist; EF: Ejection fraction

Table 2: Perioperative data

Surgical procedure (*n*=30)	
CABG	18 (60%)
Valve replacement	5 (16.6%)
Combined (CABG + valve replacement)	2 (6.6%)
ASD	4 (13.3%)
Atrial myxoma	1 (3.3%)
Duration of surgery (min)	212.96±57.55
Duration of CPB (min)	89.16±39.07
Duration of cross-clamping (min)	57.16±35.41

Number (%) or mean±SD. CABG: Coronary artery bypass grafting; ASD: Atrial septal defect; CPB: Cardiopulmonary bypass

In this study, the mean compliance of the respiratory circuit used for artificial respiration was 2.00 ± 0.21 mL/mbar and respiratory mechanics were obtained under these circumstances. Data related to the respiratory parameters that were obtained at six TPs are presented in Table 3.

A statistically significant difference was found in P_{ins} values among the six TPs of the surgical procedure ($P < 0.001$). This difference was attributed to the differences between the first and second TPs ($P < 0.001$), second and third TPs ($P < 0.001$), second and sixth TPs ($P < 0.001$), and fifth and sixth TPs ($P < 0.001$). However, there was no statistically significant difference in P_{ins} values between the first and sixth TPs ($P = 0.49$) [Table 3]. Additionally, there was no statistically significant difference in $PEEP_{auto}$ ($P = 0.21$) values measured at six TPs of the surgical procedure [Table 3].

A statistically significant difference was observed in C_{dyn} values at six TPs of the surgical procedure ($P < 0.001$). This difference was considered to be related to the differences between the first and second TPs ($P < 0.001$), second and third TPs ($P = 0.001$), second and fourth TPs ($P = 0.001$), second and sixth TPs ($P < 0.001$), fourth and fifth TPs ($P < 0.001$), fourth and sixth TPs ($P < 0.001$), and fifth and sixth TPs ($P < 0.001$). Furthermore, a significant difference was found in C_{dyn} values between the first and sixth TPs ($P = 0.001$) [Table 3 and Figure 1].

We found a statistically significant difference in R values at six TPs of the surgical procedure ($P < 0.001$). This difference was found to be associated with the differences between first and second TPs ($P = 0.002$), second and third TPs ($P < 0.001$), fourth and fifth TPs ($P < 0.001$), and fifth and sixth TPs ($P < 0.001$). However, we observed no statistically significant difference in R values between the first and sixth TPs ($P = 0.10$) [Table 3 and Figure 2].

Arterial blood gas analysis was performed at two different TPs of surgery: (i) after anesthesia induction and (ii) after discontinuation of CPB. Values of FiO_2 were between

Table 3: Values of respiratory mechanics obtained at 6 time points (TPs) intraoperatively (1: before sternotomy, 2: after sternotomy, 3: after sternotomy and after sternal retractor placement, 4: after weaning from CPB and following decannulation while sternal retractor was in place, 5: after removal of sternal retractor, and 6: after closure of sternum (*n*=30)]

	Intropetive time points						*P* between 1st and 6th TPs
	1	2	3	4	5	6	
$P_{ins\ (mbar)}$	15.2±4.2	14.0±3.5*	15.4±3.8*	15.1±3.7	13.7±3.1	16.2±3.81*	*P*=0.49
$PEEP_{auto\ (mbar)}$	2.0±0.2	1.9±0.2	2.0±0.2	2.0±0.1	2.0±0.0	2.0±0.0	*P*=0.21
$C_{dyn\ (mL/mbar)}$	49.9±17.1	56.7±18.3*	48.7±16.1*	49.6±16.5	56.5±19.6*	43.1±14.2*	***P*=0.001**
$R_{\ (mbar/L/s)}$	7.8±3.6	7.1±3.7#	8.3±4.4*	8.1±4.0	7.4±3.7*	9.6±9.1*	*P*=0.10

Mean±SD. P_{ins}: Inspiratory pressure; $PEEP_{auto}$: End expiratory intrinsic positive pressure; C_{dyn}: Dynamic compliance; R: Resistance; *(*P*<0.001): Compared with o previous time point; #(*P*=0.002): Compared with previous time point, Bold: The significance of the value in bold is *P*=0.001

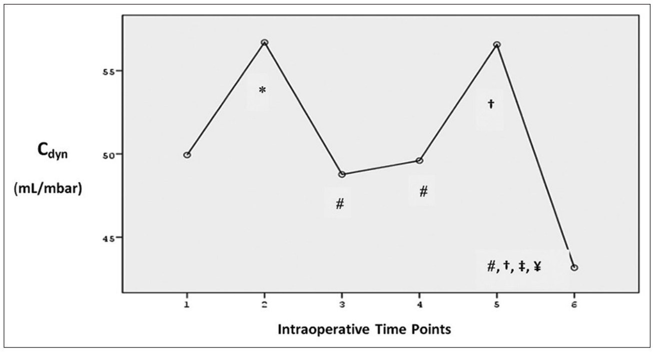

Figure 1: Mean values of dynamic compliance (C_{dyn}) at different time points of surgery [1: before sternotomy, 2: after sternotomy, 3: after sternotomy and after sternal retractor placement, 4: after weaning from CPB and following decannulation while sternal retractor was in place, 5: after removal of sternal retractor, and 6: after closure of sternum (*n* = 30)]

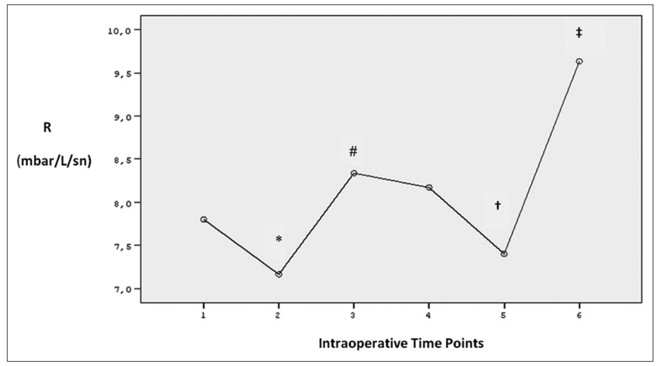

Figure 2: Mean values of resistance at different time points of surgery [1: before sternotomy, 2: after sternotomy, 3: after sternotomy and after sternal retractor placement, 4: after weaning from CPB and following decannulation while sternal retractor was in place, 5: after removal of sternal retractor, and 6: after closure of sternum (*n* = 30)]

0.5 and 1.0 when arterial blood samples were taken. No statistically significant difference was found in the values of PaO_2 (290.82 ± 147.99 and 295.23 ± 140.66, respectively, *P* = 0.88) and SaO_2 (99.37 ± 1.43 and 99.52 ± 0.89, respectively, *P* = 0.73). However, there was a statistically significant difference in pH (7.44 ± 0.03 and 7.34 ± 0.04, respectively, *P* < 0.001) and $PaCO_2$ values (31.57 ± 3.84 and 34.85 ± 4.32, respectively, *P* = 0.004). After weaning from CPB, three patients required inotropic support.

Discussion

In this clinical observational study, the changes in respiratory mechanics were investigated in patients undergoing OHS while VCAF this ventilation mode was used for mechanical ventilation. We found a decrease in C_{dyn} at the end of the surgery and found no change in R values. Based on our C_{dyn} results, pulmonary dysfunction occurred in our patients despite using VCAF ventilation mode for mechanical ventilation.

Cardiac surgery could provoke pulmonary dysfunction as a result of sternotomy,[11] dissection of mammarian artery,[12] increase in extravascular lung volume, and leukocyte sequestration in alveolar microcirculation.[1] Additionally, CPB causes structural and functional damages in the pulmonary endothelium[13] and results in lung dysfunction.[14]

A decrease in compliance and/or an increase in R causes an increase in respiratory work and myocardial load. Consequently, these changes result in more oxygen consumption in cardiac patients.[1,15] Thus, prevention of these undesired changes in respiratory mechanics is aimed during the perioperative period.[1,5,8,16]

In most of the previous studies, respiratory mechanics were investigated during VC ventilation mode,[1,3-5,8,9,16,17] and different strategies have been designed for prevention of postoperative pulmonary dysfunction in cardiac patients.[3,8,9,16,18] A-Meguid *et al*.[3] searched the effects of manual recruitment, CPAP, and PEEP on C_{dyn} in patients undergoing CABG and reported that all positive pressure maneuvers that applied maintained the ventilatory parameters. Chaney *et al*.[8] provided low tidal volume with high respiratory rate to produce low peak airway pressure and found less postoperative pulmonary dysfunction than the conventional ventilation group. Scohy *et al*.[9] investigated the effects of alveolar recruitment strategy and PEEP on C_{dyn} in patients undergoing congenital heart surgery and reported that the application of both these strategies improved C_{dyn}. In another study, Polese *et al*.[16] investigated the lung mechanics in patients undergoing cardiac surgery and found that both static and dynamic elastance significantly increased with surgical intervention. Studies are still searching the effects of different ventilation modes with or without the combination of perioperative ventilatory strategies on pulmonary function for better postoperative pulmonary function in cardiac patients.[19,20]

New ventilation modes have been added to anesthesia machines in recent years.[21] One of them is the addition of auto-flow feature to VC ventilation mode. Auto-flow is a ventilation mode that is able to deliver the preset tidal volume at the lowest inspiratory pressure. During VCAF ventilation mode, the inspiratory flow of the ventilator uses decremental (instead of constant) flow and the increase in inspiratory peak pressure is prevented and airway pressure is minimalized.[22] The ventilation strategy used in our study was VCAF ventilation mode for mechanical ventilation, and by this way, plateau pressure instead of peak airway pressure generated inspiratory pressure. This property of VCAF ventilation mode could be thought that it might not induce or might prevent postoperative lung dysfunction in patients undergoing OHS. In this respect, this is the first study that investigated the changes in lung dynamics in cardiac patients.

Bund *et al*.[1] found that C_{dyn} increased following sternotomy and decreased after closure of the thorax. They detected a reduction of 17% in compliance when compared with the basal values. We obtained the values of lung mechanics at six different periods of surgery. C_{dyn} significantly increased after sternotomy. Sternal retractor placement before CPB caused a significant decrease in C_{dyn}. The value of C_{dyn}, which was obtained after completion of CPB, while the thoracic retractor was present, was found to be similar to the value of C_{dyn} that was obtained in the presence of the retractor before institution of CPB. Removal of sternal retractor in this period increased the value of C_{dyn} to the values that were observed after sternotomy. However, C_{dyn} significantly decreased by the closure of sternum at the end of surgery. The results of our study suggest that C_{dyn} decreases after cardiac surgery even when ventilation mode is selected.

Moreover, the presence of sternal retractor is important while obtaining respiratory mechanics, and sternum closure rather than CPB plays a significant role in the reduction of C_{dyn} during cardiac surgery. The importance of presence retractor while achieving respiratory mechanics was first mentioned by Larsson *et al*.[23] They investigated the effects of subcostal or midline incision on respiratory mechanics during upper abdominal surgery and reported that retractor placement during subcostal incision decreased lung compliance.

We also obtained R values at six different periods of the surgery. R significantly decreased with sternotomy. Placement of the thoracic retractor before CPB significantly increased R to the above values that were obtained before sternotomy. The R value that was obtained after completion of CPB in the presence of the sternal retractor was found to be similar to the value which was obtained in the presence of retractor before CPB. Resistance significantly decreased after the removal of the retractor during this period. However, R significantly increased with the closure of the sternum. When compared to the value that was obtained before sternotomy, the increase in R was not statistically significant in this period. As a result, R was not negatively affected to the same degree as C_{dyn}.

Both Bund *et al*.[1] and Polese *et al*.[16] reported that airway R did not change with sternotomy and CPB. Bund *et al*.[1] have reported that R decreased with sternotomy from 5.4 cm to 5.1 H_2O/L/s and they found the value of R to be 6.3 cm H_2O/L/s after CPB, but R decreased to 5.7 cm H_2O/L/s with the closure of the thorax. In another study, Polese *et al*.[16] detected that the total respiratory system resistance was 10 cm H_2O/L/s before cardiac surgery and increased to 11 cm H_2O/L/s following surgery. In their study, airway resistance was 5.8 cm H_2O/L/s before surgery and increased to 6.6 cm H_2O/L/s following surgery. They also reported that surgical intervention did not cause a significant difference in R. The findings of our study about R were similar to the findings of the above studies.[1,16]

The effects of VCAF ventilation mode on gas exchange (alveolar-arterial oxygen difference) during cardiac surgery could not be determined in our study, because while arterial blood gas samples were taken, different FiO_2 values were applied to the patients. There are a limited number of studies investigating the effects of ventilation modes having auto-flow property on gas exchange. Lasocki *et al*.[24] who applied dual-controlled ventilation mode using assisted controlled ventilation together with auto-flow reported that this ventilation mode had no superiority in terms of gas exchange.

Arterial blood samples were obtained with a FiO_2 range of 0.5 and 1.0 in our study, and no statistically significant difference was detected in PaO_2 values before and after CPB. On the other hand, pH decreased and $PaCO_2$ increased significantly following CPB, although these values were within the normal ranges. The changes that were observed in pH and $PaCO_2$ might be due to obtaining arterial blood samples so close to reperfusion period following CPB.

Polese *et al*.[16] reported that there was a significant decrease in PaO_2 from 242 to 170 mmHg during cardiac surgery when FiO_2 was kept constant at 0.5, whereas no significant change was observed in $PaCO_2$ (32 vs 33 mmHg) and pH (7.46 vs 7.44). On the contrary, Chaney *et al*.[8] found $PaCO_2$ to be 34.8 mmHg before sternotomy and 42.3 mmHg following surgery in the conventional mechanical ventilation group, whereas $PaCO_2$ was 38.1 mmHg before sternotomy and 46.4 mmHg after surgery in the protective mechanical ventilation group. $PaCO_2$ significantly increased following surgery in both groups.

In conclusion, we investigated the changes in respiratory mechanics of adult cardiac patients by obtaining C_{dyn} and R values at six different TPs of surgery when mechanical ventilation was performed with VCAF ventilation mode. We observed that C_{dyn} was negatively affected when this ventilation mode was used. It was also found that the value of R remained same. Therefore, this ventilation mode could not prevent the pulmonary dysfunction in cardiac patients. Additionally, the presence of sternal retractor and the closure of sternum rather than the application of CPB are more important for the decrease in C_{dyn}.

Further studies searching the effects of new ventilation modes with or without the combination of perioperative ventilatory strategies on pulmonary function are required for better postoperative pulmonary care in cardiac patients.

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Conflicts of interest

There are no conflicts of interest.

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