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Comparative Analysis of Ventilator Parameter Measurements When Connected to Internal and External Nebulizers Using a Gas Flow Analyzer

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ABSTRACT This study analyzes differences in ventilator parameter measurements when using internal and external nebulizers based on the calibration method standard HK.02.02/D/43649/2024, using a Fluke VT305 Gas Flow Analyzer as the reference instrument. Experimental testing was conducted on four ventilator units operating in Volume Control mode. The evaluated parameters included Inspiratory Tidal Volume (VTi), Expiratory Tidal Volume (VTe), Minute Volume (MV), and Peak Inspiratory Pressure (PIP). The results showed differences in ventilator parameter values between internal and external nebulizer use across all tested units, with statistical analysis indicating significant differences for all parameters ($p = 0.00$). Evaluation against the ±10% tolerance limit revealed that two ventilators remained within the tolerance range when using an external nebulizer, with maximum deviations of +6.97% and +9.74% in the MV parameter. In contrast, the other two ventilators exceeded the ±10% tolerance limit for VTi, VTe, and MV when using an external nebulizer, with maximum deviations reaching +36.69% and −38.05% in the MV parameter. The use of an internal nebulizer consistently produced more stable parameter values and remained within the tolerance range for all ventilator units. These findings indicate that internal nebulizers are more recommended to maintain ventilator accuracy in accordance with calibration standards, while the use of external nebulizers requires careful consideration of the flow compensation capabilities of specific ventilator systems.

INDEX TERMS *Ventilator, Calibration, Nebulizer, Gas Flow Analyzer, Tolerance Limits.*

I. INTRODUCTION

Mechanical ventilation is a critical life-support intervention used to maintain adequate oxygenation and ventilation in patients with respiratory failure by delivering positive pressure to the lungs through an artificial airway [1], [2]. In clinical practice, ventilators are commonly operated using *Volume Control* (VC) and *Pressure Control* (PC) modes, each with distinct characteristics in regulating tidal volume and inspiratory pressure depending on the patient's lung mechanics [3], [2]. Accurate measurement performance is essential in medical equipment systems because instrument accuracy may decrease over time, making calibration and performance verification necessary[4]. The accuracy of key ventilatory parameters, such as inspiratory tidal volume (VTi), expiratory tidal volume (VTe), minute volume (MV), and peak inspiratory pressure (PIP), is essential, as it directly impacts patient safety and the effectiveness of respiratory support [5], [6]. Therefore, periodic testing and calibration of ventilators are mandatory to ensure measurement accuracy and device reliability, as regulated by national healthcare standards [7], [8].

In addition to ventilatory support, aerosol therapy is widely administered to mechanically ventilated patients, particularly in Intensive Care Units (ICUs) [9], [10]. Among various aerosol delivery devices, jet nebulizers remain commonly used due to their affordability and availability [10], [11]. However, the use of jet nebulizers—especially those powered by external gas sources (*continuous jet nebulizers*)—introduces additional airflow into the ventilator circuit, which may interfere with the accuracy of ventilator measurements [12], [13]. Previous studies have demonstrated that factors such as nebulizer type, placement position, humidification conditions, and operating mode significantly influence aerosol delivery efficiency and its interaction with ventilator performance [13], [14], [15]. External factors may influence measurement performance and contribute to deviations in calibration results[16].

A critical issue arises from the discrepancy between standard calibration conditions and real-world clinical practice. According to the Indonesian Ministry of Health calibration guidelines, ventilator performance testing must be conducted without any additional accessories, including nebulizers [8]. In contrast, the use of external nebulizers is routine in clinical settings, particularly in ICU patient management [9], [10]. This discrepancy raises concerns regarding the validity and reliability of ventilator measurements when used under actual clinical conditions that differ from standardized calibration procedures.

Previous research has highlighted the impact of external jet nebulization on ventilator performance. Li et al. [3] reported that nebulization can significantly affect ventilator parameters across different ventilation modes. This finding was further supported by Jayakumaran et al. [12], who demonstrated that external jet nebulizers could cause substantial overestimation (*over-reading*) of expiratory tidal volume (VTe) by up to 118% in ventilators equipped with internal flow sensors, while the actual delivered tidal volume increase was relatively small. Conversely, ventilators with proximal flow sensors were able to compensate for the additional flow more effectively, resulting in more accurate measurements [12], [2]. The clinical implications of these discrepancies are considerable, as inaccurate ventilator readings may lead to inappropriate clinical decisions. Notably, deviations in tidal volume of up to 30% are considered unsafe and potentially harmful to patients [17].

Despite these findings, most previous studies have relied on lung simulators as reference measurement tools [3], [12].There remains a lack of research utilizing standard calibration instruments, such as Gas Flow Analyzers, to evaluate ventilator performance under conditions involving external nebulization in accordance with established calibration standards [8], [18]. Furthermore, limited studies have systematically assessed whether the deviations caused by external nebulizers exceed the acceptable tolerance limits defined in calibration guidelines (±10%) [8].

Therefore, this study aims to analyze the differences in ventilator parameter measurements—specifically VTi, VTe, PIP, and MV—under conditions involving internal and external nebulizers using a Gas Flow Analyzer as the reference standard. Additionally, this study evaluates whether the observed deviations remain within the acceptable tolerance limits defined by national calibration standards. The findings of this study are expected to bridge the gap between standardized calibration procedures and real-world clinical practice, and to provide evidence-based insights for evaluating ventilator performance in healthcare settings.

II. METHOD

This study used a quantitative experimental approach to compare ventilator parameter measurements—VTi, VTe, MV, and PIP—under internal and external nebulizer conditions, evaluated against the ±10% tolerance limit of the Indonesian calibration standard HK.02.02/D/43649/2024. Four ventilators with different flow sensor types. Two with internal sensors (Ventilator Uji 1 dan Ventilator Uji 2) and two with external/proximal sensors (Ventilator Uji 3 dan Ventilator Uji 4) were tested in Volume Control (VC) mode using a calibrated Gas Flow Analyzer (Fluke VT305) as the reference instrument. Primary data were collected through direct measurements under both conditions and analyzed using descriptive statistics, Kolmogorov–Smirnov normality testing, and either paired sample t-test or Wilcoxon signed-rank test, along with percentage deviation analysis to assess compliance with tolerance limits.

A. RESEARCH WORKFLOW

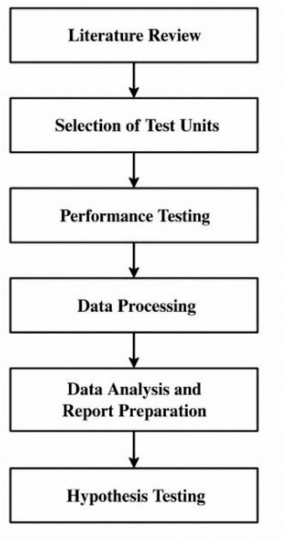

FIGURE 1. Research workflow illustrating the overall study design, data collection, and analysis procedures

The research workflow presented in Fig. 1 began with a literature review to identify research gaps and establish a theoretical framework. Subsequently, test units were selected, consisting of four ventilators (two Maquet

Servo-i with internal flow sensors and two Hamilton C2 with external/proximal flow sensors), one external jet nebulizer (DeVilbiss), and a Gas Flow Analyzer (Fluke VT305) as the reference instrument. Performance testing was conducted on all ventilators under two conditions—internal and external nebulizer use—at predefined tidal volume settings (500 mL and 600 mL). The collected data were then processed to calculate mean values, standard deviations, and individual differences. Statistical analysis was performed using SPSS, including normality testing (Kolmogorov–Smirnov) followed by either paired sample t-test or Wilcoxon signed-rank test, depending on data distribution. Finally, the results were evaluated against calibration tolerance standards to determine hypothesis acceptance and assess whether ventilator performance remained within acceptable limits under both conditions.

B. VENTILATOR PERFORMANCE TESTING SCHEME

The experimental setup consisted of a ventilator, nebulizer system, Gas Flow Analyzer Fluke VT305, and a test lung connected through the breathing circuit.

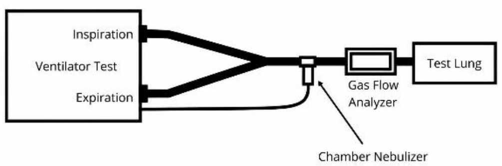

FIGURE 2. Circuit Scheme Using Internal Nebulizer

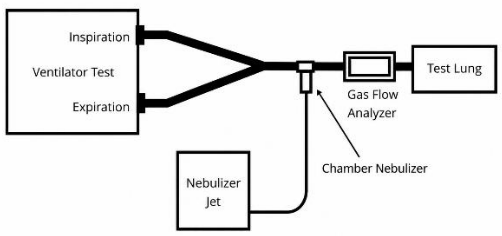

FIGURE 3. Circuit Scheme Using External Nebulizer

Fig. 2 and Fig. 3 illustrate the circuit configurations used in this study for ventilator performance testing under internal and external nebulizer conditions.

C. CONCEPTUAL FRAMEWORK

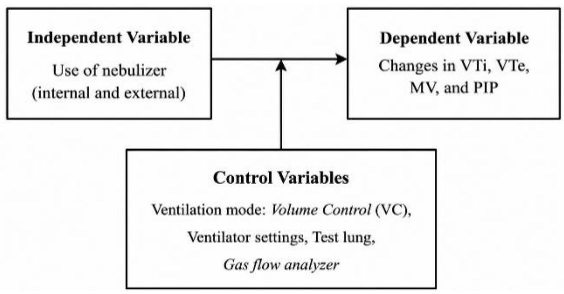

FIGURE 4. Conceptual framework of the proposed study

The conceptual framework Fig 4. illustrates the relationship between the use of nebulizer types and ventilator performance parameters. In this study, the independent variable is the nebulizer condition, consisting of internal and external jet nebulizer use connected to the ventilator. This variable is assumed to influence the dependent variables, namely inspiratory tidal volume (VTi), expiratory tidal volume (VTe), minute volume (MV), and peak inspiratory pressure (PIP), which are measured using a Gas Flow Analyzer as the reference standard.

To ensure that the observed changes in ventilator parameters are solely attributed to the nebulizer condition, several control variables are maintained constant throughout the experiment. These include the ventilation mode (Volume Control), ventilator settings (tidal volume, respiratory rate, inspiratory–expiratory ratio, and PEEP), the use of a standardized test lung to simulate consistent respiratory mechanics, and the use of the same calibrated Gas Flow Analyzer for all measurements. By controlling these factors, the study isolates the effect of nebulizer type on ventilator measurement accuracy and performance.

D. FLOWCHART

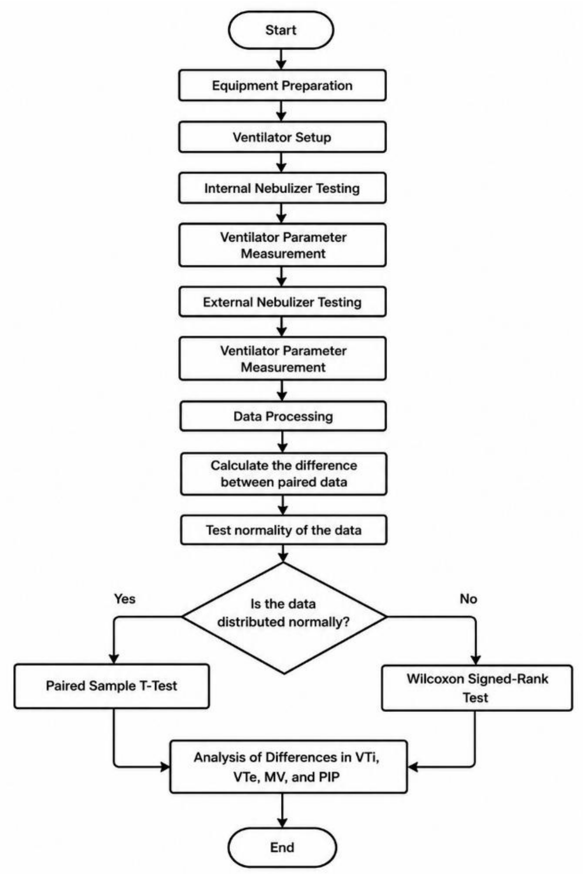

FIGURE 5. Flowchart of experimental procedure and data analysis

The Flowchart of this study, as illustrated in Fig 5., began with equipment preparation to ensure all devices were functioning properly, followed by ventilator setup according to predefined parameters. Measurements of ventilation parameters (VTi, VTe, MV, and PIP) were first conducted under internal nebulizer conditions and then repeated under external nebulizer conditions using identical settings, resulting in paired datasets. The collected data were processed to obtain mean values and calculate differences between paired measurements. These differences were then tested for normality; if normally distributed, a paired sample t-test was applied, otherwise the Wilcoxon signed-rank test was used. Finally, deviations in ventilation parameters were analyzed based on statistical results to support the study conclusions.

E. DATA COLLECTION TECHNIQUES

The data collection in this study utilized primary data obtained through direct measurements of ventilator performance. Measurements were conducted on four ventilator units under two conditions: when connected to an internal nebulizer and when connected to an external jet nebulizer, using a Gas Flow Analyzer as the reference instrument. The parameters measured included inspiratory tidal volume (VTi), expiratory tidal volume (VTe), minute volume (MV), and peak inspiratory pressure (PIP). Tidal volume was set at two predefined levels, 500 mL and 600 mL. For each ventilator unit, measurements of VTi, VTe, MV, and PIP were recorded 50 times under both internal and external nebulizer conditions, resulting in paired datasets for subsequent analysis.

F. DATA ANALYSYS TECHNIQUES

This study employed a quantitative approach, where measurements obtained from the ventilator were compared under two conditions: with and without an external jet nebulizer.

1) ***Paired Difference Calculation***

The values of VTi, VTe, MV, and PIP obtained under external nebulizer conditions were subtracted from those measured under internal nebulizer conditions to determine the individual paired differences. The difference for each measurement is defined as follows:

$$d_i = x\_Eksternal\_i - x\_Internal\_i \qquad (1)$$

Where,
d_i : difference for each paired observation

2) ***Mean Difference Calculation***

After obtaining the differences for each paired observation, the mean of these differences was calculated. The average difference is defined as follows:

$$M\_d = \frac{\Sigma d_i}{n} \qquad (2)$$

Where,
M_d : mean difference ($\bar{X}$_*Eksternal* - $\bar{X}$_*Internal*)
Σd_i : sum of differences
n : number of observation

3) ***Standard Deviation Calculation***

Standard deviation represents the precision or random variability of the measurement results. A smaller standard deviation indicates better repeatability of the instrument.

$$S\_d = \sqrt{\frac{\sum_i^n (d_i - M\_d\,)^2}{n-1}} \qquad (3)$$

Where,
S_d : standard deviation
M_d : mean difference
d_i : the i-th data value
$n-1$: degrees of freedom

4) ***Normality Test One-Sample Kolmogorov-Smirnov***

A normality test was performed on the difference data between external and internal nebulizer conditions to determine the appropriate statistical test. The One-Sample Kolmogorov–Smirnov test was applied, where a significance value $(p) > 0.05$ indicates normally distributed data, while $(p) \leq 0.05$ indicates non-normal distribution.

5) ***Paired Sample T-Test***

A paired sample t-test was used to compare measurement results under two different conditions (internal and external nebulizer) on the same subjects. Prior to applying the paired sample t-test, a normality test was performed on the difference data between the two measurements. If the differences were normally distributed, the data were further analyzed using the paired sample t-test. The t-statistic is calculated as follows:

$$t = \frac{M\_d}{(S_d/\sqrt{n}} \qquad (4)$$

Where,
t : t-value
M_d : mean difference
S_d : standard deviation
n : number of paired observations

- If the p-value (Sig.) < 0.05, there is a statistically significant difference
- If the p-value (Sig.) > 0.05, there is no statistically significant difference

6) ***Wilcoxon Signed-Rank Test***

The Wilcoxon Signed-Rank Test was used to assess differences in VTi, VTe, MV, and PIP between internal and external nebulizer conditions when the data were not normally distributed. The analysis involves computing paired differences, ranking their absolute values, and summing positive and negative ranks. The test statistic is defined as:

$$Z = (T - \mu\_T) / \sigma\_T \quad (5)$$

Where,

$$\mu T = \frac{n\,(n+1)}{4} \quad (6)$$

$$\sigma T = \sqrt{\frac{n(n+1)(2n+1)}{24}} \quad (7)$$

Where,
n : number of paired observations (excluding zero differences),
T : Wilcoxon test statistic,
μT : mean of the Wilcoxon distribution,
σT :standard deviation of the Wilcoxon distribution.

7) ***Deviation Analysis and Tolerance Evaluation***

This analysis was conducted to assess whether ventilator performance under internal and external nebulizer conditions complies with calibration tolerance standards. The percentage deviation between the measured values obtained using a Gas Flow Analyzer and the preset (target) ventilator values was calculated as follows:

$$\%\,Deviasi = \frac{\bar{x} - x_0}{x_0}\; x\; 100\% \quad (8)$$

Where,
$\%\,Deviasi$: percentage deviation
$\bar{x}$: mean measured value,
x_0 : set (target) value.

III. RESULTS

A. GRAPHICAL RESULTS AT TIDAL VOLUME SETTING OF 500 ML

This section presents graphs of ventilator parameter measurements at a 500 mL tidal volume setting for each test unit, based on mean values. The parameters include VTi, VTe, MV, and PIP, providing a visual comparison between internal and external nebulizer conditions to identify trends prior to inferential statistical analysis.

1) ***Graph of Mean Inspiratory Tidal Volume (VTi) at the 500 mL Tidal Volume Setting***

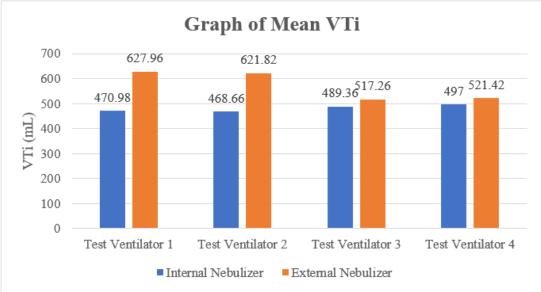

FIGURE 6. Graph of Mean Inspiratory Tidal Volume (VTi) at the 500 mL Tidal Volume Setting

Based on Fig. 6., mean VTi values are higher with the external nebulizer across all test ventilators. The increase is more pronounced in Test Ventilators 1 and 2, while Test Ventilators 3 and 4 show smaller differences. Overall, the external nebulizer tends to produce higher VTi at the 500 mL setting.

2) ***Graph of Mean Expiratory Tidal Volume (VTe) at the 500 mL Tidal Volume Setting***

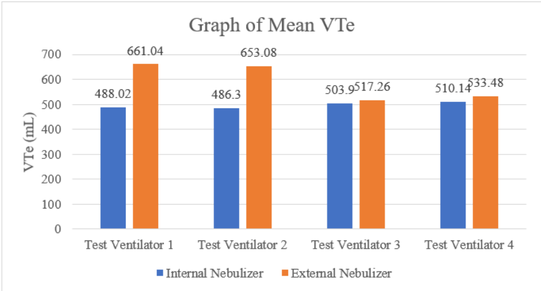

FIGURE 7. Graph of Mean Expiratory Tidal Volume (VTe) at the 500 mL Tidal Volume Setting

Based on Fig. 7., mean VTe values are higher with the external nebulizer across all test ventilators. The increase is more pronounced in Test Ventilators 1 and 2, while smaller differences are observed in Test Ventilators 3 and 4. Overall, the external nebulizer tends to increase VTe at the 500 mL setting.

3) ***Graph of Mean Minute Volume (MV) at the 500 mL Tidal Volume Setting***

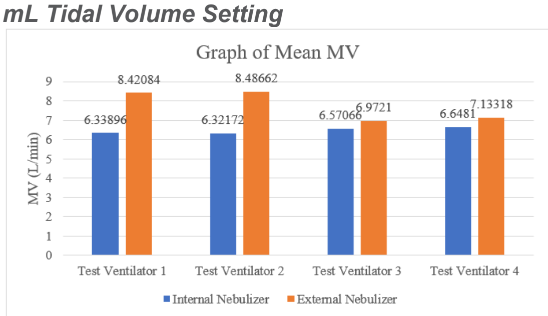

FIGURE 8. Graph of Mean Minute Volume (MV) at the 500 mL Tidal Volume Setting

Based on Fig. 8., mean MV values are higher with the external nebulizer across all test ventilators. The increase is more pronounced in Test Ventilators 1 and 2, while smaller differences are observed in Test Ventilators 3 and 4. Overall, the external nebulizer tends to increase MV at the 500 mL setting.

4) Graph of Mean Peak Inspiratory Pressure (PIP) at the 500 mL Tidal Volume Setting

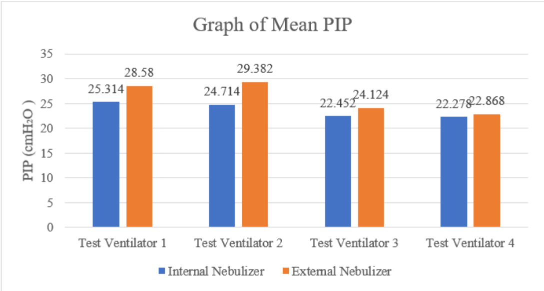

FIGURE 9. **Graph of Mean Peak Inspiratory Pressure (PIP) at the 500 mL Tidal Volume Setting**

Based on Fig. 9., mean PIP values are higher with the external nebulizer across all test ventilators. The increase is more pronounced in Test Ventilators 1 and 2, while smaller differences are observed in Test Ventilators 3 and 4. Overall, the external nebulizer tends to increase PIP at the 500 mL setting.

B. GRAPHICAL RESULTS AT TIDAL VOLUME SETTING OF 600 ML

This section presents graphs of ventilator parameters at the 600 mL tidal volume setting using mean values, including VTi, VTe, MV, and PIP, to compare performance between internal and external nebulizer conditions and identify trends prior to inferential analysis.

1) Graph of Mean Inspiratory Tidal Volume (VTi) at the 600 mL Tidal Volume Setting

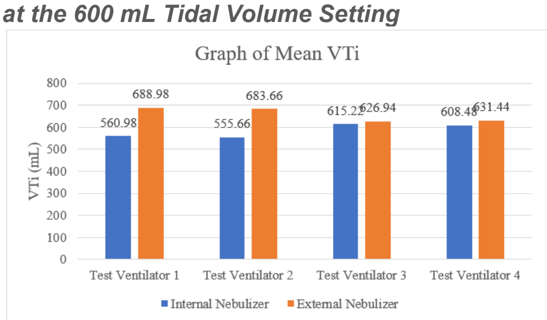

FIGURE 10. **Graph of Mean Inspiratory Tidal Volume (VTi) at the 600 mL Tidal Volume Setting**

Based on Fig. 10., mean VTi values are higher with the external nebulizer across all test ventilators. The increase is more pronounced in Test Ventilators 1 and 2, while smaller differences are observed in Test Ventilators 3 and 4. Overall, the external nebulizer tends to increase VTi at the 600 mL setting

2) Graph of Mean Expiratory Tidal Volume (VTe) at the 600 mL Tidal Volume Setting

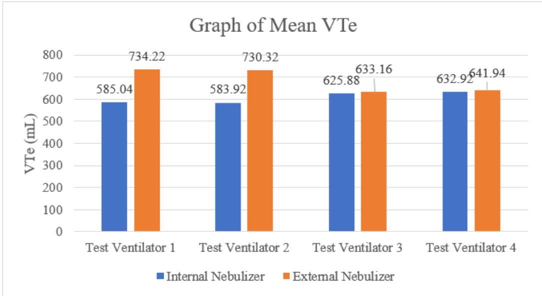

FIGURE 11. **Graph of Mean Expiratory Tidal Volume (VTe) at the 600 mL Tidal Volume Setting**

Based on Fig. 11., mean VTe values are higher with the external nebulizer across all test ventilators. The increase is more pronounced in Test Ventilators 1 and 2, while smaller differences are observed in Test Ventilators 3 and 4. Overall, the external nebulizer tends to increase VTe at the 600 mL setting.

3) Graph of Mean Minute Volume (MV) at the 600 mL Tidal Volume Setting

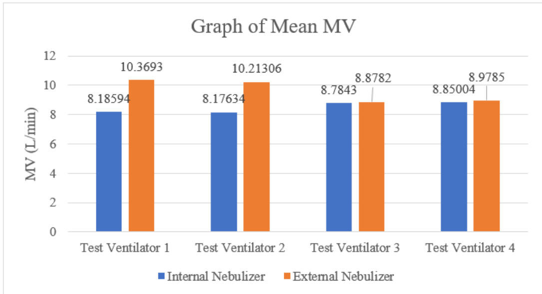

FIGURE 12. **Graph of Mean Minute Volume (MV) at the 600 mL Tidal Volume Setting**

Based on Fig. 12., mean MV values are generally higher with the external nebulizer across most test ventilators. The increase is more pronounced in Test Ventilators 1 and 2, while only slight differences are observed in Test Ventilators 3 and 4. Overall, the external nebulizer tends to increase MV at the 600 mL setting.

4) *Graph of Mean Peak Inspiratory Pressure (PIP) at the 600 mL Tidal Volume Setting*

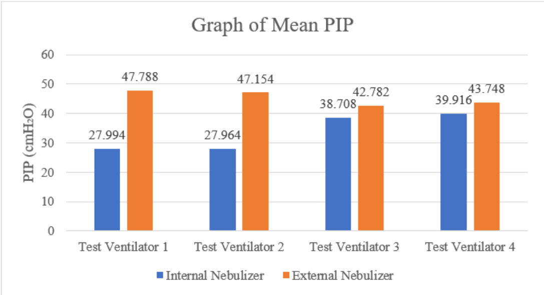

FIGURE 13. Graph of Mean Peak Inspiratory Pressure (PIP) at the 600 mL Tidal Volume Setting

Based on Fig. 13., mean Peak Inspiratory Pressure (PIP) values are consistently higher with the external nebulizer across all test ventilators. The increase is most pronounced in Test Ventilators 1 and 2, while Ventilators 3 and 4 show smaller differences. Overall, at the 600 mL tidal volume setting, the external nebulizer tends to elevate PIP compared to the internal nebulizer.

C. HYPOTHESIS TESTING

Hypothesis testing was conducted to assess differences in ventilator parameters (VTi, VTe, MV, and PIP) between internal and external nebulizer use at tidal volume settings of 500 mL and 600 mL. Normally distributed data were analyzed using the Paired Sample T-Test, while non-normal data were analyzed using the Wilcoxon Signed-Rank Test. The results are presented in Table I (500 mL) and Table II (600 mL).

TABLE I
SUMMARY OF COMPARATIVE TEST RESULTS AT 500 ML TIDAL VOLUME SETTING

VT 500		V 1	V 2	V 3	V 4
Normality Test	Normal ($p > 0,05$)	PIP	VTe, PIP	VTi, VTe, MV	VTi, VTe, MV
	Not Normal ($p < 0,05$)	VTi, VTe, MV	VTi, MV	PIP	PIP
Paired Sample T-Test	Significant ($p < 0,05$)	PIP	VTe, PIP	VTi, VTe, MV	VTi, VTe, MV
	Not Significant ($p > 0,05$)	-	-	-	-
Wilcoxon Signed Ranks Test	Significant ($p < 0,05$)	VTi, VTe, MV	VTi, MV	PIP	PIP
	Not Significant ($p > 0,05$)	-	-	-	-

TABLE II
SUMMARY OF COMPARATIVE TEST RESULTS AT 600 ML TIDAL VOLUME SETTING

VT 600		V1	V2	V3	V 4
Normality Test	Normal ($p > 0,05$)	VTe	VTi, MV	VTi, VTe, MV, PIP	VTe
	Not Normal ($p < 0,05$)	VTi, MV, PIP	VTe, PIP	-	VTi, MV, PIP
Paired Sample T-Test	Significant ($p < 0,05$)	VTe	VTi, MV	-	VTe
	Not Significant ($p > 0,05$)	-	-	-	-
Wilcoxon Signed Ranks Test	Significant ($p < 0,05$)	VTi, MV, PIP	VTe, PIP	VTi, VTe, MV, PIP	VTi, MV, PIP
	Not Significant ($p > 0,05$)	-	-	-	-

Based on Table I and Table II, all ventilator parameters show significant differences ($p < 0.05$) between internal and external nebulizer use. Thus, H_0 is rejected and H_1 is accepted, confirming that nebulizer type significantly affects VTi, VTe, MV, and PIP.

D. CONFORMITY TO CALIBRATION TOLERANCE LIMITS

After identifying significant differences, parameter conformity was evaluated against HK.02.02/D/43649/2024 tolerance limits. VTi and VTe were referenced to set values, while MV and PIP to displayed values. Mean values and percentage deviations were calculated; results within tolerance were classified as compliant, otherwise non-compliant.

Parameter conformity was evaluated against a ±10% calibration tolerance. Results show that Test Ventilators 1 and 2 met tolerance limits under internal nebulizer conditions at both tidal volumes (500 mL and 600 mL), but exhibited significant deviations—particularly in VTi, VTe, and MV—when using the external nebulizer, indicating non-compliance in most parameters. In contrast, Test Ventilators 3 and 4 consistently met tolerance limits under both internal and external nebulizer conditions, with only minor deviations. These findings indicate that ventilators with internal flow sensors are more susceptible to measurement inaccuracies when using external nebulizers, while those with external flow sensors maintain stable and compliant performance, as shown in Tables III, IV, V, and VI.

TABLE III
CONFORMITY TO TOLERANCE LIMITS OF TEST VENTILATOR 1

Test Ventilator	Parameter	Setting / Display	Measured Value (Average)	Deviation (%)	Tolerance Limit	Compliance
Test Ventilator 1 – Internal Nebulizer VT500	VTi (mL)	500	470,98	-5,80	±10%	Compliant
	VTe (mL)	500	488,02	-2,40	±10%	Compliant
	MV (L/menit)	6,5	6,34	-2,46	±10%	Compliant
	PIP (cmH_2O)	27	25,31	-6,26	±10%	Compliant
Test Ventilator 1 – External Nebulizer VT500	VTi (mL)	500	627,96	+25,59	±10%	Non-Compliant
	VTe (mL)	500	661,04	+32,20	±10%	Non-Compliant
	MV (L/menit)	13,3	8,42	-36,69	±10%	Non-Compliant
	PIP (cmH_2O)	29	28,58	-1,45	±10%	Compliant
Test Ventilator 1 – Internal Nebulizer VT600	VTi (mL)	600	560,98	-6,50	±10%	Compliant
	VTe (mL)	600	585,04	-2,49	±10%	Compliant
	MV (L/menit)	8,3	8,19	-1,37	±10%	Compliant
	PIP (cmH_2O)	30	27,99	-6,69	±10%	Compliant
Test Ventilator 1 – External Nebulizer VT600	VTi (mL)	600	688,98	+14,83	±10%	Non-Compliant
	VTe (mL)	600	734,22	+22,37	±10%	Non-Compliant
	MV (L/menit)	15,4	10,37	-32,67	±10%	Non-Compliant
	PIP (cmH_2O)	42	47,79	+13,78	±10%	Non-Compliant

TABLE IV
CONFORMITY TO TOLERANCE LIMITS OF TEST VENTILATOR 2

Test Ventilator	Parameter	Setting / Display	Measured Value (Average)	Deviation (%)	Tolerance Limit	Compliance
Test Ventilator 2 – Internal Nebulizer VT500	VTi (mL)	500	468,66	-6,27	±10%	Compliant
	VTe (mL)	500	486,30	-2,74	±10%	Compliant
	MV (L/menit)	6,6	6,32	-4,22	±10%	Compliant
	PIP (cmH_2O)	27	24,71	-8,47	±10%	Compliant
Test Ventilator 2 – External Nebulizer VT500	VTi (mL)	500	621,82	+24,36	±10%	Non-Compliant
	VTe (mL)	500	653,08	+30,62	±10%	Non-Compliant
	MV (L/menit)	13,7	8,49	-38,05	±10%	Non-Compliant
	PIP (cmH_2O)	30	29,38	-2,06	±10%	Compliant
Test Ventilator 2 – Internal Nebulizer VT600	VTi (mL)	600	555,66	-7,39	±10%	Compliant
	VTe (mL)	600	583,92	-2,68	±10%	Compliant
	MV (L/menit)	8,2	8,18	-0,29	±10%	Compliant
	PIP (cmH_2O)	31	27,96	-9,79	±10%	Compliant
Test Ventilator 2 – External Nebulizer VT600	VTi (mL)	600	683,66	+13,94	±10%	Non-Compliant
	VTe (mL)	600	730,32	+21,72	±10%	Non-Compliant
	MV (L/menit)	15,4	10,21	-33,68	±10%	Non-Compliant
	PIP (cmH_2O)	43	47,15	+9,66	±10%	Compliant

TABLE V
CONFORMITY TO TOLERANCE LIMITS OF TEST VENTILATOR 3

Test Ventilator	Parameter	Setting / Display	Measured Value (Average)	Deviation (%)	Tolerance Limit	Compliance
Test Ventilator 3 – Internal Nebulizer VT500	VTi (mL)	500	489,36	-2,13	±10%	Compliant
	VTe (mL)	500	503,9	+0,78	±10%	Compliant
	MV (L/menit)	6,3	6,57	+4,30	±10%	Compliant
	PIP (cmH_2O)	23	22,45	-2,38	±10%	Compliant
Test Ventilator 3 – External Nebulizer VT500	VTi (mL)	500	517,26	+3,45	±10%	Compliant
	VTe (mL)	500	532,28	+6,46	±10%	Compliant
	MV (L/menit)	6,6	6,97	+5,64	±10%	Compliant
	PIP (cmH_2O)	24	24,12	+0,52	±10%	Compliant
Test Ventilator 3 – Internal	VTi (mL)	600	615,22	+2,54	±10%	Compliant
	VTe (mL)	600	625,88	+4,31	±10%	Compliant

Test Ventilator	Parameter	Setting / Display	Measured Value (Average)	Deviation (%)	Tolerance Limit	Compliance
Nebulizer VT600	MV (L/menit)	8,6	8,78	+2,14	±10%	Compliant
	PIP (cmH_2O)	38	38,71	+1,86	±10%	Compliant
Test Ventilator 3 – External Nebulizer VT600	VTi (mL)	600	626,94	+4,49	±10%	Compliant
	VTe (mL)	600	633,16	+5,53	±10%	Compliant
	MV (L/menit)	8,3	8,88	+6,97	±10%	Compliant
	PIP (cmH_2O)	42	42,78	+1,86	±10%	Compliant

TABLE VI
CONFORMITY TO TOLERANCE LIMITS OF TEST VENTILATOR 4

Test Ventilator	Parameter	Setting / Display	Measured Value (Average)	Deviation (%)	Tolerance Limit	Compliance
Test Ventilator 4 – Internal Nebulizer VT500	VTi (mL)	500	497	-0,60	±10%	Compliant
	VTe (mL)	500	510,14	+2,03	±10%	Compliant
	MV (L/menit)	6,5	6,65	+2,28	±10%	Compliant
	PIP (cmH_2O)	23	22,28	-3,14	±10%	Compliant
Test Ventilator 4 – External Nebulizer VT500	VTi (mL)	500	521,42	+4,28	±10%	Compliant
	VTe (mL)	500	533,48	+6,70	±10%	Compliant
	MV (L/menit)	6,5	7,13	+9,74	±10%	Compliant
	PIP (cmH_2O)	23	22,87	-0,57	±10%	Compliant
Test Ventilator 4 – Internal Nebulizer VT600	VTi (mL)	600	608,48	+1,41	±10%	Compliant
	VTe (mL)	600	632,92	+5,49	±10%	Compliant
	MV (L/menit)	8,7	8,85	+1,72	±10%	Compliant
	PIP (cmH_2O)	38	39,92	+5,04	±10%	Compliant
Test Ventilator 4 – External Nebulizer VT600	VTi (mL)	600	631,44	+5,24	±10%	Compliant
	VTe (mL)	600	641,94	+6,99	±10%	Compliant
	MV (L/menit)	8,3	8,98	+8,17	±10%	Compliant
	PIP (cmH_2O)	42	43,75	+4,16	±10%	Compliant

IV. DISCUSSION

This study aimed to analyze differences in ventilator parameter measurements when using internal and external nebulizers based on the national calibration standard HK.02.02/D/43649/2024, using the Gas Flow Analyzer Fluke VT305 as a reference. The results demonstrate statistically significant differences in all measured parameters—VTi, VTe, MV, and PIP—across all test ventilators at both tidal volume settings (500 mL and 600 mL). Statistical analysis (Paired Sample T-Test and Wilcoxon Signed-Rank Test) consistently showed $p < 0.05$ for all parameters, indicating a strong influence of nebulizer type on ventilator performance. These findings are consistent with previous studies (e.g., Li et al., 2022), which reported that external jet nebulizers significantly affect ventilator output, particularly tidal volume.

From a performance perspective, the use of external nebulizers tends to increase measured values of VTi, VTe, MV, and PIP, especially in ventilators equipped with internal flow sensors. This trend was clearly observed in the descriptive and graphical analyses, indicating systematic measurement deviation rather than random variation. In contrast, all ventilators met calibration tolerance limits (±10%) under internal nebulizer conditions, confirming baseline measurement accuracy.

However, when external nebulizers were used, ventilators with internal flow sensors (V1 and V2) showed substantial deviations beyond tolerance limits, particularly in VTi, VTe, and MV, indicating reduced measurement reliability. Conversely, ventilators equipped with external (proximal) flow sensors (V3 and V4) maintained compliance across all conditions, demonstrating greater robustness against additional flow disturbances.

These findings highlight the critical role of flow sensor design in ventilator measurement accuracy**.** Internal sensors are more susceptible to interference from additional flow sources, such as external nebulizers, as they cannot effectively distinguish between ventilator-delivered flow and aerosol flow. In contrast, external sensors positioned closer to the patient interface (Y-piece) are better able to compensate for such disturbances. This is in line with previous research (Jayakumaran et al., 2024), which reported that external nebulizer flow can cause overestimation of tidal volume, particularly in systems using internal flow sensing.

Overall, this study emphasizes the importance of considering nebulizer type and sensor design in ventilator calibration and clinical application, as these factors can significantly impact measurement accuracy and patient safety.

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V. CONCLUSION

External nebulizers significantly alter ventilator measurements (VTi, VTe, MV, and PIP) compared to internal nebulizers ($p < 0.05$), generally increasing measured values. All ventilators meet ±10% tolerance with internal nebulizers, but only those with external flow sensors remain within limits when using external nebulizers. Ventilators with internal sensors show substantial deviations, indicating that flow sensor design critically affects measurement accuracy.

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