Volume of Tidal Gas Movement in the Nonventilated Lung during One-lung Ventilation and its Relevant Factors

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Abstract

Background: The passive ventilation of nonventilated lung results in tidal gas movement (TGM) and thus affects lung collapse. The present study aimed to measure the volume of TGM and to analyse the relevant factors of the TGM index (TGM/body surface area).Methods: One hundred eight patients scheduled for elective thoracoscopic surgeries were enrolled. Lung isolation was achieved with a double-lumen endobronchial tube (DLT). The paediatric spirometry sensor was connected to the double-lumen connector of the nonventilated lung to measure the volume of TGM during one-lung ventilation (OLV) in the lateral position. The TGM index was calculated. The multiple linear regression was analysed using the TGM index as the dependent variables. Independent variables were also recorded: 1) age, sex, body mass index (BMI); 2) forced vital capacity (FVC), FEV1/FVC, minute ventilation volume (MVV); 3) dynamic lung compliance (Cdyn) and peak inspiratory pressure (PIP) during dual lung ventilation; 4) the side of OLV; and 5) whether lung puncture for localization of the pulmonary nodule was performed on the day of surgery. The oxygen concentration in the nonventilated lung was measured at 5 min after OLV, and its correlation with the TGM index was analysed.Results: The volume of TGM in the nonventilated lung during OLV was 78 [37] mL. The TGM index was 45 [20] mL/m2 and was negatively correlated with the oxygen concentration in the nonventilated lung at 5 min after OLV. The multiple linear regression model for the TGM index was deduced as follows: TGM index (mL/m2)=C+12.770×a-3.987×b-1.237×c-2.664×d, where C is a constant 95.621 mL/m2, a is 1 for males and 0 for females, b is 1 for right OLV and 0 for left OLV, c is BMI (kg/m2), and d is PIP (cmH2O).Conclusions: The TGM index is negatively correlated with the oxygen concentration of the nonventilated lung at 5 min after OLV. Sex, side of OLV, BMI and PIP are independently correlated with the TGM index.Trial registration: This study was registered at ChiCTR (www.chictr.org.cn, ChiCTR1900024220) on July 1, 2019.Key Words: tidal gas movement, TGM index, one-lung ventilation, lung collapse, double-lumen endobronchial tube, dynamic lung compliance, thoracoscopy

Background

Effective collapse of nonventilated lung is important for exposure of critical structures during thoracoscopic surgery [1]. Prior to thoracic cavity being opened to atmosphere, positive pressure ventilation of dependent lung results in mediastinal displacement during one-lung ventilation (OLV) [2]. Subsequently, the transient pressure change in the contralateral hemithorax will cause tidal gas movement (TGM), which was also known as passive ventilation [3−5]. Nitrogen can freely go out of and back into the nonventilated lung during passive ventilation. Progressive influx of nitrogen into non-dependent lung delays lung collapse [4,6−7]. However, the magnitude of the tidal gas movement in the nonventilated lung and its relevant factors remain unknown.

The present study aimed to measure the volume of tidal gas passively ventilated into the nonventilated lung and to identify the factors associated with the volume of TGM. Furthermore, a mathematical model was established to predict the volume of TGM using multiple linear regression.

Methods

After approval of the Ethics Committee of Huadong Hospital affiliated to Fudan University and after obtaining written informed consent, adult patients who were scheduled for elective thoracoscopic surgeries were recruited in our prospective observational study from July 2019 to September 2019. All patients received lung function test and chest computed tomography (CT) examination preoperatively. Patients with following conditions were excluded: 1) difficulty in airway management detected by preoperative assessment. 2) unable to receive double-lumen tube intubation. 3) unable to maintain SpO_2<90% during OLV. 4) lung separation failure. 5) lung bullae or pleural adhesion confirmed by the preoperative CT.

Electrocardiography (ECG), non-invasive blood pressure (NIBP) and pulse oximetry were monitored in all patients before anesthesia. One hundred percent oxygen was inhaled during induction of anesthesia and measurement of the volume of TGM.

All patients received total intravenous anesthesia [8]. Anesthesia was induced with propofol (1–2 mg/kg), sufentanil (0.3 μg/kg), rocuronium (1 mg/kg) and was maintained with infusion of propofol (100–150 $\mu g.kg^{-1}.min^{-1}$) and remifentanil (0.15–0.2 $\mu g.kg^{-1}.min^{-1}$). Intermittent boluses of rocuronium were injected according to train of four neuromuscular monitoring.

The tidal volume was set as 7 mL/kg (ideal body weight) during two-lung ventilation and 6 mL/kg (ideal body weight) during OLV, respectively. The respiratory rate was 12/min, and I:E ratio was 1:2 without positive end-expiratory pressure (PEEP) [9–10].

Lung isolation was achieved with an appropriate-sized left-sided double-lumen endobronchial tube (DLT) [11]. Before placement of the DLT, fiberoptic bronchoscopy examination was performed to inspect the bronchial anatomy and pathology and to remove secretions. The position of the DLT was confirmed under fiber bronchoscopy. Dynamic lung compliance (Cdyn) and airway resistance (Raw) during dual lung ventilation were measured for three times and the average values were calculated for analysis. The patients were turned to the lateral position when the exhaled oxygen concentration reached to 90%. The position of DLT was reconfirmed and adjusted as needed under fiberoptic bronchoscopy [12–13]. OLV of the dependent lung was started immediately after placement of DLT. The accurate location of DLT was important to lung isolation. If the difference between the actual tidal volumes and the pre-set tidal volumes was more than 10 mL, the case had to be excluded due to lung separation failure. All procedures were performed by one anesthesiologist (J. W.)

The volume of the TGM in the nonventilated lung was measured in lateral position using pediatric spirometry sensor (Pedi-lite Sensor, REF73393, GE, Finland). The sensor was connected to the double-lumen connector of the nonventilated lung [14] which was open to atmosphere. When the OLV was started, the volume of the TGM was measured consecutively for three times. The average value was calculated and used for analysis.

The following variables were also recorded: 1) age, gender, height, the difference between actual body weight and ideal body weight (ABW-IBW). 2) forced vital capacity (FVC), FEV1/FVC, minute ventilation volume (MVV) from the pulmonary function test. 3) dynamic lung compliance (Cdyn) and airway resistance (Raw) during dual lung ventilation. 4) side of OLV (left/right). 5) lung puncture for localization of pulmonary nodule on the surgery day (yes/no).

Statistical analysis

The volume of TGM was defined as a continuous outcome variable (dependent variable). The other variables (independent variables) were showed according to the following rules. Continuous variables were analyzed with Shapiro-Wilk test for Normality test. Normally distributed variables were expressed as mean (standard deviation), abnormally distributed variables were expressed as median [interquartile range]. Binomial variables were expressed as numbers (percentages).

All data were analyzed by single factor correlation analysis. For normally distributed continuous variables, correlation analysis was performed with Pearson correlation test, while abnormally distributed data were analyzed with Spearman correlation test. Binomial variables were analyzed with Student's t test.

Variables with *P* < 0.25 were selected to the next step of multiple linear regression analysis. Statistical differences were considered to be significant if *P* < 0.05.

Results

One hundred and sixty-five patients were enrolled. The volume of TGM was 78 ± 26 mL.

There was significant correlation between the volume of TGM and age, gender, height, ABW-IBW, FVC, Cdyn or Raw (Table 1).

Nine variables with P< 0.25, including gender, age, height, ABW-IBW, FVC, Cdyn, Raw, side of OLV and lung puncture on the surgery day, were selected to perform multiple linear regression analysis. Gender, side of OLV, FVC and Cdyn independently correlated with the volume of TGM (P<0.05) (Table 2). The unstandardized coefficients were shown in table 2. B values were the partial regression coefficients. The constant of regression model was 26.915 mL. According to the multiple linear regression analysis, a linear regression model was deduced for the volume of TGM:

$$\text{TGM(mL)} = C + 16.452 \times a - 8.371 \times b + 14.017 \times c + 0.206 \times d$$

C: Constant= 26.915mL;

a: male=1, female= − 1;

b: right OLV=1, left OLV= − 1;

c: volume of FVC (L)

d: Cdyn (mL/cmH_2O)

Discussion

The present study confirmed that transient changes in pleural pressure in nonventilated lung existed during one-lung positive pressure ventilation before opening of the thoracic cavity of nonventilated lung. As a result, it caused tidal movement of gas out of and back into the nonventilated lung. The volume of TGM in the nonventilated lung in lateral position was in the range of 21 mL to 180 mL.

The measurement of the volume of TGM was performed using a pediatric spirometry sensor. The measurement range is 5 to 300 ml with accuracy of ± 6% or 4 mL. It is more accurate to measure small gas movement than adult spirometer. The volume of TGM in the present study was smaller than that in other studies (65–265 mL) [3]. The authors attribute this to the race difference.

Previous studies used different ways to measure the volume of TGM, such as a potentiometer attached to the counter-balance wheel of the spirometer [2], a water-filled spirometer [3], or an ambient pressure oxygen reservoir bag apparatus [4]. As compare to above methods, the pediatric spirometry sensor used in the present study makes the measurement simpler and more accurate. In addition, the volume of TGM can be measured in a real-time and repeatable way by using the pediatric spirometry sensor.

Since there was no research about analysis of factors associated with the volume of TGM, eleven variables were chosen for the single factor correlation analysis. These variables are the most commonly used clinical indicators, including patients’ general information, lung function variables and basic anesthesia-related factors. Among these factors, ABW-IBW was included to study the effect of obesity on the TGM. According to the multiple regression analysis, gender, side of OLV, FVC or dynamic lung compliance independently correlated with the volumes of the TGM. To the best of our knowledge, it was the first time that a regression model was established to predict the volume of the TGM. Using this model, anesthesiologists can calculate the volume of TGM before surgery and evaluate the impact of TGM on the collapse of the nonventilated lung.

In the present study, male patients had more TGM than female ones. Gender independently correlated with the volume of TGM ($P < 0.001$) (Table 2, Figure 2). The correlation between male and the volume of TGM was positive, while the correlation between female and the volume of TGM was negative. The B value of gender was 16.452 mL, which is the largest coefficient of the four correlated variables. The underlying reason may be related to sexual anatomical differences. The lung volume of adult female is typically 10–12% smaller than that of male who have the same height and age as female. It results from the differences in thoracic dimensions between male and female. Because of a greater inclination of ribs, female rib cages could accommodate a greater volume expansion [15]. During OLV, there is more space for the ventilated lung to expand, less mediastinal movement and less TGM of the nonventilated lung in female patients.

The side of OLV also independently correlated with the volume of TGM. Patients with right side OLV produced less volume of TGM than those with left side OLV (Figure 2, Table 2). It may be caused by the anatomical difference between the left and right lung. The volume of right lung is bigger than that of the left lung, which shares space in chest with heart. The right lung has three lobes with 10 segments, while the left lung has only two lobes with 8 segments. Since the tidal volume was same between left OLV and right OLV, the mediastinal movement was more significant during left OLV than that during right OLV. Therefore, the volume of TGM was bigger during left OLV than that during right OLV.

The FVC from the pulmonary function tests before surgery positively correlated with the volume of TGM (Figure 1, Table 2). The B value is 14.017mL. FVC is the volume of air that can be forcibly blown out after full inspiration. It is an important indicator in the pulmonary function test. Larger FVC means larger ventilation potential of the lung, which may be reasonable to produce more TGM of the nonventilated lung by the same magnitude of the mediastinal movement.

Dynamic lung compliance is an important variable in respiratory physiology. It represents pulmonary compliance during periods of gas flow. In the present study, it was measured during dual lung ventilation immediately after DLT intubation using spirometry sensor. The results indicated that the Cdyn positively correlated with the volume TGM (Figure 1, Table 2). The Lung with better Cdyn produces more tidal gas under the same external force. However, the effect of Cdyn was smaller than the other three variables (B = 0.206).

There were several limitations in the present study. Firstly, as a single-center research, sample size was small. Multicenter, large sample observation study need to be performed in the future. Secondly, the TGM was measured only when the tidal volume was set as 6 mL/kg of ideal body weight during OLV. Although 6 mL/kg of ideal body weight is the commonly used tide volume during OLV, the presented regression model may be unsuitable for other tidal volume.

In conclusion, the tidal gas movement of the non-ventilated lung during one-lung ventilation does exist. Gender, FVC, side of OLV and Cdyn independently correlated with the volume of TGM. The regression model in the present study may be used to predict the volume of TGM before surgery and to guide OLV management.

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Declarations

Abbreviations

TGM: tidal gas movement; DLT: double-lumen tube; OLV: one-lung ventilation; ABW: actual body weight; IBW: ideal body weight; FVC: forced vital capacity; FEV1: forced expiratory volume in the first second; MVV: minute ventilation volume; PEEP: positive end-expiratory pressure; Cdyn: dynamic lung compliance; Raw: airway resistance.

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Not applicable.

Authors’ contributions

JLW and LG were the co-first authors of this article, responsible for the design and implementation of this project, data collection, data statistics, and article writing. FFS contributed to the patient data collection, analysis and interpretation. MTZ contributed to the collection and analysis of the patient data. WDG was the corresponding author of this article in charge of the project, responsible for the expenses, and was involved in the design of the project and modified the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The raw data of the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

The study was approved by the ethics committee of Huadong Hospital affiliated to Fudan University and the reference number was IRB20180074. This trial was registered at http://www.chictr.org.cn (ChiCTR1900024220). Written consents to participate were obtained from all participants after enrollment.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Tables

Table 1. Results of single factor correlation analysis

	Distribution	*P* value
Age (y), median [IQR]	58 [18]	0.005
Gender (female/male), N	97/68	<0.001
Height (cm) , median [IQR]	164 [12]	<0.001
ABW-IBW (kg), median [IQR]	3 [10]	<0.001
Pulmonary function tests		
FVC (L), median [IQR]	2.6 [0.9]	<0.001
MVV (L/min), median [IQR]	36 [34]	0.728
FEV_1/FVC (%), median [IQR]	89 [10]	0.865
Pulmonary dynamics during two-lung ventilation		
Cdyn (mL/cmH_2O), mean (SD)	49 (13)	<0.001
Raw (cmH_2O), median [IQR]	14.0 [2.7]	<0.001
Side of one-lung ventilation (Right/Left), N	61/104	0.093
Lung puncture on the surgery day (Yes/No), N	64/101	0.244

Continuous data were shown as mean (SD) or median [IQR] according to Normality tests. Binary classification data were shown as N.

SD, standard deviation. IQR, interquartile range. N, number.

ABW-IBW, the difference between actual body weight and ideal body weight.

FVC, forced vital capacity. MVV, minute ventilation volume. FEV1, forced expiratory volume at 1 second. Cdyn, dynamic lung compliance. Raw, airway resistance.

Table 2. Results of multiple linear regression

	Unstandardized Coefficients		Standardized Coefficients			95%C.I. for B	
	B	Std. Error	Beta	t	*P*	Lower	Upper
Constant	26.915	8.383		3.211	0.002	10.295	43.536
sex (male)	16.452	4.402	0.315	3.738	<0.001	7.726	25.179
OLV (right	-8.371	3.844	-0.157	-2.178	.032	-15.992	-0.750
FVC (L)	14.017	3.268	0.364	4.290	<0.001	7.539	20.496
Cdyn (mean) (mL/cmH_2O)	0.206	0.074	0.203	2.777	0.006	0.059	0.353

OLV, one-lung ventilation. FVC, forced vital capacity. Cdyn, the volume of dynamic lung compliance.

Figures

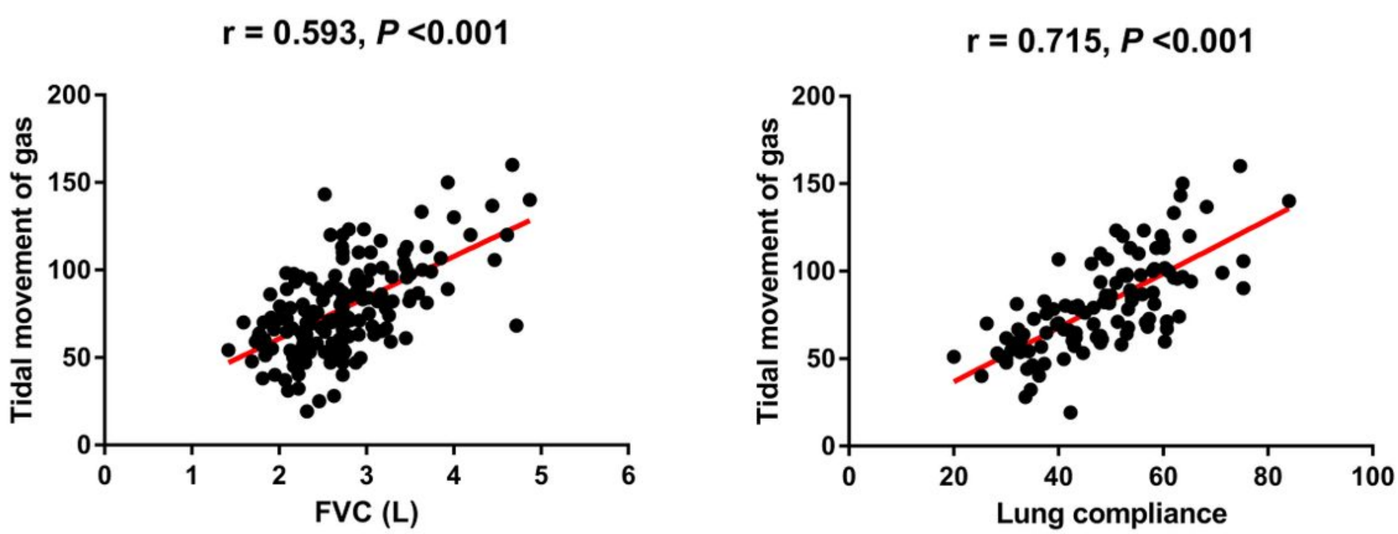

Figure 1

Figure 1 showed the correlation between volume of TGM and FVC or dynamic lung compliance with multiple regression analysis. For FVC, the r value was 0.593 (P<0.001). For dynamic lung compliance, the r value was 0.715 (P<0.001). They both showed well correlated to the TGM.

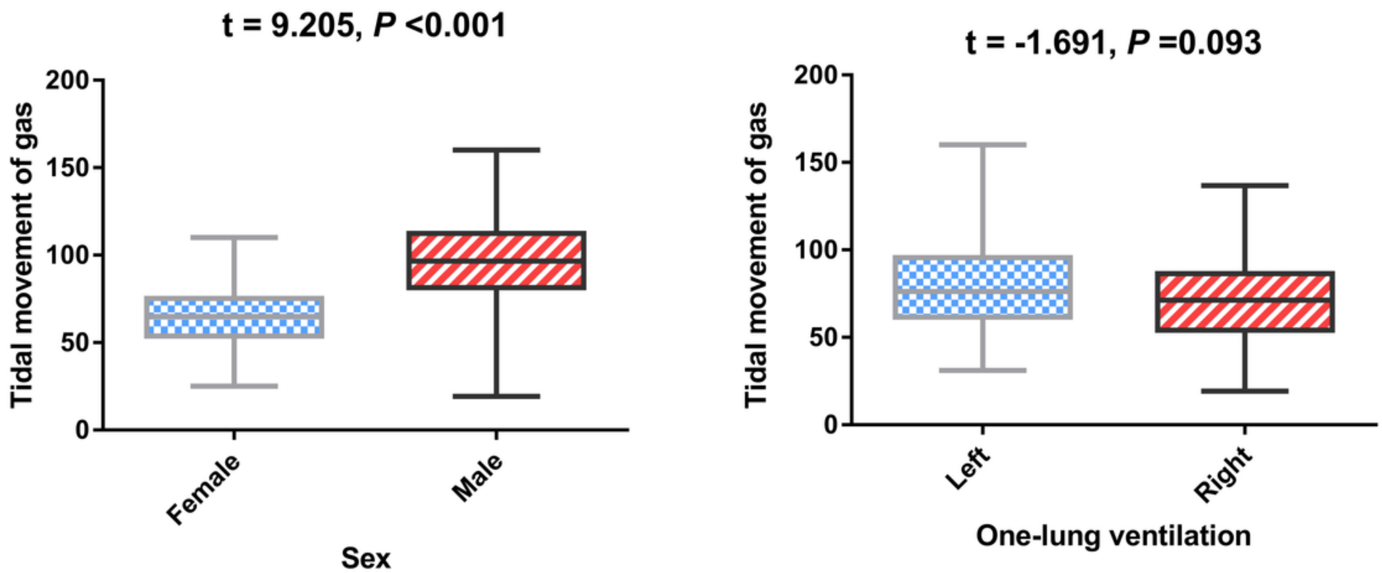

Figure 2

Figure 2 showed the correlation between volume of TGM and gender or side of OLV, which are two of binary classification variables, with multiple regression analysis by box plots. The box showed the interquartile range (IQR) and the median of each variables. For gender, the t value was 9.205 (P<0.001). For side of OLV, the t value was -1.691 (P=0.093). They both showed well correlated to the TGM.