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Modified use of the Triflo II® incentive spirometer and its effects on feedback ball elevation, selective closure of air inlets, and inspiratory flow and pressure: A bench study

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ABSTRACT

Background: The Triflo II® incentive spirometer (TF) is widely prescribed for lung expansion exercise, but its high inspiratory flow rate and short inspiratory time, leading to increased effort and lower tidal volume, are recognized limitations. Modifying its use may improve its effectiveness.

Objectives: As an initial step before human studies, a bench test was conducted to evaluate inspiratory flow and pressure responses under controlled conditions.

Materials and methods: A bench test was conducted under two conditions: (1) three target ball elevation levels were marked on the wall of each TF chamber, and airflow rate and pressure responses were evaluated during simulated airflow at each target level; and (2) selective closure of air inlets was performed by closing one or two of the three air inlet holes of the TF device, and the corresponding airflow rate and pressure responses were evaluated.

Results: No significant differences were observed in the 900 mL/sec chamber. In the 600 mL/sec chamber, the fourth quarter had a significantly higher flow rate (652±6 mL/sec) than the second (605±5 mL/sec, $p<0.001$) and third (601±8 mL/sec, $p<0.001$). Similarly, in the 1200 mL/sec chamber, the fourth quarter (994±13 mL/sec) had a significantly higher flow rate than the second (917±8 mL/sec, $p<0.001$) and third (914±7 mL/sec, $p<0.001$). Closing the second and third air inlet holes while lifting the 600 mL/sec ball produced the lowest inspiratory flow rate (432±15 mL/sec) and pressure (-4.0±0.3 cm H_2O) among conditions.

Conclusion: Feedback ball elevation influenced inspiratory flow and pressure in the 600 and 1200 mL/sec chambers, whereas no significant differences were observed in the 900 mL/sec chamber. Selective closure of air inlets, particularly closure of two inlets, markedly reduced inspiratory flow and pressure. Further in vivo studies in human subjects are warranted to validate these findings.

Introduction

Incentive spirometry is performed using a device that provides feedback when the user inhales at a preset flow rate or volume and maintains lung inflation for at least five seconds. It is commonly used in both preoperative and postoperative settings to help prevent atelectasis, improve pulmonary function, and reduce postoperative complications.[1]

Incentive spirometry devices are typically categorized into volume-oriented incentive spirometers (VIS), such as Coach® and Voldyne®, and flow-oriented incentive spirometers (FIS), which provide feedback based on inspiratory flow rate, such as Triflo®, Clini Flow®, and Respirex®.[2] Another type of spirometer is the water pressure-threshold spirometer, which provides audio feedback through bubble sounds, such as BreatheMAX®.[3] Among these devices, Triflo II® (TF) is one of the most popular and widely prescribed in clinical practice. It is a FIS and consists of three chambers, each containing a lightweight ball that rises in response to inspiratory effort, providing visual feedback on airflow performance. The three balls correspond to flow rates of 600 mL/sec, 900 mL/sec, and 1,200 mL/sec.

Although TF is widely used and remains one of the most prescribed incentive spirometers, several limitations have been reported in previous studies. Compared with deep breathing and VIS, TF has been associated with reduced tidal volume, shorter inspiratory time, increased breathing frequency, greater sternocleidomastoid muscle activation, and lower diaphragm excursion.[3-6] In addition, TF and other flow-oriented incentive spirometers, such as Respiron®, have been reported to reduce abdominal motion and thoracoabdominal synchrony, potentially limiting inflation of the lower lung regions.[5,7] The rapid breathing pattern and higher inspiratory pressure generated during TF use may also increase the sensation of effort, which could make it less suitable for some patients.[3]

Inspiratory flow rate plays a crucial role in airflow distribution within the lungs. A slow inspiratory flow rate of 210±90 mL/sec has been shown to enhance air distribution to the dependent lung regions, where atelectasis is most likely to occur [8]. Additionally, a flow rate of 280±100 mL/sec using a water pressure-threshold spirometer (BreatheMAX® with a -5 cm H_2O threshold) and 430 ± 200 mL/sec during deep breathing have been associated with larger tidal volumes and lower inspiratory effort compared to TF (960±100 mL/sec).[3] Since the minimum inspiratory flow rate required to raise at least one ball in TF is 600 mL/sec (as specified by the manufacturer), it requires a relatively high inspiratory effort, which may result in shorter inspiratory times, reduced tidal volume, and increased reliance on upper chest movement. This could lead to greater airflow distribution in the apical region rather than the lower lung, which is less effective for preventing atelectasis and promoting optimal lung expansion.[8] Therefore, optimizing the operating characteristics of the Triflo II® may help overcome some of its reported limitations.

Although a recent bench study investigated the effect of closing air entry holes in a three-chamber flow-dependent incentive spirometer, the specific device model was not reported, and inspiratory flow rate was not evaluated.[9] Accordingly, the effects of selective air inlet closure on both inspiratory flow and inspiratory pressure in a Triflo II® remain unclear. We hypothesized

that lower TF feedback ball elevation levels (marking four levels on the wall of each TF chamber and raising the feedback ball to a specific target level) and selective closure of air inlets (closing one or two of the three air inlet holes of the TF device) would reduce inspiratory flow rate and inspiratory pressure compared with the maximum elevation level within the same chamber. Because the study involved modifications to the TF device's airflow mechanics, we selected a bench test as an initial step to evaluate inspiratory flow and pressure responses under controlled conditions before future studies in humans.

Therefore, this study aimed to investigate inspiratory flow and pressure responses at different TF feedback ball elevation levels and during selective closure of the TF device's air inlets.

Materials and methods

Experiment I: Inspiratory flow and pressure response at different TF feedback ball elevation levels

Triflo II® device and marking levels

This study utilized the Triflo II® (Hudson RCI, USA), which contains three flow feedback chambers, each housing a ball and featuring an opening at the bottom (Figure 1). In this study, the chambers were divided into four equal quarters based on the height of the feedback ball, with each quarter corresponding to one ball height (2.7cm per quarter) and marked using a permanent marker on both sides (Figure 1).

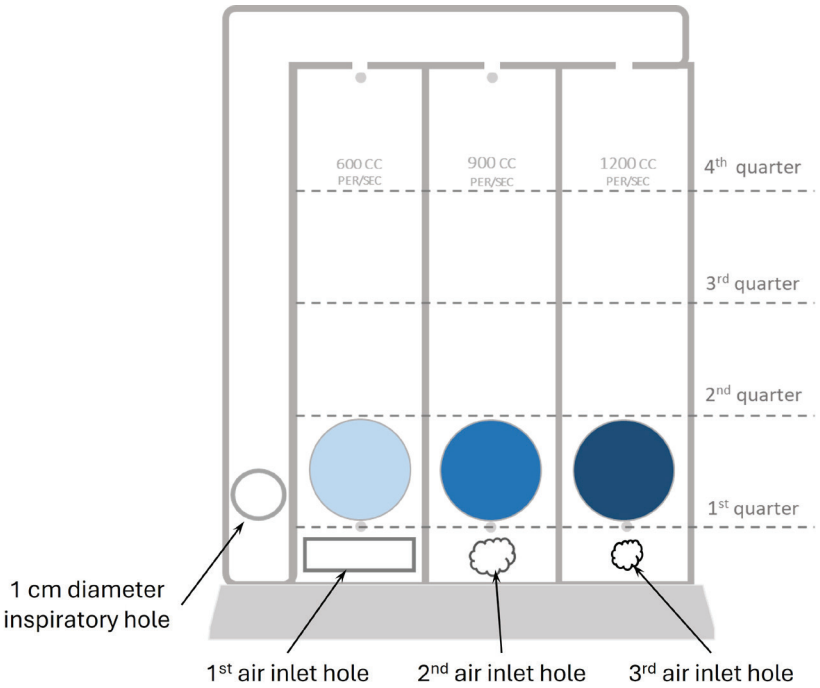


Figure 1. Schematic overview of Triflo II® device and marking of quarters.

Bench test setup for inspiratory pressure-flow measurement

The TF device was connected to an airflow transducer (SS11LA, Biopac MP36 system) and a pressure transducer (SS19L, Biopac MP36 system) through a one-way valve T-piece and a corrugated tube. A bacterial filter was placed between the 3-L syringe and airflow transducer to ensure diffuse airflow. Inspiratory flow and pressure were generated by pulling the plunger of the 3-L syringe, simulating inhalation (Figure 2). Before each test, flow and pressure were calibrated according to the manufacturer, and all connections were checked to ensure no air leaks.

Procedure and measurement

Inspiratory flow and pressure were applied using the syringe until each ball reached specific height levels within the chambers. The following conditions were tested:

- First ball (600 mL/sec chamber): Lifted to the second, third, and fourth quarters.
- Second ball (900 mL/sec chamber): Lifted to the second, third, and fourth quarters.
- Third ball (1,200 mL/sec chamber): Lifted to the second, third, and fourth quarters (Figure 3).

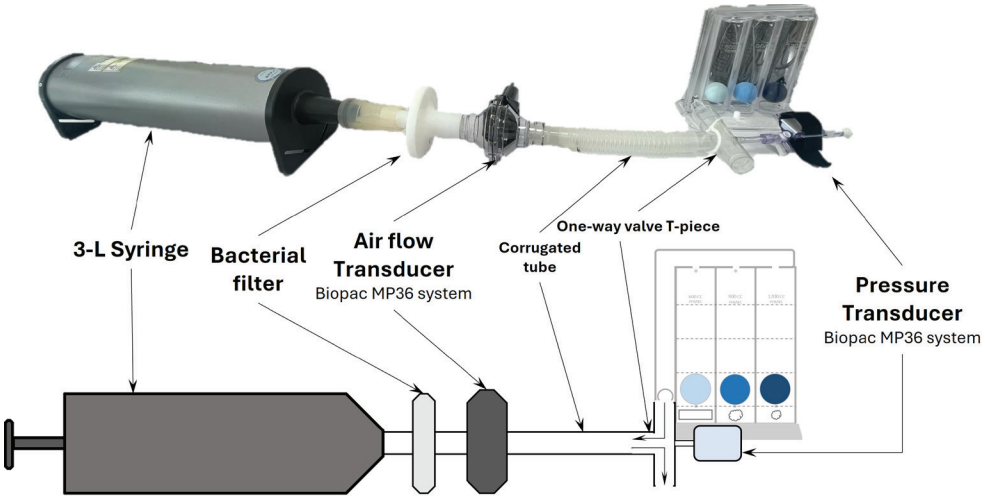


Figure 2. The bench test setup.

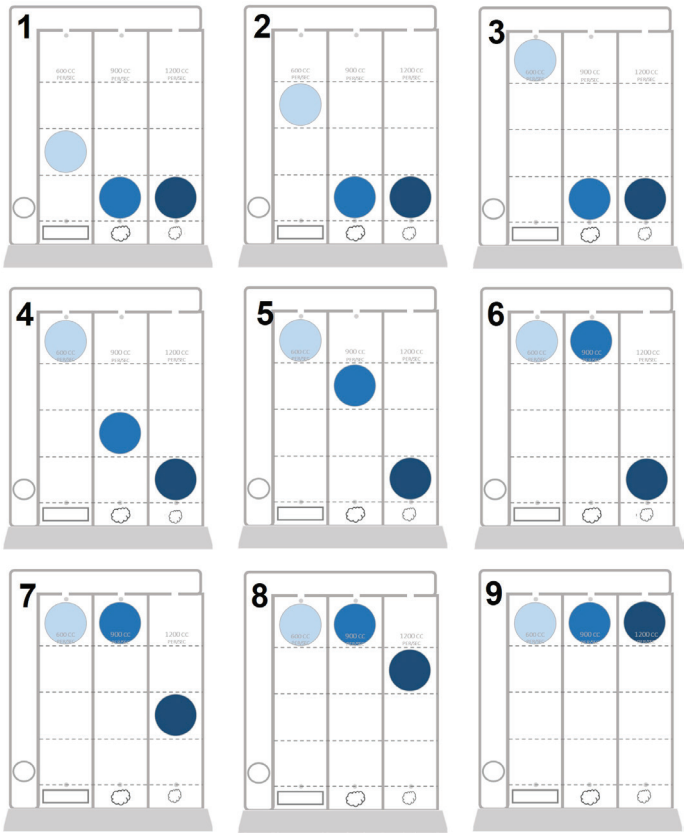


Figure 3. Different levels of TF balls lifting during experiment I.

Each condition was performed 10 times, and trials were considered consistent if the ball remained stable at the target level for a 2-sec segment in 7 out of 10 attempts. Data were recorded using the Biopac MP36 software on a computer with a sampling rate of 500 Hz. A mean 2-sec segment of flow and pressure at the targeted ball elevation level was extracted from the Biopac MP36 recordings for analysis. All bench testing was performed by a single researcher.

Experiment II: Inspiratory flow and pressure response in TF with selective closure of air inlets

bench test setup for inspiratory pressure-flow measurement

The setup for this experiment was the same as in Experiment I (Figure 2).

Procedure and measurement

Inspiratory flow and pressure were applied using the syringe until each ball reached its maximum achievable level within the chamber(s). Different configurations were tested by selectively blocking the air inlet of one or more chambers using adhesive tape, and the corresponding flow-pressure response was recorded (Figure 4). Each condition was performed 10 times. A trial was considered valid if the ball remained stable at its maximum achievable elevation level for at least a 2-second segment in 7 out of 10 attempts. Data were recorded using the Biopac MP36 software on a computer with a sampling rate of 500 Hz. A mean 2-second segment of flow and pressure at the maximum achievable ball elevation level in each chamber was extracted from the Biopac MP36 recordings for analysis. All bench testing was performed by a single researcher.

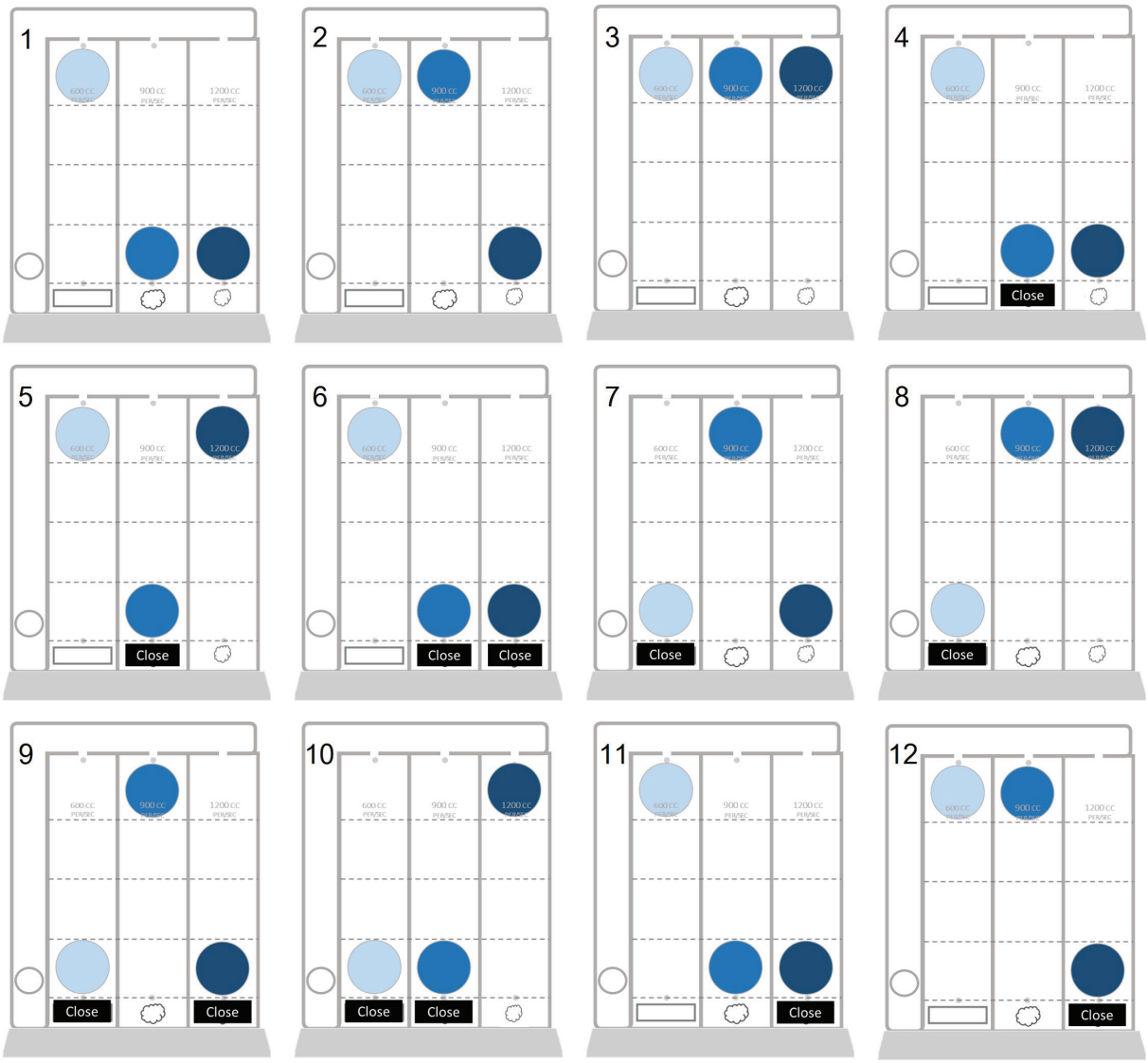


Figure 4. Selective closure of air inlet holes during experiment II.

Data analysis

Descriptive statistics, including the mean and standard deviation, were used to summarize the data. The Shapiro-Wilk test was conducted to assess the normality of data distribution. Differences between conditions in both Experiment I and Experiment II were analyzed using a one-way ANOVA, followed by a post hoc Bonferroni test. A $p<0.05$ was considered statistically significant. Data analysis was performed using SPSS version 29.0.2.0 (20).

Results

Experiment I: Inspiratory Flow and Pressure Response at Different TF Feedback Ball Elevation Levels

The inspiratory flow rate response to different levels of TF feedback ball elevation and pairwise comparisons using the Bonferroni post hoc test are shown in Figure 5. Inspiratory flow rate differed significantly across conditions (F=2111.798, $p<0.001$). The highest value was lifting the 1,200 mL/sec ball to the fourth quarter (994±13 mL/sec), and the lowest was lifting the 600 mL/sec ball to the third quarter (601±8 mL/sec). Post hoc analysis revealed five distinct groups. Lifting the 600 mL/sec ball to the second and third quarters did not differ significantly (605±5 and 601±8 mL/sec, respectively) but was significantly lower than all other conditions. The 600 mL/sec ball lifted to the fourth quarter (652±6 mL/sec) was significantly different from all remaining conditions. The 900 mL/sec ball lifted to the second, third, and fourth quarters (854±11, 854±6, and 855±10 mL/sec, respectively) did not differ significantly among these conditions. Similarly, the 1200 mL/sec ball lifted to the second and third quarters (917±8 and 914±7 mL/sec, respectively) did not differ significantly. The 1200 mL/sec ball lifted to the fourth quarter (994±13 mL/sec) produced the highest inspiratory flow rate and was significantly different from all other conditions.

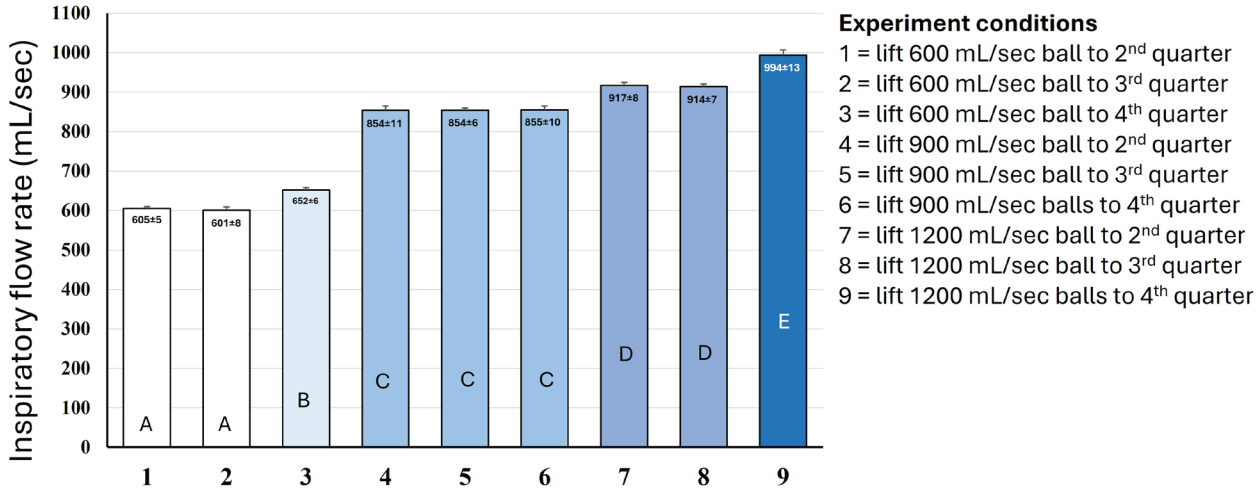


Figure 5. Inspiratory flow rate at different TF feedback ball elevation levels. Data are presented as means±SD. Bars sharing at least one uppercase letter indicate no statistically significant difference; bars with no letters in common indicate a statistically significant difference at $p<0.05$, determined by one-way ANOVA with a Bonferroni post hoc test.

The inspiratory pressure response to different levels of TF feedback ball elevation and pairwise comparisons using the Bonferroni post hoc test are shown in Figure 6. Inspiratory pressure differed significantly across conditions (F=1092.295, $p<0.001$). The highest pressure was observed when lifting the 1200 mL/sec ball to the fourth quarter (-17.7±0.6 cm H_2O) and the lowest when lifting the 600 mL/sec ball to the second quarter (-6.4±0.2 cm H_2O). Post hoc analysis revealed five distinct groups. The 600 mL/sec ball lifted to the second and third quarters did not differ significantly from each other (-6.4±0.2 and -6.5±0.1 cm H_2O, respectively) but was significantly lower in magnitude than all other conditions. The 600 mL/sec ball lifted to the fourth quarter (-8.1±0.3 cm H_2O) was significantly different from all remaining conditions. The 900 mL/sec ball lifted to the second, third, and fourth quarters (-12.7±0.3, -12.6±0.2, and -13.0±0.4 cm H_2O, respectively) did not differ significantly among themselves. Similarly, the 1200 mL/sec ball lifted to the second and third quarters (-15.0±0.2 and -14.8±0.2 cm H_2O, respectively) did not differ significantly. The 1,200 mL/sec ball lifted to the fourth quarter (-17.7±0.6 cm H_2O) produced the greatest inspiratory pressure and was significantly different from all other conditions.

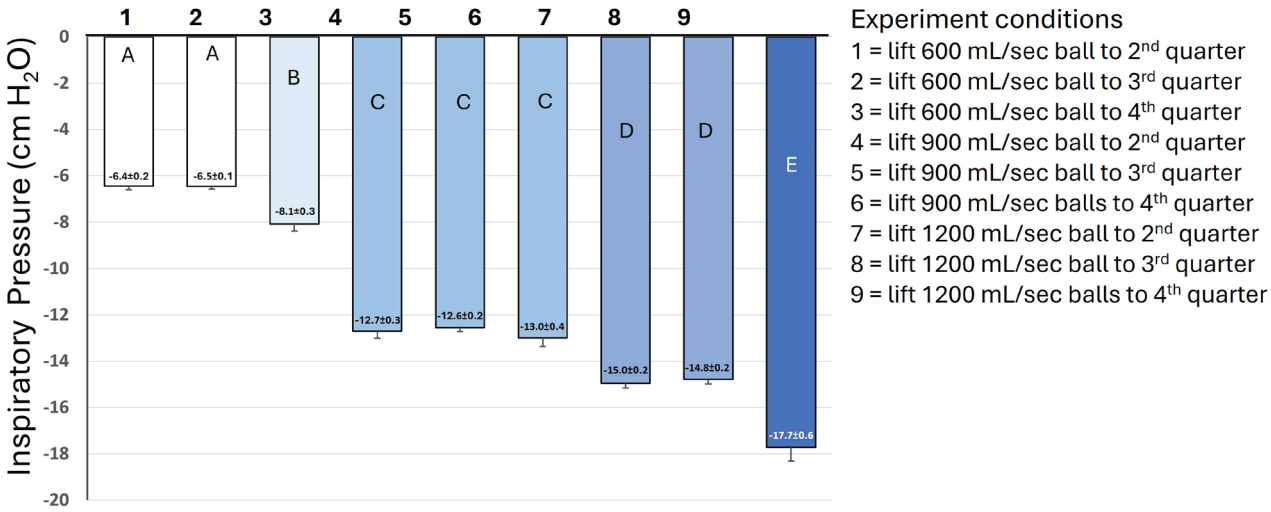


Figure 6. Inspiratory pressure response at different TF feedback ball elevation levels. Data are presented as means±SD. Bars sharing at least one uppercase letter indicate no statistically significant difference; bars with no letters in common indicate a statistically significant difference at $p<0.05$, determined by one-way ANOVA with a Bonferroni post hoc test.

Experiment II: Inspiratory flow and pressure response in TF with selective closure of air inlets

The inspiratory flow rate response to TF feedback balls with selective closure of air inlets and pairwise comparisons using the Bonferroni post hoc test are shown in Figure 7. Inspiratory flow rate differed significantly across conditions (F=236.008, $p<0.001$). The highest flow rate was observed when closing the second inlet while lifting the 1,200 mL/sec ball (1066±60 mL/sec), and the lowest when closing the second and third inlets while lifting the 600 mL/sec ball (432±15 mL/sec). Post hoc analysis revealed five distinct groups. Conditions involving closure of two inlets (conditions 6, 9, and 10: 432±15, 473±8, and 446±8 mL/sec, respectively) produced the lowest flow rates and did not differ significantly from one another. Conditions using the 600 mL/sec ball lifting with all inlets open, closure of the second inlet, and closure of the third inlet (conditions 1, 4, and 11: 652±6, 593±17, and 606±7 mL/sec, respectively) did not differ significantly from one another. Closing the first inlet while lifting the 900 mL/sec ball (condition 7: 749±23 mL/sec) formed a distinct group and differed significantly from all other conditions. Opening all inlets with the 900 mL/sec ball lifting and closing the third inlet with the 900 mL/sec ball lifting (conditions 2 and 12: 855±10 and 847±15 mL/sec, respectively) did not differ significantly from each other. Finally, opening all inlets with the 1,200 mL/sec ball lifting, closure of the second inlet with the 1200 mL/sec ball lifting, and closure of the first inlet with the 1200 mL/sec ball lifting (conditions 3, 5, and 8: 994±13, 1066±60, and 1013±114 mL/sec, respectively) produced the highest flow rates with no significant differences among themselves.

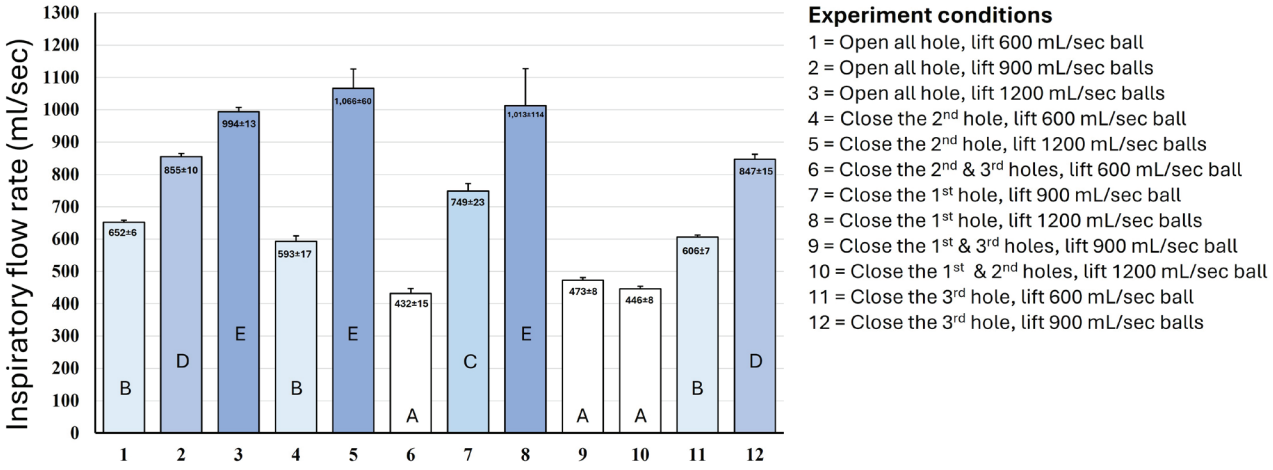


Figure 7. Inspiratory flow response in TF with selective closure of air inlets. Data are presented as means±SD. Bars sharing at least one uppercase letter indicate no statistically significant difference; bars with no letters in common indicate a statistically significant difference at $p<0.05$, determined by one-way ANOVA with a Bonferroni post hoc test.

The inspiratory pressure response to TF feedback balls with selective closure of air inlets and pairwise comparisons using the Bonferroni post hoc test are shown in Figure 8. Inspiratory pressure differed significantly across conditions ($F=534.997$, $p<0.001$). The greatest inspiratory pressure magnitude was observed when all inlets were open while lifting the 1200 mL/sec ball (-17.7±0.6 cm H_2O), and the lowest when closing the second and third inlets while lifting the 600 mL/sec ball (-4.0±0.3 cm H_2O). Closing the second and third inlets while lifting the 600 mL/sec ball (condition 6: -4.0±0.3 cm H_2O) produced the lowest inspiratory pressure magnitude and differed significantly from all other conditions. Closure of the second inlet with the 600 mL/sec ball, closure of the first and third inlets with the 900 mL/sec ball lifting, and closure of the third inlet with the 600 mL/sec ball lifting (conditions 4, 9, and 11: -5.3±0.3, -5.5±0.1, and -5.1±0.1 cm H_2O, respectively) did not differ significantly from one another. The inspiratory pressure in condition 10 (-6.2±0.2 cm H_2O, closure of the first and second inlets with the 1200 mL/sec ball lifting) did not differ significantly from that in condition 9 ($p=0.439$), but differed significantly from those in conditions 4 ($p=0.021$) and 11 ($p=0.002$). Opening all inlets with the 600 mL/sec ball, closing the first inlet with the 900 mL/sec ball lifting, and closing the third inlet with the 900 mL/sec ball lifting (conditions 1, 7, and 12: -8.1±0.3, -7.9±0.4, and -8.7±0.1 cm H_2O, respectively) showed no significant differences among themselves. Closing the second inlet with the 1200 mL/sec ball lifting and closing the first inlet with the 1200 mL/sec ball lifting (conditions 5 and 8: -11.3±0.5 and -11.0±1.1 cm H_2O, respectively) did not differ significantly from each other. Opening all inlets with the 900 mL/sec ball lifting (condition 2: -13.0±0.4 cm H_2O) formed a distinct group and was significantly different from all other conditions. Finally, opening all inlets with the 1200 mL/sec ball lifting (condition 3: -17.7±0.6 cm H_2O) produced the greatest inspiratory pressure magnitude and differed significantly from all other conditions.

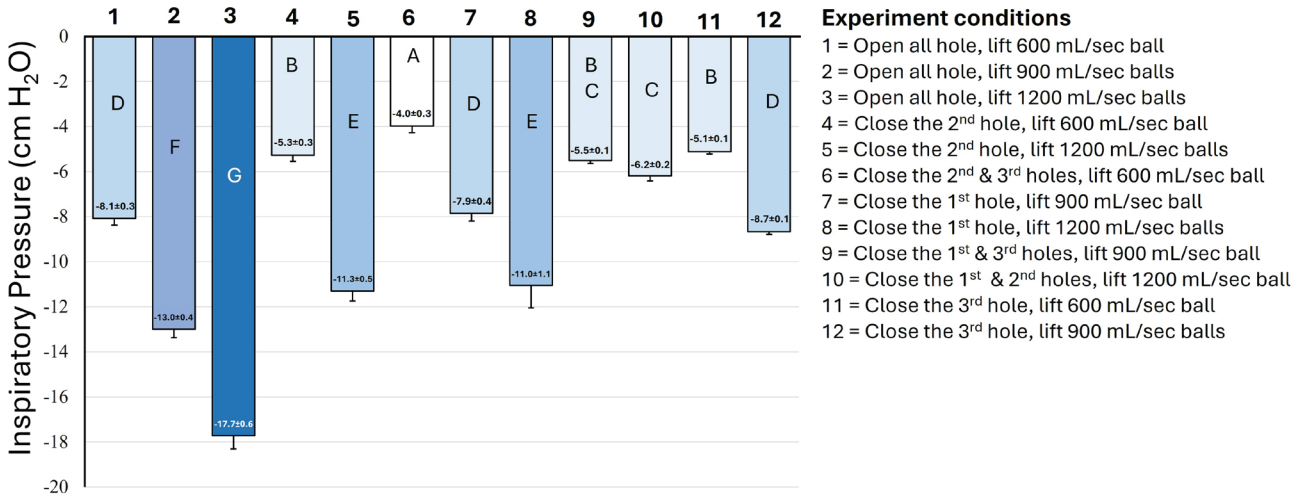


Figure 8. Inspiratory pressure response in TF with selective closure of air inlets. Data are presented as means±SD. Bars sharing at least one uppercase letter indicate no statistically significant difference; bars with no letters in common indicate a statistically significant difference at $p<0.05$, determined by one-way ANOVA with a Bonferroni post hoc test.

Discussion

This study investigated a modified use of the TF breathing device by examining inspiratory flow rate and pressure responses to TF feedback balls at different elevation levels (four quarters in each chamber), as well as the impact of selective air-entry closure on inspiratory flow rate and pressure in a bench test setting. Our findings indicate that differences between quarter levels within the same chamber were not clinically significant for flow rate and pressure. Additionally, closing the second and third air entry holes while lifting the 600 mL/sec ball required the lowest inspiratory flow rate and pressure.

Inspiratory flow rate ranged from 601 mL/sec to 994 mL/sec across elevation levels. At maximum elevation (fourth quarter), the flow rate was 652±6 mL/sec for the 600 mL/sec chamber, 855±10 mL/sec for the 900 mL/sec chamber, and 994±13 mL/sec for the 1200 mL/sec chamber. Based on these rounded mean values, the deviations from the manufacturer's specified flow rates were +8.67% (+52 mL/sec), -5.00% (-45 mL/sec), and -17.17% (-206 mL/sec), respectively. The bench test carried out by Mang *et al*. reported deviations of 25-50% above the manufacturer-declared flow rates in flow-oriented incentive spirometers, including Respi-Flo III®, Mediflom®, TF, Respirex®.[10] Although our findings also indicate deviations, they do not fully align with Mang et al.'s results.

We expected airflow to be lower at the lower quarter levels compared to the maximum elevation (fourth quarter) within the same chamber. No significant differences were observed in the 900 mL/sec chamber. However, statistically significant differences were observed in the 600 mL/sec chamber, where the fourth quarter (652±6 mL/sec) was significantly higher than the second (605±5 mL/sec) and third quarters (601±8 mL/sec). Similarly, in the 1200 mL/sec chamber, the fourth quarter (994±13 mL/sec) was significantly higher than the second (917±8 mL/sec) and third quarters (914±7 mL/sec). Despite these statistical differences, the absolute differences in airflow within the same chamber were relatively small (approximately 47-81 mL/sec). Previous research has reported considerable variability in inspiratory flow during deep breathing, with a mean inspiratory flow rate of 430±200 mL/sec.[3] Therefore, the airflow variation observed between different ball elevation levels within the same chamber appears relatively small compared with the range of inspiratory flows reported during breathing exercises. These findings suggest that the same chamber can provide a relatively consistent airflow range despite differences in ball elevation. During clinical use, patients may not need to raise the ball to the highest position within the targeted chamber, as achieving ball elevation within that chamber may be sufficient to generate the intended airflow range.

A possible explanation for the similar airflow within the same chamber is the threshold load effect. Air enters through the bottom inlet hole of each chamber, moves upward through the top hole, and lifts the ball positioned above the bottom inlet. Each ball requires a minimum negative inspiratory pressure to overcome its threshold and initiate airflow. Once the threshold is reached in the 600 mL/sec chamber, any further increase in inspiratory effort or negative pressure meets the minimum requirement to lift the 900 mL/sec ball, allowing it to rise. The same process occurs sequentially, enabling the 1200 mL/sec ball to lift as negative inspiratory pressure continues to increase. This mechanism explains why airflow remains similar within the same chamber despite different ball elevations (Figure 9A).

In Experiment II, which examined the effect of selectively closing air inlets on inspiratory flow rate and pressure response, we found that closing more air inlets decreased both inspiratory flow rate and pressure. This can be explained by the threshold load effect, where each ball requires a minimum inspiratory effort to be lifted. When all inlet holes are open, airflow is distributed across all chambers, requiring a higher total inspiratory effort. However, when one or two entry holes are closed, airflow is restricted to the remaining open chamber, meaning only one ball is lifted, thereby reducing the total inspiratory demand (see Figure 9B-9D). Additionally, in this study, we measured the minimum inspiratory flow and pressure required to lift each ball, rather than maximum values, which may further explain why increasing air inlet closure reduced both flow rate and pressure more.

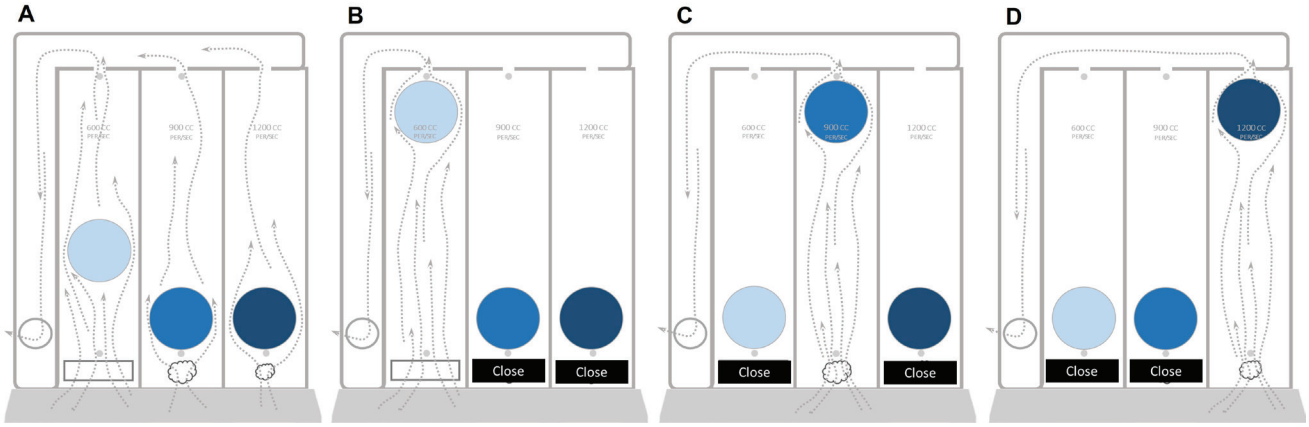


Figure 9. Schematic overview of airflow direction through the device.

From a physiological perspective, a slower inspiratory flow rate allows for a greater time constant, promoting more homogeneous air distribution throughout the lungs.[11] Conversely, higher inspiratory flow rates are associated with increased work of breathing.[12] The American Association for Respiratory Care (AARC) clinical practice (2011) guidelines recommend slow, deep inspiration during incentive spirometry to optimize lung expansion and minimize respiratory effort.[1]

Ubolsakka-Jones et al. reported that deep breathing, performed at an inspiratory flow rate of 430±200 mL/sec and an inspiratory pressure of -1.3±0.6 cm H_2O, and water pressure-threshold spirometry, performed at an inspiratory flow rate of 280±100 mL/sec and an inspiratory pressure of -5.5±1.2 cm H_2O, both produced significantly larger tidal volumes than traditional TF performed by raising two balls, which required an inspiratory flow rate of 960±100 mL/sec and an inspiratory pressure of -12.8±3.6 cm H_2O, in healthy older adults. Both deep breathing and water pressure-threshold spirometry were rated as requiring mild breathing effort based on the modified Borg rating of perceived breathless scale.[3] In our study, closing the second and third air-inlet holes while raising the 600 mL/sec ball resulted in an inspiratory flow rate of 432±15 mL/sec and an inspiratory pressure of -4.0±0.3 cm H_2O. The inspiratory flow rate was similar to that reported for deep breathing, while the inspiratory pressure fell between those reported for deep breathing and water pressure-threshold spirometry by Ubolsakka-Jones *et al.*[3] Therefore, our findings suggest that this modified TF configuration may provide flow and pressure characteristics comparable to breathing techniques associated with larger tidal volumes and mild breathing effort. Although tidal volume and breathing effort were not directly measured in our bench study, the similar flow and pressure characteristics provide a basis for further investigation of whether this configuration can facilitate larger tidal volumes with low perceived breathing effort.

Inspiratory flow rate plays a crucial role in medication deposition when using inhalers, as different inhaler devices require specific flow rates for optimal drug delivery.[13] Our findings on flow rate variations while lifting the 600 mL/sec, 900 mL/sec, and 1,200 mL/sec balls of the TF under selective closure of air inlets showed that the inspiratory flow rate ranged from 432 mL/sec to 1,066 mL/sec. Because the TF provides visual feedback of inspiratory flow, these measured flow ranges and corresponding inlet configurations may serve as a reference for future investigations into its potential application for inhaler training. Further studies are needed to determine whether TF can assist users in achieving the inspiratory flow requirements of specific inhaler devices.

Our findings showed that inspiratory pressure ranged from -4.0 cm H_2O to -17.7 cm H_2O while lifting the 600 mL/sec, 900 mL/sec, and 1,200 mL/sec balls of the TF with selective air-entry hole closures. This technique and its corresponding pressure levels may be applicable for initial inspiratory muscle training, allowing adjustments based on individual subject needs.

Limitations

This study has some limitations. Because this was a preliminary bench test conducted in a laboratory

setting, interpret the findings with caution, as results may differ when applied to healthy individuals and patients due to factors such as dead space, mouthpiece seal, lung mechanics, and fatigue. Lung volume is the clinically relevant outcome when incentive spirometry is used to promote lung expansion. However, the present study was designed as a bench study to evaluate the mechanical characteristics of the Triflo II® device rather than physiological responses in humans. Therefore, lung expansion and inspiratory lung volume could not be assessed using the present experimental model.

Future study

Further studies in healthy individuals and patients with different clinical conditions are needed to determine whether the mechanical characteristics observed in this study translate into physiological and clinical outcomes. In our study, only one Triflo II® device was evaluated; therefore, potential variability between devices or manufacturing batches was not assessed. Additionally, the study was conducted using the Triflo II® manufactured by Hudson RCI, and the results may not be directly applicable to other three-chamber flow IS models such as Respiron®, Tri Ball®, and Paramount 3 Ball®.

Practical implications

Because this study was conducted solely in a laboratory setting, the findings have limited applicability to clinical practice.

Conclusion

This study explored the modified use of the TF breathing device, analyzing inspiratory flow rate and pressure response at different ball elevation levels and under selective air entry closure in a bench test setting. Differences between quarter levels within the same chamber were unlikely to be clinically meaningful based on the magnitude of airflow and pressure variation observed. However, closing the second and third air inlet holes while lifting the 600 mL/sec ball resulted in the lowest inspiratory flow rate and pressure, which may facilitate slow, deep inspiration with reduced effort when using TF. Further research is needed to determine whether these bench-test findings are applicable during actual device use in healthy individuals and patients with different clinical conditions.

Ethical approval

Ethical approval was not applicable because this laboratory bench study did not involve human participants.

Declaration of generative AI and AI-assisted technologies

During the preparation of this manuscript, the authors used ChatGPT (GPT-6.1 Sol Light) solely for English language editing and grammar correction. The tool was not used to generate the research concept, design the study, or analyze the data. The authors reviewed and edited the output and take full responsibility for the manuscript's content.

Conflict of interest

There are no conflicts of interest in this study.

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CRediT authorship contribution statement

Vatcharaporn Khaweephab-Phimphasak: conceptualization, methodology, formal analysis, investigation, data curation, writing-review and editing, visualization; **Aung Aung Nwe**: writing-original draft, writing-review and editing; **Buranat Audsavachula-manee**: methodology, investigation; **Wanpen Poomsuk-charoen**: conceptualization; **Chatchai Phimphasak**: conceptualization, methodology, validation, formal analysis, data curation, writing-review and editing, visualization, supervision, project administration, funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Supplementary data

Inspiratory flow rate results of the normality test for Experiment I.

Conditions		**Inspiratory flow rate** (mL/sec)			**Shapiro-Wilk test** (*p* value)
		mean	SD	95% CI	
1	Lift 600 mL/sec ball to 2nd quarter	605	5	601 to 610	0.739
2	Lift 600 mL/sec ball to 3rd quarter	601	8	594 to 608	0.815
3	Lift 600 mL/sec ball to 4th quarter	652	6	646 to 658	0.898
4	Lift 900 mL/sec ball to 2nd quarter	854	11	844 to 864	0.332
5	Lift 900 mL/sec ball to 3rd quarter	854	6	849 to 860	0.661
6	Lift 900 mL/sec ball to 4th quarter	855	10	846 to 864	0.665
7	Lift 1,200 mL/sec ball to 2nd quarter	917	8	910 to 924	0.304
8	Lift 1,200 mL/sec ball to 3rd quarter	914	7	907 to 920	0.261
9	Lift 1,200 mL/sec ball to 4th quarter	994	13	982 to 1,006	0.903

Pairwise comparison of inspiratory flow rate for Experiment I.

Conditions		1	2	3	4	5	6	7	8
		600/2nd 605±5 mL/sec	600/3rd 601±8 mL/sec	600/4th 652±6 mL/sec	900/2nd 854±11 mL/sec	900/3rd 854±6 mL/sec	900/4th 855±10 mL/sec	1,200/2nd 917±8 mL/sec	1,200/3rd 914±7 mL/sec
2	600/3rd 601±8 mL/sec	Δ -5 [-20, 11] *p*=1.000							
3	600/4th 652±6 mL/sec	Δ 47 [31, 62] *p*<0.001	Δ 51 [36, 67] *p*<0.001						
4	900/2nd 854±11 mL/sec	Δ 249 [233, 264] *p*<0.001	Δ 253 [238, 269] *p*<0.001	Δ 202 [186, 217] *p*<0.001					
5	900/3rd 854±6 mL/sec	Δ 249 [234, 264] *p*<0.001	Δ 253 [238, 269] *p*<0.001	Δ 202 [187, 217] *p*<0.001	Δ 0 [-15, 15] *p*=1.000				
6	900/4th 855±10 mL/sec	Δ 249 [234, 265] *p*<0.001	Δ 254 [239, 269] *p*<0.001	Δ 203 [187, 218] *p*<0.001	Δ 1 [-15, 15] *p*=1.000	Δ 1 [-15, 16] *p*=1.000			
7	1,200/2nd 917±8 mL/sec	Δ 312 [296, 327] *p*<0.001	Δ 316 [301, 331] *p*<0.001	Δ 264 [250, 280] *p*<0.001	Δ 63 [48, 78] *p*<0.001	Δ 63 [47, 78] *p*<0.001	Δ 62 [47, 77] *p*<0.001		
8	1,200/3rd 914±7 mL/sec	Δ 308 [293, 323] *p*<0.001	Δ 313 [297, 328] *p*<0.001	Δ 261 [246, 277] *p*<0.001	Δ 59 [44, 75] *p*<0.001	Δ 59 [44, 74] *p*<0.001	Δ 59 [43, 74] *p*<0.001	Δ -4 [-19, 12] *p*=1.000	
9	1,200/4th 994±13 mL/sec	Δ 389 [374, 404] *p*<0.001	Δ 393 [378, 409] *p*<0.001	Δ 342 [327, 357] *p*<0.001	Δ 140 [125, 155] *p*<0.001	Δ 140 [125, 155] *p*<0.001	Δ 139 [124, 155] *p*<0.001	Δ 77 [62, 93] *p*<0.001	Δ 81 [66, 96] *p*<0.001

Note: Δ: mean difference; 95% CI is presented in square brackets.

Inspiratory pressure results of the normality test for Experiment I.

	Conditions	Inspiratory pressure (cm H_2O)			Shapiro-Wilk test (*p* value)
		mean	SD	95% CI	
1	Lift 600 mL/sec ball to 2nd quarter	-6.4	0.2	-6.6 to -6.3	0.269
2	Lift 600 mL/sec ball to 3rd quarter	-6.5	0.1	-6.6 to -6.3	0.266
3	Lift 600 mL/sec ball to 4th quarter	-8.1	0.3	-8.4 to -7.8	0.966
4	Lift 900 mL/sec ball to 2nd quarter	-12.7	0.3	-12.9 to -12.5	0.743
5	Lift 900 mL/sec ball to 3rd quarter	-12.6	0.2	-12.7 to -12.4	0.170
6	Lift 900 mL/sec ball to 4th quarter	-13.0	0.4	-13.4 to -12.6	0.158
7	Lift 1,200 mL/sec ball to 2nd quarter	-15.0	0.2	-15.2 to -14.7	0.344
8	Lift 1,200 mL/sec ball to 3rd quarter	-14.8	0.2	-15.0 to -14.6	0.126
9	Lift 1,200 mL/sec ball to 4th quarter	-17.7	0.6	-18.3 to -17.1	0.372

Pairwise comparison of inspiratory pressure for Experiment I.

Conditions		1	2	3	4	5	6	7	8
		600/2nd -6.4±0.2 cm H_2O	600/3rd -6.5±0.1 cm H_2O	600/4th -8.1±0.3 cm H_2O	900/2nd -12.7±0.3 cm H_2O	900/3rd -12.6±0.2 cm H_2O	900/4th -13.0±0.4 cm H_2O	1,200/2nd -15.0±0.2 cm H_2O	1,200/3rd -14.8±0.2 cm H_2O
2	600/3rd -6.5±0.1 cm H_2O	Δ 0.0 [-0.6, 0.6] *p*=1.000							
3	600/4th -8.1±0.3 cm H_2O	Δ -1.6 [-2.2, -1.0] *p*<0.001	Δ -1.6 [-2.2, -1.0] *p*<0.001						
4	900/2nd -12.7±0.3 cm H_2O	Δ -6.3 [-6.8, -5.7] *p*<0.001	Δ -6.3 [-6.8, -5.7] *p*<0.001	Δ -4.6 [-5.2, -4.1] *p*<0.001					
5	900/3rd -12.6±0.2 cm H_2O	Δ -6.1 [-6.7, -5.5] *p*<0.001	Δ -6.1 [-6.7, -5.5] *p*<0.001	Δ -4.5 [-5.1, -3.9] *p*<0.001	Δ 0.1 [-0.4, 0.7] *p*=1.000				
6	900/4th -13.0±0.4 cm H_2O	Δ -6.5 [-7.1, -6.0] *p*<0.001	Δ -6.5 [-7.1, -6.0] *p*<0.001	Δ -4.9 [-5.5, -4.3] *p*<0.001	Δ -0.3 [-0.9, 0.3] *p*=1.000	Δ -0.4 [-1.0, 0.1] *p*=0.544			
7	1,200/2nd -15.0±0.2 cm H_2O	Δ -8.5 [-9.1, -7.9] *p*<0.001	Δ -8.5 [-9.1, -7.9] *p*<0.001	Δ -6.9 [-7.5, -6.3] *p*<0.001	Δ -2.3 [-2.8, -1.7] *p*<0.001	Δ -2.4 [-3.0, -1.8] *p*<0.001	Δ -2.0 [-2.5, -1.4] *p*<0.001		
8	1,200/3rd -14.8±0.2 cm H_2O	Δ -8.3 [-8.9, -7.8] *p*<0.001	Δ -8.3 [-8.9, -7.8] *p*<0.001	Δ -6.7 [-7.3, -6.1] *p*<0.001	Δ -2.1 [-2.7, -1.5] *p*<0.001	Δ -2.2 [-2.8, -1.6] *p*<0.001	Δ -1.8 [-2.4, -1.2] *p*<0.001	Δ 0.2 [-0.4, 0.8] *p*=1.000	
9	1,200/4th -17.7±0.6 cm H_2O	Δ -11.3 [-11.8, -10.7] *p*<0.001	Δ -11.3 [-11.8, -10.7] *p*<0.001	Δ -9.6 [-10.2, -9.1] *p*<0.001	Δ -5.0 [-5.6, -4.4] *p*<0.001	Δ -5.2 [-5.7, -4.6] *p*<0.001	Δ -4.7 [-5.3, -4.1] *p*<0.001	Δ -2.8 [-3.3, -2.2] *p*<0.001	Δ -2.9 [-3.5, -2.4] *p*<0.001

Note: Δ: mean difference; 95% CI is presented in square brackets.

Inspiratory flow rate results of the normality test for Experiment II.

Conditions		**Inspiratory flow rate** (mL/sec)			**Shapiro-Wilk test** (*p* value)
		mean	SD	95% CI	
1	Open all holes, lift 600 mL/sec ball	652	6	646 to 658	0.898
2	Open all holes, lift 900 mL/sec balls	855	10	846 to 864	0.665
3	Open all holes, lift 1200 mL/sec balls	994	13	982 to 1,006	0.903
4	Close the 2nd hole, lift 600 mL/sec ball	593	17	578 to 608	0.704
5	Close the 2nd hole, lift 1200 mL/sec balls	1,066	60	1,011 to 1,121	0.071
6	Close the 2nd & 3rd holes, lift 600 mL/sec ball	432	15	418 to 446	0.476
7	Close the 1st hole, lift 900 mL/sec ball	749	23	728 to 770	0.167
8	Close the 1st hole, lift 1200 mL/sec balls	1,013	114	907 to 1,119	0.145
9	Close the 1st & 3rd holes, lift 900 mL/sec ball	473	8	466 to 481	0.659
10	Close the 1st & 2nd holes, lift 1200 mL/sec ball	446	8	438 to 454	0.700
11	Close the 3rd hole, lift 600 mL/sec ball	606	7	600 to 612	0.969
12	Close the 3rd hole, lift 900 mL/sec balls	847	15	834 to 861	0.727

Pairwise comparison of inspiratory flow rate for Experiment II.

Conditions		1	2	3	4	5	6	7	8	9	10	11
		652±6 mL/sec	855±10 mL/sec	994±13 mL/sec	593±17 mL/sec	1,066±60 mL/sec	432±15 mL/sec	749±23 mL/sec	1,013±114 mL/sec	473±8 mL/sec	446±8 mL/sec	606±7 mL/sec
2	855±10 mL/sec	Δ 203 [129, 276] *p*<0.001										
3	994±13 mL/sec	Δ 342 [269, 416] *p*<0.001	Δ 139 [66, 213] *p*<0.001									
4	593±17 mL/sec	Δ -59 [-133, 15] *p*=0.408	Δ -262 [-335, -188] *p*<0.001	Δ -401 [-474, -328] *p*<0.001								
5	1,066±60 mL/sec	Δ 414 [340, 487] *p*<0.001	Δ 211 [138, 285] *p*<0.001	Δ 72 [-1, 145] *p*=0.066	Δ 473 [399, 546] *p*<0.001							
6	432±15 mL/sec	Δ -220 [-293, -146] *p*<0.001	Δ -423 [-496, -349] *p*<0.001	Δ -562 [-636, -488] *p*<0.001	Δ -161 [-234, -87] *p*<0.001	Δ -634 [-707, -560] *p*<0.001						
7	749±23 mL/sec	Δ 96 [23, 170] *p*=0.001	Δ -106 [-180, -33] *p*<0.001	Δ -246 [-319, -172] *p*<0.001	Δ 155 [82, 229] *p*<0.001	Δ -317 [-391, -244] *p*<0.001	Δ 316 [243, 390] *p*<0.001					
8	1,013±114 mL/sec	Δ 361 [286, 435] *p*<0.001	Δ 158 [85, 232] *p*<0.001	Δ 19 [-54, 93] *p*=1.000	Δ 420 [347, 494] *p*<0.001	Δ -53 [-126, 21] *p*=0.920	Δ 581 [507, 655] *p*<0.001	Δ 265 [191, 338] *p*<0.001				
9	473±8 mL/sec	Δ -178 [-252, -105] *p*<0.001	Δ -381 [-454, -307] *p*<0.001	Δ -521 [-594, -447] *p*<0.001	Δ -119 [-193, -46] *p*<0.001	Δ -592 [-666, -519] *p*<0.001	Δ 41 [-32, 115] *p*=1.000	Δ -275 [-348, -201] *p*<0.001	Δ -540 [-613, -466] *p*<0.001			
10	446±8 mL/sec	Δ -206 [-280, -133] *p*<0.001	Δ -409 [-482, -335] *p*<0.001	Δ -548 [-622, -475] *p*<0.001	Δ -147 [-221, -74] *p*<0.001	Δ -620 [-694, -546] *p*<0.001	Δ 14 [-60, 87] *p*=1.000	Δ -303 [-376, -229] *p*<0.001	Δ -567 [-641, -494] *p*<0.001	Δ -28 [-101, 45] *p*=1.000		
11	606±7 mL/sec	Δ -46 [-120, 27] *p*=1.000	Δ -249 [-322, -175] *p*<0.001	Δ -388 [-461, -315] *p*<0.001	Δ 13 [-61, 86] *p*=1.000	Δ -460 [-534, -386] *p*<0.001	Δ 173 [100, 247] *p*<0.001	Δ -142 [-216, -69] *p*<0.001	Δ -407 [-480, -334] *p*<0.001	Δ 132 [59, 205] *p*<0.001	Δ 160 [86, 234] *p*<0.001	
12	847±15 mL/sec	Δ 195 [121, 269] *p*<0.001	Δ -8 [-81, 66] *p*=1.000	Δ -147 [-221, -73] *p*<0.001	Δ 254 [181, 328] *p*<0.001	Δ -218 [-292, -145] *p*<0.001	Δ 415 [341, 489] *p*<0.001	Δ 99 [25, 172] *p*<0.001	Δ -166 [-240, -92] *p*<0.001	Δ 374 [300, 447] *p*<0.001	Δ 401 [328, 475] *p*<0.001	Δ 241 [167, 315] *p*<0.001

Note: Δ: mean difference; 95% CI is presented in square brackets.

Inspiratory pressure results of the normality test for Experiment II.

Conditions		**Inspiratory pressure** (cm H_2O)			**Shapiro-Wilk test** (*p* value)
		mean	SD	95% CI	
1	Open all holes, lift 600 mL/sec ball	-8.1	0.3	-8.4 to -7.8	0.966
2	Open all holes, lift 900 mL/sec balls	-13.0	0.4	-13.4 to -12.6	0.158
3	Open all holes, lift 1200 mL/sec balls	-17.7	0.6	-18.3 to -17.1	0.372
4	Close the 2nd hole, lift 600 mL/sec ball	-5.3	0.3	-5.6 to -5.0	0.523
5	Close the 2nd hole, lift 1200 mL/sec balls	-11.3	0.5	-11.8 to -10.8	0.119
6	Close the 2nd & 3rd holes, lift 600 mL/sec ball	-4.0	0.3	-4.3 to -3.7	0.159
7	Close the 1st hole, lift 900 mL/sec ball	-7.9	0.4	-8.2 to -7.5	0.390
8	Close the 1st hole, lift 1200 mL/sec balls	-11.0	1.1	-12.0 to -10.1	0.094
9	Close the 1st & 3rd holes, lift 900 mL/sec ball	-5.5	0.1	-5.6 to -5.4	0.079
10	Close the 1st & 2nd holes, lift 1200 mL/sec ball	-6.2	0.2	-6.4 to -6.0	0.301
11	Close the 3rd hole, lift 600 mL/sec ball	-5.1	0.1	-5.2 to -5.0	0.937
12	Close the 3rd hole, lift 900 mL/sec balls	-8.7	0.1	-8.8 to -8.6	0.536

Pairwise comparison of inspiratory pressure for Experiment II.

Conditions		1	2	3	4	5	6	7	8	9	10	11
		-8.1±0.3 cm H_2O	-13.0±0.4 cm H_2O	-17.7±0.6 cm H_2O	-5.3±0.3 cm H_2O	-11.3±0.5 cm H_2O	-4.0±0.3 cm H_2O	-7.9±0.4 cm H_2O	-11.0±1.1 cm H_2O	-5.5±0.1 cm H_2O	-6.2±0.2 cm H_2O	-5.1±0.1 cm H_2O
2	-13.0±0.4 cm H_2O	Δ -4.9 [-5.8, -4.0] *p*<0.001										
3	-17.7±0.6 cm H_2O	Δ -9.6 [-10.5, -8.8] *p*<0.001	Δ -4.7 [-5.6, -3.9] *p*<0.001									
4	-5.3±0.3 cm H_2O	Δ 2.8 [1.9, 3.7] *p*<0.001	Δ 7.7 [6.9, 8.6] *p*<0.001	Δ 12.4 [11.6, 13.3] *p*<0.001								
5	-11.3±0.5 cm H_2O	Δ -3.2 [-4.1, -2.4] *p*<0.001	Δ 1.7 [0.8, 2.6] *p*<0.001	Δ 6.4 [5.6, 7.3] *p*<0.001	Δ -6.0 [-6.9, -5.2] *p*<0.001							
6	-4.0±0.3 cm H_2O	Δ 4.1 [3.2, 5.0] *p*<0.001	Δ 9.0 [8.2, 9.9] *p*<0.001	Δ 13.7 [12.9, 14.6] *p*<0.001	Δ 1.3 [0.4, 2.2] *p*<0.001	Δ 7.3 [6.5, 8.2] *p*<0.001						
7	-7.9±0.4 cm H_2O	Δ 0.2 [-0.6, 1.1] *p*=1.000	Δ 5.1 [4.3, 6.0] *p*<0.001	Δ 9.9 [9.0, 10.7] *p*<0.001	Δ -2.6 [-3.5, -1.7] *p*<0.001	Δ 3.4 [2.6, 4.3] *p*<0.001	Δ -3.9 [-4.7, -3.0] *p*<0.001					
8	-11.0±1.1 cm H_2O	Δ -3.0 [-3.8, -2.1] *p*<0.001	Δ 1.9 [1.1, 2.8] *p*<0.001	Δ 6.7 [5.8, 7.5] *p*<0.001	Δ -5.8 [-6.6, -4.9] *p*<0.001	Δ 0.2 [-0.6, 1.1] *p*=1.000	Δ -7.1 [-7.9, -6.2] *p*<0.001	Δ -3.2 [-4.0, -2.3] *p*<0.001				
9	-5.5±0.1 cm H_2O	Δ 2.6 [1.7, 3.4] *p*<0.001	Δ 7.5 [6.6, 8.3] *p*<0.001	Δ 12.2 [11.3, 13.1] *p*<0.001	Δ -0.2 [-1.1, 0.6] *p*=1.000	Δ 5.8 [4.9, 6.6] *p*<0.001	Δ -1.5 [-2.4, -0.7] *p*<0.001	Δ 2.3 [1.5, 3.2] *p*<0.001	Δ 5.5 [4.7, 6.4] *p*<0.001			
10	-6.2±0.2 cm H_2O	Δ 1.9 [1.0, 2.7] *p*<0.001	Δ 6.8 [5.9, 7.7] *p*<0.001	Δ 11.5 [10.7, 12.4] *p*<0.001	Δ -0.9 [-1.8, -0.1] *p*=0.021	Δ 5.1 [4.2, 6.0] *p*<0.001	Δ -2.2 [-3.1, -1.4] *p*<0.001	Δ 1.7 [0.8, 2.5] *p*<0.001	Δ 4.9 [4.0, 5.7] *p*<0.001	Δ -0.7 [-1.5, 0.2] *p*=0.439		
11	-5.1±0.1 cm H_2O	Δ 3.0 [2.1, 3.8] *p*<0.001	Δ 7.9 [7.0, 8.7] *p*<0.001	Δ 12.6 [11.7, 13.5] *p*<0.001	Δ 0.2 [-0.7, 1.0] *p*=1.000	Δ 6.2 [5.3, 7.0] *p*<0.001	Δ -1.1 [-2.0, -0.3] *p*<0.001	Δ 2.7 [1.9, 3.6] *p*<0.001	Δ 5.9 [5.1, 6.8] *p*<0.001	Δ 0.4 [-0.5, 1.3] *p*=1.000	Δ 1.1 [0.2, 1.9] *p*=0.002	
12	-8.7±0.1 cm H_2O	Δ -0.6 [-1.5, 0.3] *p*=1.000	Δ 4.3 [3.5, 5.2] *p*<0.001	Δ 9.0 [8.2, 9.9] *p*<0.001	Δ -3.4 [-4.3, -2.5] *p*<0.001	Δ 2.6 [1.8, 3.5] *p*<0.001	Δ -4.7 [-5.6, -3.8] *p*<0.001	Δ -0.8 [-1.7, 0.1] *p*=0.097	Δ 2.4 [1.5, 3.2] *p*<0.001	Δ -3.2 [-4.0, -2.3] *p*<0.001	Δ -2.5 [-3.3, -1.6] *p*<0.001	Δ -3.6 [-4.4, -2.7] *p*<0.001

Note: Δ: mean difference; 95% CI is presented in square brackets.