ORIGINAL

Effect of Positive End-expiratory Pressure on Sevoflurane Washout Times from Anesthesia Workstations

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Abstract : This study examined the effect of positive end-expiratory pressure (PEEP) on sevoflurane washout from anesthesia workstations using a test lung model. Two workstations (Perseus A500 and Carestation 650) were tested with fresh gas flows (FGF) of 2–8 L/min at PEEP levels of 0 and 8 cmH_2O. Washout time was the interval for sevoflurane concentration to fall from 8% to 0%. In the Perseus A500, PEEP prolonged washout at 2 L/min (2562 [92] s vs. 2266 [17] s, p = 0.027), 4 L/min (1397 [36] s vs. 1275 [32] s, p = 0.012), and 6 L/min (756 [8] s vs. 533 [34] s, p = 0.006), but not at 8 L/min (115 [2] s vs. 113 [2] s, p = 0.23). In the Carestation 650, washout was prolonged at 2 L/min (5254 [229] s vs. 4447 [113] s, p = 0.013), 4 L/min (3597 [101] s vs. 2911 [230] s, p = 0.022), and 6 L/min (1816 [94] s vs. 1492 [115] s, p = 0.021), but not at 8 L/min (252 [3] s vs. 212 [35] s, p = 0.187). Our findings indicated that PEEP delayed anesthetic washout most at lower FGFs, which warrants caution in low-flow anesthesia. J. Med. Invest. 73 : 111-115, February, 2026

Keywords **:** *Anesthetics, Inhalation; Anesthesia, Closed-Circuit; Anesthesia Recovery Period; Positive-Pressure Respiration; PEEP*

INTRODUCTION

The washout of inhalational anesthetics from anesthesia workstations is an important determinant of emergence from general anesthesia (1). Residual anesthetics in the workstation can lead to delayed recovery during emergence (2-4). Identifying and optimizing the factors that influence anesthetic washout from anesthesia circuits is therefore of clinical relevance, as these processes directly affect both patient safety and perioperative efficiency.

Previous studies have demonstrated that workstation characteristics—such as circuit volume, absorbent properties, and internal flow paths—modify the washout profile of volatile anesthetics (5-10). Fresh gas flow (FGF) and ventilatory parameters, including tidal volume and respiratory rate, also influence elimination (7, 10, 11). Positive end-expiratory pressure (PEEP), widely used to prevent atelectasis and improve oxygenation (12-14), increases functional residual capacity (FRC) (15) and alters ventilatory mechanics (16). Thus, PEEP may influence anesthetic elimination, but its impact on washout from anesthesia circuits has not been systematically investigated.

We hypothesized that the application of PEEP prolongs the washout time of sevoflurane, one of the most widely used inhalational anesthetics, from the anesthesia workstations. To examine this hypothesis, we conducted an experimental study using a test lung model and two anesthesia workstations with different driving mechanisms. The objective was to quantitatively evaluate the influence of PEEP settings on sevoflurane washout times in an *in-vitro* model.

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MATERIALS AND METHODS

This study with an *in-vitro* lung model did not involve human participants or animals ; therefore, approval from an institutional ethics committee was not required.

Experimental Equipment and Setup

Two anesthesia workstations were used : the Perseus A500 (Drägerwerk AG & Co. KGaA, Lübeck, Germany) and the Carestation 650 (GE HealthCare Technologies Inc., Chicago, IL). Their technical specifications are summarized in Table 1, and schematic diagrams are presented in Figure 1.

An anesthesia breathing circuit (Portex® 84–221 cm Adult Expandable Circuits, ICU Medical, Inc., San Clemente, CA) was connected to a test lung system (TL2PRO Test Lung™ System, South Pacific Biomedical, Inc., Temecula, CA). The test lung was configured for bilateral ventilation without leakage and an airway resistance of 5 cmH_2O/L/sec. The compliance was set at 20 mL/cmH_2O per lung, giving a total compliance of 50 mL/cmH_2O, which was the highest setting achievable with this model. A heat and moisture exchanger (DAR™ Adult-Pediatric Electrostatic Filter HME, Small, VT 150–1200 mL, Covidien plc., Dublin, Ireland) was inserted between the breathing circuit and the test lung. A new CO_2 absorbent was installed before each trial. Standard pre-use checks of the anesthesia workstations, including leak testing and verification of circuit integrity, were performed before each trial.

Sevoflurane was delivered using the vaporizers integrated into each workstation, which were calibrated before each experimental series. Sevoflurane concentrations were continuously monitored using a gas analyzer (GF-220R, Nihon Kohden Corp., Tokyo, Japan), operating on the sidestream sampling principle with a flow rate of 200 mL/min. Sampling was performed at the heat and moisture exchanger positioned between the breathing circuit and the test lung. The analyzer was calibrated before each experimental series. Numerical data were recorded every 3 seconds.

Table 1. Technical characteristics of the anesthesia workstations

	Internal volume	Respiratory system	Vaporizer
Perseus A500	2.18 L	Turbine-driven	Vapor 3000 (variable-bypass, mechanical)
Carestation 650	2.99 L*	Bellows-driven	Tec 7 (variable-bypass, mechanical)

* Ventilator-side volume (2,006 mL) + disposable canister volume (985 mL)

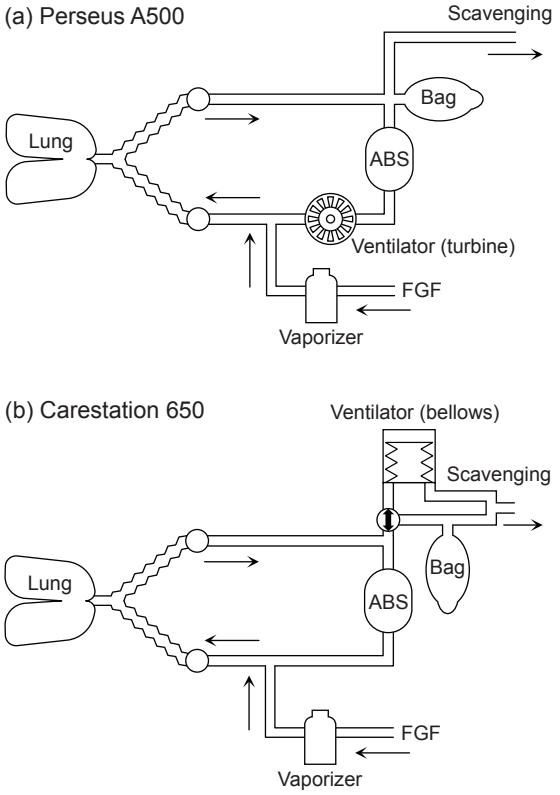

Figure 1. Schematic diagrams of the two anesthesia workstations used in this study.
(a) Perseus A500 and (b) Carestation 650. Key components, including vaporizers, fresh gas flow, CO_2 absorber, bag, and scavenging system, are shown.
ABS, CO_2 absorber ; FGF, fresh gas flow.

Experimental Protocol

Volume-controlled ventilation was applied with a tidal volume of 500 mL, a respiratory rate of 12 breaths/min, and an inspiratory-to-expiratory ratio of 1:2, incorporating a 20% plateau phase. PEEP was set at either 0 cmH_2O (control) or 8 cmH_2O. This PEEP level of 8 cmH_2O was selected as a commonly used setting in intraoperative lung-protective ventilation reported in previous clinical studies (12, 17). FGF of 100% oxygen was delivered at four rates : 2, 4, 6, and 8 L/min.

For each condition, the vaporizer was set to deliver sevoflurane at 8 vol% until the circuit concentration reached a stable plateau, after which the vaporizer was abruptly switched off. Washout time was defined as the interval required for the circuit concentration of sevoflurane to decrease from plateau to 0%.

At each FGF level, three independent measurements were obtained under both PEEP settings on each anesthesia workstation. Consistent with prior bench studies (7-9), three replicates per condition were adopted as an appropriate design.

Statistical Analysis

All data are expressed as mean values with standard deviations. The Welch's t-test was used for pairwise comparisons between PEEP and non-PEEP conditions, and results are reported as mean differences (MD) with 95% confidence intervals. In addition, a linear model analysis of washout time was performed to simultaneously assess the main and interaction effects of PEEP and FGF, thereby accounting for multiple comparisons. A two-sided p-value < 0.05 was considered statistically significant. A sample size calculation was not performed ; however, based on previous bench studies (7-9), three replicate measurements per condition were considered sufficient.

All statistical analyses were performed using EZR (Saitama Medical Center, Jichi Medical University, Saitama, Japan), a graphical user interface for R version 4.4.0 (The R Foundation for Statistical Computing, Vienna, Austria). EZR is a modified version of R commander designed to incorporate statistical functions frequently used in biostatistics (18).

RESULTS

In the Perseus A500, the washout time of sevoflurane at an FGF of 2 L/min was significantly longer with PEEP than without PEEP (2562 [92] s vs. 2266 [17] s, MD : 296 [79–513] s, p = 0.027). Significant differences were also observed at 4 L/min (1397 [36] s vs. 1275 [32] s, MD : 122 [44–200], p = 0.012) and 6 L/min (756 [8] s vs. 533 [34] s, MD : 223 [144–302], p = 0.006), but not at 8 L/min (115 [2] s vs. 113 [2] s, MD : 2 [−2–6], p = 0.230). (Figure 2a)

In the Carestation 650, sevoflurane washout times were significantly prolonged by PEEP at 2 L/min (5254 [229] s vs. 4447 [113] s, MD : 807 [330–1284], p = 0.013), 4 L/min (3597 [101] s vs. 2911 [230] s, MD : 686 [198–1174], p = 0.022), and 6 L/min (1816 [94] s vs. 1492 [115] s, MD : 324 [82–566], p = 0.021). At 8 L/min, however, the difference was not statistically significant (252 [3] s vs. 212 [35] s, MD : 40 [−46–126], p = 0.187). (Figure 2b)

Linear model analysis of washout time showed that for the Perseus A500, FGF (p < 0.001) and PEEP (p = 0.039) both had significant effects, whereas their interaction was not significant (p = 0.198). For the Carestation 650, FGF (p < 0.001), PEEP (p < 0.001), and their interaction (p < 0.001) were all significant. (Table 2)

Residual lung volume at 8 cmH_2O PEEP was 220 mL compared with 25 mL without PEEP. Detailed ventilatory parameters are summarized in Table 3.

DISCUSSION

This study examined the effect of PEEP on sevoflurane washout using two anesthesia workstations, the Perseus A500 and the Carestation 650. Washout times were significantly prolonged by the application of 8 cmH_2O PEEP at FGFs of 2, 4, and 6 L/min, whereas no significant difference was observed at 8 L/min. This effect was most pronounced in the Carestation 650, particularly

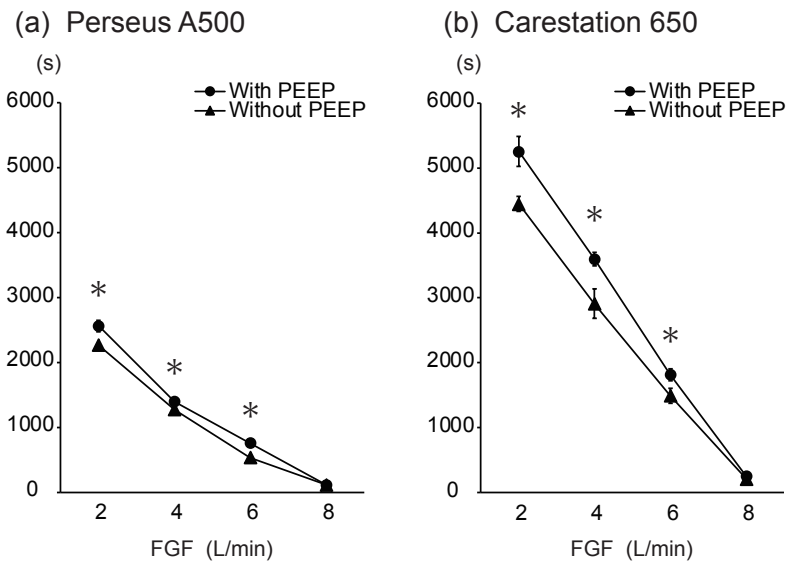

Figure 2. Sevoflurane washout times with and without PEEP.
Washout times of sevoflurane at fresh gas flows (2, 4, 6, and 8 L/min) in (a) Perseus A500 and (b) Carestation 650. Data are shown as mean ± standard deviation. Asterisks (*) indicate statistically significant differences between PEEP and non-PEEP conditions.
FGF, fresh gas flow ; PEEP, positive end-expiratory pressure.

Table 2. Linear model analysis of washout time

	Estimate	Standard error	p-value
Perseus A500			
Intercept	2847.00	113.69	< 0.001
FGF	−360.05	20.76	< 0.001
PEEP	356.00	160.78	0.039
FGF × PEEP	−39.05	29.35	0.198
Carestation 650			
Intercept	5796.50	97.11	< 0.001
FGF	−706.20	17.73	< 0.001
PEEP	1130.00	137.33	< 0.001
FGF × PEEP	−133.15	25.07	< 0.001

FGF, fresh gas flow ; PEEP, Positive End-expiratory Pressure.

Table 3. Ventilatory parameters measured in the test lung model

	Measured tidal volume (mL)		Peak pressure (cmH_2O)	
	With PEEP	Without PEEP	With PEEP	Without PEEP
Perseus A500				
FGF 2 L/min	460	477	31	23
4 L/min	459	474	30	22
6 L/min	451	452	30	22
8 L/min	452	463	30	22
Carestation 650				
FGF 2 L/min	443	443	33	27
4 L/min	447	450	34	27
6 L/min	443	445	33	28
8 L/min	442	440	33	28

FGF, fresh gas flow ; PEEP, Positive End-expiratory Pressure.

at lower FGFs. To our knowledge, this is the first study to demonstrate that PEEP prolongs sevoflurane elimination.

Differences in washout kinetics and ventilatory performance were also observed between the two workstations. In both, PEEP prolonged sevoflurane washout ; however, the effect was more pronounced in the Carestation 650. This discrepancy may be attributable to technical characteristics such as its larger internal volume and bellows-driven ventilation system, compared with the smaller volume and turbine-driven Perseus A500. Supporting this, Shin *et al*. reported that the Perseus responds more rapidly to changes in volatile anesthetic concentrations than conventional workstations (19), and Morimoto *et al*. found faster recovery after desflurane anesthesia with the Perseus A500 compared with a conventional workstation (1). The prolonged washout with PEEP observed at the Perseus A500 may be of limited clinical relevance, whereas in the Carestation 650 it warrants caution under low-flow anesthesia.

Although the mechanisms underlying the delayed washout observed with PEEP were not clarified in this study, two plausible explanations can be considered. First, PEEP can increase the residual capacity of the test lung, reducing the proportion of volume exchanged with each breath and slowing anesthetic turnover. Second, in bellows-based systems such as the Carestation 650, PEEP can maintain a positive baseline pressure that prevents complete bellows collapse, thereby enlarging the breathing system volume. Consistent with this, Dosch *et al*. reported that breathing system volume and FGF are the primary determinants of anesthetic gas concentration changes in anesthesia workstations (20). On the other hand, because PEEP had little effect on tidal volume in this study, changes in ventilatory mechanics are unlikely to explain the delayed washout.

Our findings suggest that the delaying effect of PEEP on anesthetic washout may be particularly relevant under low-flow conditions. Low-flow anesthesia (often defined as FGF <1 L/min, or even lower) has been increasingly adopted to reduce environmental impact and conserve medical resources (21-24). In this context, discontinuing PEEP before emergence may help avoid unnecessary delays in anesthetic elimination, particularly under low-flow anesthesia. Previous studies suggest that discontinuing PEEP during emergence does not adversely affect post-extubation oxygenation, supporting the applicability of this approach in clinical practice (17, 25).

This study focused on the mechanical effects of positive end-expiratory pressure (PEEP) within a controlled test-lung system, and several aspects of the setup do not fully replicate clinical conditions. Although the ventilatory parameters were configured with an adult model in mind, the peak airway pressures measured were higher than those typically observed in clinical practice. Moreover, it should be acknowledged that the physiological effects of PEEP on FRC were not reproduced in this model. The predicted FRC in a healthy adult male (20 years old, 170 cm in height) is 3.1 L (95% confidence interval, 2.15–4.13 L) (26). In biological lungs, PEEP increases FRC by preventing alveolar collapse and recruiting atelectatic regions, thereby improving ventilation–perfusion matching (12-15). These physiological mechanisms can influence anesthetic gas elimination but were not incorporated into the present setup. Furthermore, the test lung represents a simplified single-compartment system, whereas human lungs are multi-compartmental, exhibiting heterogeneous ventilation, perfusion, and anesthetic uptake (27, 28). The release of anesthetic agents from blood back into the alveoli also contributes to washout *in-vivo*. Therefore, our results should be interpreted as reflecting the relative mechanical influence of PEEP on anesthetic washout rather than the physiological responses observed in patients. Further clinical studies are warranted to determine the applicability of these findings to patient care.

This study has additional limitations. First, mechanical conditions were standardized in this model, with fixed ventilatory parameters such as tidal volume and respiratory rate. Different ventilatory settings could, however, alter gas exchange dynamics and modify the effect of PEEP. Second, it remains uncertain whether similar findings would be obtained with other inhalational anesthetics or carrier gases, as differences in solubility and viscosity may affect washout kinetics. Third, only two anesthesia workstations were tested, thus limiting the generalizability of the findings to other devices. Finally, anesthetic concentrations were not measured at multiple locations within the test lung or circuit, limiting a more detailed understanding of the washout dynamics.

In conclusion, within the constraints of this bench-model study, PEEP significantly prolonged the washout of sevoflurane from anesthesia workstations at FGFs of 2, 4, and 6 L/min, but not at 8 L/min. The delaying effect was more pronounced at lower FGFs, particularly in the bellows-driven system. These findings suggest that, particularly under low-flow anesthesia, discontinuing PEEP before emergence may facilitate more efficient anesthetic elimination. Further clinical studies are warranted to verify the applicability of these observations to clinical practice.

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We used ChatGPT (GPT-5, OpenAI, San Francisco) exclusively for improving the clarity and accuracy of our English text. We thoroughly reviewed and verified the accuracy of the suggestions provided by the artificial intelligence before incorporation. All statements related to the hypotheses, interpretations, results, conclusions, limitations, and implications of the study represent our own original ideas and work.

COMPETING INTERESTS

All authors declare no competing interests.

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