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Flow-volume curves as measurement of respiratory mechanics during ventilatory support: the effect of the exhalation valve

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Abstract *Objective:* To assess the feasibility of expiratory flow-volume curves as a measurement of respiratory mechanics during ventilatory support: to what extent is the shape of the curve affected by the exhalation valve of the ventilator?
Design: Prospective, comparative study.
Setting: Medical intensive care unit of a university hospital.
Patients: 28 consecutive patients with various conditions, mechanically ventilated with both the Siemens Servo 900C and 300 ventilators, were studied under sedation and paralysis.
Interventions: The ventilator circuit was intermittently disconnected from the ventilator at end-inspiration in order to obtain flow-volume curves with and without the exhalation valve in place.
Measurements and results: Peak flow (PEF) and the slope of the flow-volume curve during the last 50 % of expired volume (SF50) were obtained both with and without the exhalation valve in place. The exhalation valve caused a significant reduction in peak flow of 0.3 l/s (from 1.27 to 0.97 l/s) with the Siemens Servo 900 C ventilator and of 0.42 l/s (from 1.36 to 0.94 l/s) with the Siemens Servo 300 ventilator ($p < 0.001$). The SF50 was not affected.
Conclusion: In mechanically ventilated patients, the exhalation valve causes a significant reduction in peak flow, but does not affect the SF50. This study further suggests that the second part of the expiratory flow-volume curve can be used to estimate patients' respiratory mechanics during ventilatory support.

Key words Flow-volume curve · Mechanical ventilation · Exhalation valve · Intensive care

Introduction

The importance of monitoring respiratory mechanics in patients on ventilatory support is generally accepted. With the current generation of mechanical ventilators, respiratory variables such as flow, volume and pressure are displayed on a screen on-line. Also, pressure-volume and flow-volume relationships are easily visualized. The flow-volume curve provides an easy way to obtain information on conditions like chronic obstructive pulmonary disease (COPD), intrinsic positive end-expiratory pressure (iPEEP), airway secretions, obstruction of the ventilator circuits and the expiratory time constant [1–6]. In a previous study, we showed that the relaxed expiratory flow-volume curve can be used to assess airflow obstruction in mechanically ventilated patients with COPD [7]. When the expiratory flow-volume curve is used to estimate the patient's respiratory mechanics, it is important to establish to what extent external elements affect the shape of the flow-volume curve. The endotracheal tube has been recognized as a major resistive element [8,9]. In the ventilatory circuit, the exhalation valve is considered to cause the principal resistance [10]. The resistance of exhalation

Table 1 Patient characteristics (*Days MV* days on mechanical ventilation; *APACHE II* Acute Physiology and Chronic Health Evaluation II score on day of measurement, *TIPS* transjugular intrahepatic portosystemic shunt, *COPD* chronic obstructive pulmonary disease)

Patient	Age (years)	Diagnosis	Sex	Days MV	Apache II
1	47	Interstitial pneumonia	M	2	15
2	66	Bacterial pneumonia	M	2	20
3	66	Drug-induced lung injury	M	2	18
4	43	Post-TIPS procedure	M	6	10
5	52	Post-TIPS procedure	M	2	19
6	69	Guillain-Barré syndrome	F	1	9
7	46	Aspiration pneumonia	F	2	15
8	51	Cytomegalovirus pneumonia	M	7	21
9	49	Interstitial lung disease	F	17	14
10	61	Congestive heart failure	M	7	10
11	43	Pleural empyema	M	2	8
12	77	Congestive heart failure	F	2	17
13	47	Bacterial pneumonia	M	4	11
14	81	Bacterial pneumonia	F	2	10
15	42	Porphyria acuta	M	100	1
16	81	Aspiration pneumonia	F	15	10
17	66	Congestive heart failure	M	6	19
18	71	Muscle weakness, cardiac surgery	F	5	11
19	43	Tetraplegia	M	180	5
20	65	COPD	M	1	18
21	72	COPD	F	3 years	10
22	78	COPD	M	1	24
23	78	COPD	M	1	12
24	81	COPD	M	2	14
25	76	COPD	M	2	11
26	56	COPD	M	1	17
27	71	COPD, pneumonia	F	2	13
28	74	COPD	F	5	12

valves has been investigated predominantly under experimental conditions using test lungs [11, 12]. In this study, we examined, in patients on ventilatory support, expiratory flow-volume curves obtained both with and without the exhalation valve of the ventilator in place. We also compared two different ventilators.

Patients and methods

Patients

Twenty-eight consecutive patients admitted to the medical intensive care unit of Erasmus Medical Centre Rotterdam were studied. The patients were included if they met the following criteria: mechanical ventilation via an endotracheal or tracheostomy tube with an inner diameter exceeding 7 mm, a ventilator PEEP level < 10 cm H_2O and the absence of air leaks. The patients were mechanically ventilated for various medical conditions: patients' characteristics are given in Table 1. Prior to mechanical ventilation, the patients with COPD ($n = 9$) had a mean forced expiratory volume in 1 s (FEV_1) of 31 % of predicted (range 19–45 %). Twenty-three patients had been intubated with an endotracheal tube (i. d. range 7.5–9 mm), 5 patients with a tracheostomy tube (i. d. range 7–8.5 mm). In all patients, measurements were obtained while a Siemens Servo 900 C ventilator (Siemens-Elema, Solna, Sweden) was being used. In 23 patients, the study was repeated with a Siemens Servo 300 ventilator (Siemens-Elema, Solna, Sweden), applying the same ventilator settings. Ventilator settings were set by the primary physician and remained unchanged during the study, except that if ventilator PEEP was present it was removed. The volume-controlled mode was used in 21 patients, while the pressure controlled mode was used in 7 patients. The average minute volume was 10 l/min (6–15 l/min) . The average respiratory rate was 15 breaths per min (10–30 bpm). At volume-controlled ventilation, the ratio between inspiratory and expiratory time was 35:65 in all patients. At pressure-controlled ventilation, this ratio was 50:50. During the study, all patients were sedated with midazolam (Roche Nederland B. V., Mijdrecht, The Netherlands) and paralysed with vecuronium (Organon Teknika, Boxtel, The Netherlands). Informed consent was obtained from the patient or their next of kin. The study was approved by the local ethics committee.

Interventions and respiratory measurements

A heated pneumotachometer (Lilly, Jaeger, Wurzburg, Germany) was connected to the endotracheal tube to measure flow. Volume was obtained by computerized integration of the flow signal. Data were stored and analysed using a personal computer (Commodore 486 SX33, Commodore Business Machines, West Chester, Penna., USA) at a sample frequency of 100 Hz.

Expiratory flow-volume curves were obtained both with and without the exhalation valve of the ventilator in place. To obtain measurements without the exhalation valve in place, the expiratory line of the ventilator circuit was disconnected from the ventilator at an end-inspiratory pause. Subsequently, the patient was allowed to expire till no flow was detected. By disconnecting the tubings at the ventilator side, not only the exhalation valve, but the total expiratory circuit inside the ventilator, including the flow transducer and connecting tubes, were bypassed during expiration. For simplicity, the expiratory circuit inside the ventilator is referred to as the exhalation valve. All measurements were obtained in triplicate.

Analysis of the flow-volume curve

In order to describe the relevant components of the flow-volume curve relationship, we determined the peak flow (PEF) and the angle of the slope of the flow-volume curve during the last 50 % of expired volume (SF50, in degrees). In formula:

$$\mathrm{SF50} = \mathrm{arctg}\left(\frac{(V'50,\ ex - V'end,\ ex)}{V_t 50}\right)$$

where V′ 50,ex = the flow at 50 % of exhaled volume (l/s), V′end,ex = the flow at end-expiration (l/s), V_t50 = 50 % of expiratory tidal volume (l), and arctg = arctangents (s^{-1}).

The flow-volume curves of two consecutive breaths, the first with and the second without the exhalation valve in place, were compared, using PEF and SF50 determined at corresponding volume range. The average of three measurements was calculated.

Data analysis

Student's *t*-test was used. Results were considered significantly different when $p < 0.05$. Mean differences between SF50 with valve and SF50 without valve were plotted against the mean values of SF50 with valve and SF50 without valve according to Bland and Altman, limits of agreement were estimated as ± 2SD of the differences [13].

Results

The results of the study are shown in Table 2. For both types of ventilators studied, the presence of the exhalation valve was associated with a significant decrease in PEF (both $p < 0.001$). In contrast, the SF50 remained unchanged by the exhalation valve of both ventilators ($p = 0.68$ and $p = 0.063$, for the Servo 900 C and 300 ventilator, respectively). No significant differences were found in instantaneous flows with and without valve at both mid- and end-expiration. The average change in SF50 was 0.2 ° (SD 2.7 °) for the Servo 900 C ventilator and 0.9 ° (SD 2.2 °) for the Servo 300 ventilator. In Fig. 1, the differences between SF50 with valve and without valve are plotted against their means. Mean difference and limits of agreement are indicated. In this figure, a slight SF50 dependent systematic deviation is observed. In patients with higher SF50's removal of the valve tends to increase the SF50, while, in contrast, in patients with lower SF50's, removal of the valve tended to decrease the SF50. In patients with COPD, the mean SF50 was 21 ° (SD 11 °), while in patients with other pathology the mean SF50 was 50 ° (SD 12 °). Examples of expiratory flow-volume curves of a patient with a low SF50 and a patient with a high SF50 with and without exhalation valve are shown in Fig. 2.

Table 2 Results of study

Exhalation valve	Servo ventilator 900C		Servo ventilator 300	
	With valve	Without valve	With valve	Without valve
Mean peak flow (l/s)	0.97	1.27*	0.94	1.36*
SD	0.23	0.30	0.22	0.41
Range	0.60–1.60	0.74–1.80	0.45–1.32	0.65–2.16
Mean SF50 (°)	40	40	44	45
SD	18	19	15	16
Range	9–68	8–72	15–68	12–70

* Significant difference between peak flow with and without the ventilator valve in place: $p < 0.001$ for both ventilators

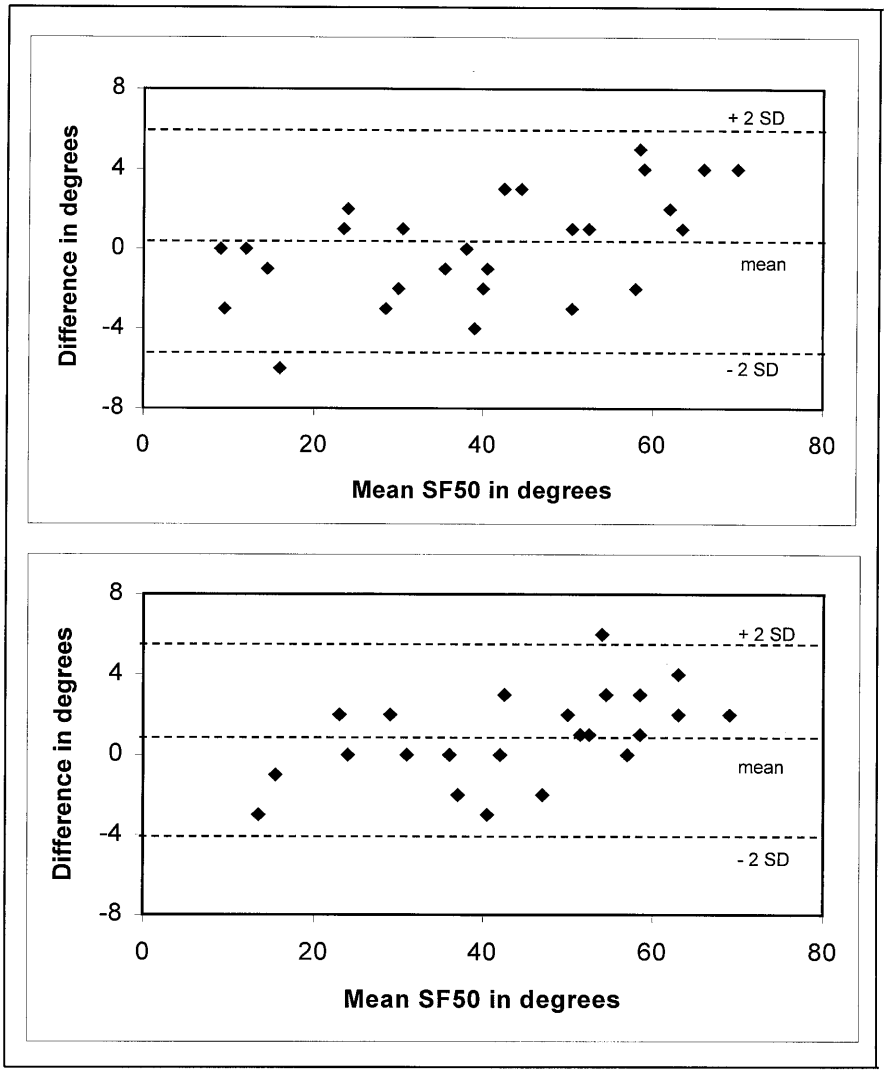
Discussion

This study shows that in mechanically ventilated patients the exhalation valve of the ventilator decreases the PEF but does not appreciably affect the SF50. This study further suggests that the second part of the expiratory flow-volume curve can be used to estimate patients' respiratory mechanics during ventilatory support.

The passive expiration can be described as an early, rapid component, which reflects the resistive behaviour of predominantly extrathoracic resistive elements and a consecutive slower component, mainly reflecting viscous and elastic properties of lung, chest wall and the endotracheal tube [6,14,15]. In the expiratory flow-volume curve, the transition between the two components has been referred to as the inflection point, defined as the point of maximum slope following the peak expiratory flow [6]. In order to describe both components of the flow-volume curve relationship, we determined the PEF and the SF50.

The concept of the SF50 is based on a mono-exponential lung emptying pattern, assuming a constant elastance and resistance. In patients with diseased lungs and mechanical inhomogeneity, however, this assumption cannot be fulfilled. Chelucci et al. described the time course of volume change during passive expiration by a two-compartment model [14, 16]. Emptying of the first compartment, representing about 80 % of total exhaled volume, lasted for approximately 1.5 s. For emptying of the second compartment, 8 s of expiration time was allowed. As our study was performed during uninterrupted mechanical ventilation with an average expiration time of about 2 s, the two-compartment model could not be applied. Also, in the present study, the analysed part of the flow-volume curves approached linearity. Application of a two-compartment model would

Fig. 1 Bland and Altman analysis of difference (SF50 without exhalation valve minus SF50 with exhalation valve) plotted against the mean of SF50 with and without exhalation valve. The *upper figure* displays the results of the Servo 900 C ventilator, the lower figure those of the the Servo 300 ventilator



introduce unacceptable inaccuracy. It has been shown that the use of a linear model was acceptable when the expired airflow pattern was analysed in spontaneously breathing patients [17,18]. In patients with varying pathology, this should be considered as an effective single compartment behaviour, covering peripheral airways obstruction, visco-elastic properties and unequal ventilation.

We used the SF50 instead of the respiratory time constant (τ), calculated as the quotient of the volume change and the corresponding flow difference. Since both the SF50 and the τ are calculated from the same variables, it is clear that they are closely related: SF50 is equal to arctangents τ^{-1}. The inverse exponential relationship explains that at low flows minor alterations in flow lead to large changes in τ, but only minimally affect the SF50. In a patient with severe COPD, a minor change in SF50 of 3° from 11 to 8° corresponds to a change in time constant from 5.1 to 7.1 s. An equal change in SF50 from 53 to 50°, however, does not affect the time constant. Therefore, in patients with COPD, the SF50 is a better way to describe the slope, as these minor changes in flow are clinically irrelevant.

In a previous study, the SF50 was found to discriminate between patients with COPD and patients with other pathology. In the patients with COPD, a linear relationship was established between SF50 and FEV_1 assessed in the period prior to ventilatory support [7]. In the present study, a mean SF50 of 21° (SD 11°) was found in the patients with COPD, while the mean SF50 was 50° (SD 12°) in the patients with other pathology.

Our results show that the exhalation valve decreases PEF significantly, emphasizing the influence of the flow resistance of the valve [12]. Brunner et al. calculated the expiratory time constant from PEF and expiratory tidal volume [5]. A disadvantage of their method is that

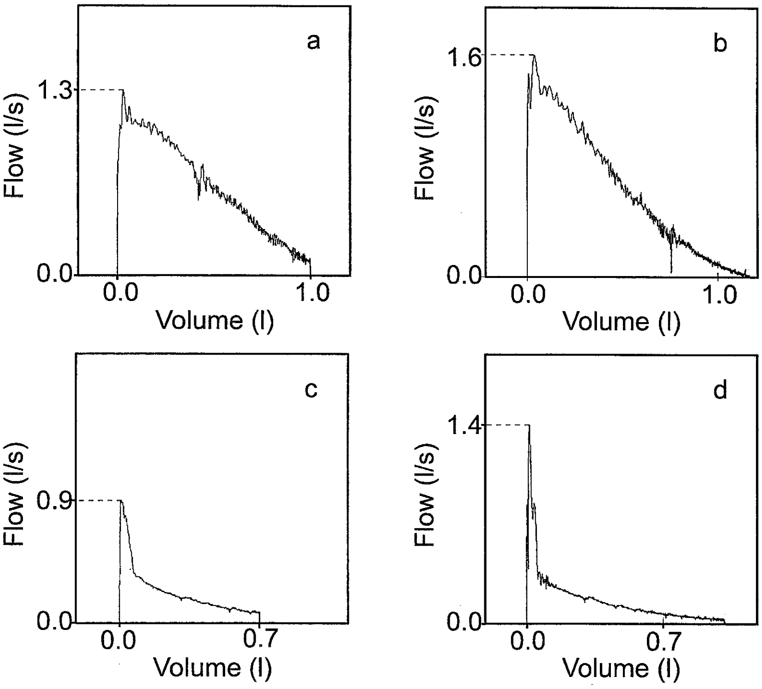


Fig. 2 Flow-volume curves of a patient with a high SF50 **a** and **b** and of a patient with a low SF50 **c** and **d**, with exhalation valve **a** and **c** and without exhalation valve **b** and **d**

it is less applicable in patients with COPD. In patients with COPD, the contribution of PEF to exhalation is minimal and the rate of lung emptying is determined by the slope of the flow-volume curve beyond the inflection point (Fig. 2). Therefore, this part of the flow-volume curve seems more informative .

In our study, the exhalation valve did not appreciably affect the SF50. This was verified for a wide range of slopes from patients with various medical conditions. Our results are not in agreement with the findings of Guttmann et al., who describe a higher time constant when the ventilator equipment was included compared to the value without the ventilator equipment [6]. In their study, the effects of both exhalation valve and ventilator tubing were assessed. In order to determine the resistance of the ventilator tubings used in our study, we assessed the relationship between resistive pressure and airflow for these tubings . For the highest flow at mid expiration found in our patients (0.71 l/s), the resistive pressure was 0.4 cm H_2O. Therefore, the resistance of the tubings may be considered negligible. In contrast to our study, Guttmann et al. only included patients with acute respiratory distress syndrome, who have low "internal" resistances and steep slopes. In those patients, the effect of the exhalation valve can be explained by the proportionally greater contribution of the valve to the sum of internal and external resistance.

Bypassing the expiratory circuit during exhalation has been used to detect flow limitation [19]. According to that approach, no change in SF50 after removal of the valve is expected, in the case of flow limitation. In contrast, the SF50 would increase in patients without flow limitation. As can be seen in Fig. 1, removal of the valve tends to decrease the SF50 in the patients with lower SF50's and to increase the SF50 in the patients with higher SF50's. However, these changes are small and it is not possible to discriminate between patients with and without flow limitation. The decrease in SF50 after removal of the valve in patients with COPD can be explained if the exhalation valve is considered as an external resistor. In mechanically ventilated patients with severe COPD, flow limitation develops even during relaxed expiration [1, 2, 7, 20]. Application of an external resistor can counteract airway compression and reduce flow limitation [1, 2, 20]. As a consequence a steeper slope is found.

The design of the study precluded removal of the endotracheal tube, since all patients were on controlled ventilation with sedation and paralysis. Tube resistance at the flow at mid-expiration was calculated for each patient, using resistive pressure and flow characteristics assessed for the same kind of tubes as used in this study [2]. The average resistive pressure at mid-expiratory flow was 0.7 cm H_2O (SD 0.4 cm H_2O) in the group of COPD patients and 2.5 cm H_2O (SD1.5 cm H_2O) in the patients with other pathology. To estimate the effect of the endotracheal tube on the results of our study, we recalculated the SF50 for the theoretical condition of absence of the endotracheal tube for the two patients with the highest and the lowest flow at mid-expiration. For the patient with the highest flow (0.71 l/s), the SF50 of the theoretical curve was 65 ° against 61 ° of the flow-volume curve with the endotracheal tube. In the patient with the lowest flow rate (0.16 l/s) the SF50's remained equal: 12 ° for both conditions. Therefore, we conclude that in patients with COPD, tube resistance does not appreciably influence the SF50 due to the low flow rates at the second half of expiration. In patients with a higher SF50, these values can be an underestimation of the SF50 without the endotracheal tube.

Flow dynamics of exhalation valves are determined by their physical properties. In this study, the Siemens Servo 900 C and 300 ventilators, both equipped with scissor valves, were compared. The scissor valve contains a narrow tube of silicone rubber, the i. d. of this tube measures 8 mm in the Servo 900 C ventilator valve and 10 mm in the Servo 300 ventilator valve [12]. We assessed the resistance of the entire expiratory circuit within the ventilator and found that the resistive pressure – flow characteristics were comparable for both ventilators: 4.3 and 4.7 cm H_2O/l/s for the 900 C and 300 ventilator respectively.

In summary, in mechanically ventilated patients the exhalation valve affects the flow-volume curve by causing a significant decrease in PEF. The SF50, however, is not affected. In patients with COPD, the presence of the endotracheal tube does not appreciably affect the SF50. In patients with higher SF50's, the endotracheal tube can cause a slight underestimation of the SF50. No difference was found between the two types of Servo ventilators studied. This study suggests that in mechanically ventilated patients expiratory flow-volume curves can be used to estimate patients' respiratory mechanics at the bedside.

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