Optimum Design Parameters for a Therapist-Constructed Positive-Expiratory-Pressure Therapy Bottle Device

Régis Gemerasca Mestriner PT, Rafael Oliveira Fernandes PT, Luís Carlos Steffen, and Márcio Vinícius Fagundes Donadio PT PhD

BACKGROUND: Positive-expiratory-pressure (PEP) therapy uses positive airway pressure generated by a either a fixed-orifice resistor or a threshold resistor. We hypothesized that tubing diameter and length, and the diameter of the PEP bottle's air-escape orifice would impact the PEP pressure delivered to the airway and determine whether the PEP bottle acts as a threshold resistor or a fixed-orifice resistor. METHODS: We designed a model composed of a bottle partially filled with water, a compressed air source, a pneumotachometer, and a manometer, to evaluate the effects of various tubing diameters (range 2–25 mm inner diameter) and lengths (range 20–80 cm long). In the first set of experiments, the PEP bottle had an open top, so there was no pressure other than the atmospheric pressure against the air escaping from the immersed tubing. The distal tip of the tube was 10 cm below the surface of the water (ie, a water-column pressure of 10 cm H_2O), and we tested flows of 1, 5, 10, 15, 20, and 25 L/min. In the second set of experiments we tested a PEP bottle, the top of which was closed except for an air-escape orifice (4, 6, 8, 9, or 10 mm). RESULTS: With tubing of 2–6 mm inner diameter, the length of the tubing and the flow significantly affected the PEP pressure (ie, the system was not a threshold resistor). With tubing ≥ 8 mm inner diameter there were no significant PEP-pressure differences with any of the tubing lengths or flows tested, which indicates a threshold-resistor system. The 4-mm and 6-mm air-escape orifices significantly increased the PEP pressure, whereas the 8 mm air-escape orifice did not increase the PEP pressure. CONCLUSIONS: To obtain a threshold-resistor PEP bottle system (ie, the PEP pressure is generated only by the water-column pressure), the tubing must be ≥ 8 mm inner diameter, and the air-escape orifice must be ≥ 8 mm. *Key words: positive expiratory pressure, PEP, respiratory therapy.*
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Introduction

Positive-expiratory-pressure (PEP) therapy is a respiratory therapy that applies resistance to expiration, to produce positive airway pressure.[1-4] Since the 1930s, PEP has been used to improve oxygenation, increase lung volume, and reduce venous return in patients with congestive heart failure.[2] PEP improves collateral ventilation,[2,5-7] secretion clearance,[8-11] aerosol distribution,[2,12,13] and functional residual capacity.[2,3,14]

The physiologic effects of PEP therapy are based mainly on the equal-pressure-point theory. The equal-pressure point is where the intraluminal and extraluminal pressures equalize across the airway. Proximal to the equal-pressure point (ie, toward the mouth), the external pressure around the airway is greater than the pressure within it, and the airway is compressed, which limits the flow.[15,16] PEP prevents small airways from collapsing, promotes better gas distribution, and increases expiratory time and volume.[2,16] The American Association for Respiratory Care recommends a PEP pressure of 10–20 cm H_2O.[17]

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The authors declare no conflicts of interest.

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Several types of PEP device are available. Some PEP devices produce expiratory resistance by passing the exhaled flow through a fixed orifice; the pressure generated increases with the expiratory flow. On the other hand, with a threshold-resistor PEP device, the pressure remains constant at any flow.[18]

A simple threshold-resistor PEP system is the PEP bottle. A container is partially filled with water, the distal tip of a tube is submerged in the water, and the patient exhales through the tube. The distance of the tube tip beneath the water surface determines the pressure required to force gas through the tube. Once the pressure in the tube is sufficient to overcome the weight of the water column, the threshold is reached, and the pressure required to continue the flow is consistent and not flow-dependent.[2] A clinician can easily build a PEP bottle from low-cost parts, and a "homemade" PEP bottle is an inexpensive alternative to manufactured, marketed PEP devices.[2,7] However, the Hagen-Poiseuille law, which relates flow, pressure, tubing radius and length, and viscosity,[19] suggests that the tubing diameter and length will impact PEP bottle performance. We hypothesized that building a PEP bottle with too-narrow tubing, and/or a bottle with a too-small top, could cause higher-than-recommended PEP pressure and create a nonthreshold system.[17]

We developed a "homemade" PEP bottle setup model to study the effects of (1) tube diameter and length, and (2) the diameter of the top of the PEP bottle (the "air-escape orifice") on the PEP pressure, and the extent to which the PEP bottle acted as a threshold resistor or a fixed-orifice resistor.

Methods

This study was conducted in the biomedical engineering laboratory of Hospital São Lucas, and approved by the research committee of Pontifícia Universidade Católica do Rio Grande do Sul, Porto Alegre, Brasil.

Experiment Setup

In both the experiments, the distal tip of the PEP bottle tube was 10 cm below the surface of the water (ie, a 10-cm water column), and 3 cm above the bottom of the bottle. We chose a 10-cm water column so that we could compare our results to those of previous studies.[18,20]

We chose a maximum flow of 25 L/min, based on the fact that the mean PEP flow in healthy subjects is approximately 18–19 L/min,[21,22] and flow > 25 L/min can cause water spillage from the PEP bottle.

We calibrated all meters prior to the experiments, and carefully examined the connections in the PEP bottle system to make sure there were no air leaks. We performed all measurements in triplicate and recorded each PEP pressure measurement for at least 30 s, to obtain a stable value. If we observed a pressure variation, we repeated the measurement until we obtained a stable value. We measured the compressed air flow with a digital calibration analyzer (RT-200, Timeter, Lancaster, Pennsylvania), which has a precision of ± 1%.

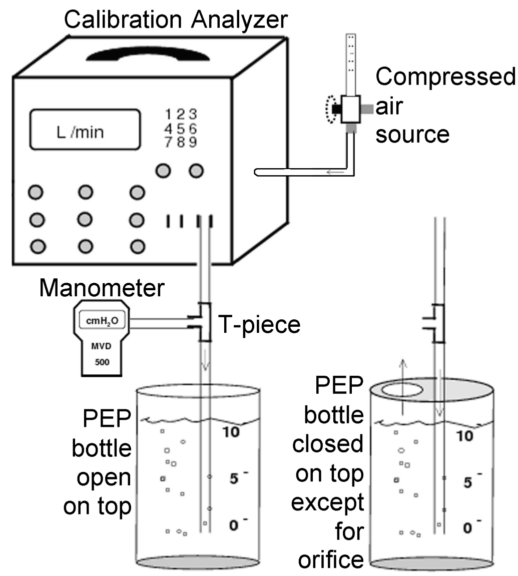

Fig. 1. Experiment setup.

We connected a T-piece to the calibration analyzer's outflow port. To that T-piece we connected (1) the tubing that led to the PEP bottle, and (2) a manometer (MVD-500, Globalmed, Porto Alegre, Brazil), which has a precision of ± 1.2 cm H_2O between −500 and 500 cm H_2O.

Experiment 1

In Experiment 1, the PEP bottle (Fig. 1) was an acrylic container (height 25 cm, width 10 cm) with an open top (so there was no pressure except atmospheric pressure against the air escaping from the tube). We tested polyvinyl chloride tubing with inner diameters of 5, 6, 7, 8, 9, 10, 15, and 25 mm, and lengths of 20, 40, and 80 cm. We also tested nasotracheal catheters (MarkMed, São Paulo, Brasil) with 2-mm and 4-mm inner diameters, and lengths of 20, 40, and 50 cm. We tested each length/diameter of tubing/catheter at 1, 5, 10, 15, 20 and 25 L/min.

Experiment 2

In Experiment 2, we used a plastic container (height 18 cm, diameter 9 cm), the top of which was closed except for an air-escape orifice (4, 6, 8, 9, or 10 mm), to determine the minimum air-escape orifice diameter necessary to allow the air to escape without increasing the PEP pressure. Based on our findings in Experiment 1, in Experi-

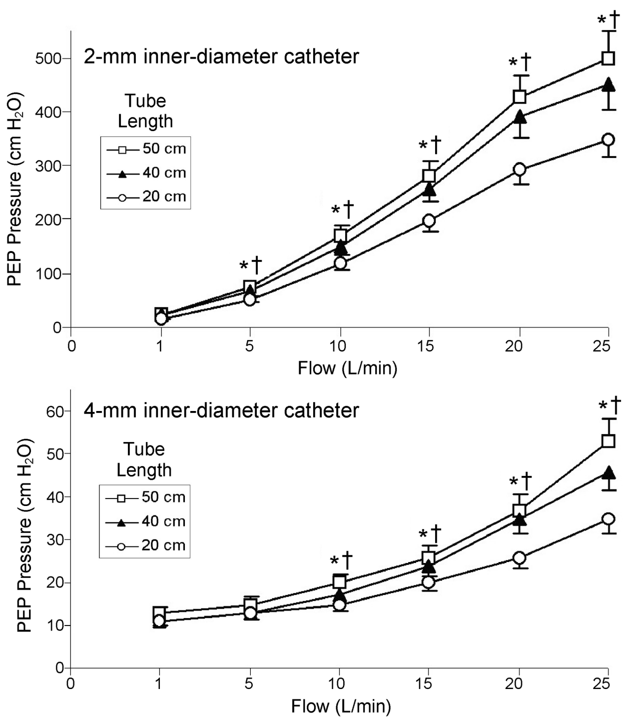

Fig. 2. Flow versus pressure in the catheter, with 2 catheter diameters and 3 catheter lengths. * indicates a significant PEP (positive-expiratory-pressure therapy) pressure difference between the tube lengths with a given flow. † indicates significant PEP-pressure difference between the flows with a given tube length.

ment 2 we used tubing with an inner diameter of 8 mm. As in Experiment 1, the water column was 10 cm.

Statistical Analysis

Values are expressed as mean ± SD. With statistics software (SPSS 11.5, SPSS, Chicago, Illinois) we analyzed the relationships between the tubing lengths and flows with 2-way analysis of variance for repeated measures, followed by the Bonferroni test for multiple comparisons, when indicated. Differences were considered significant when $P < .05$. Because a 10-cm water column was used in both experiments, all systems that showed pressures > 10 cm H_2O were considered inadequate.

Results

Experiment 1

Figures 2 and 3 show the effects of catheter/tubing length and diameter on PEP pressure. With tubing inner diameters from 2 mm to 7 mm, the catheter/tubing length affected the PEP pressure by > 10 cm H_2O. The 2-mm catheter caused inappropriately high PEP pressure ($P < .001$) at all flows, and the 4-mm catheter caused inappropriately high pressure ($P < .001$) at flows > 5 L/min.

Figure 3 shows that the PEP pressure was independent of the flow and tubing length only with tubing ≥ 8 mm inner diameter. That is, all the tubes with inner diameter ≥ 8-mm had no significant effect ($P = .99$) on the PEP pressure. Thus, with the ≥ 8-mm tubes, only the water-column pressure (10 cm H_2O) determined the PEP pressure.

Experiment 2

Figure 4 shows the relationship between the air-escape orifice diameter and the PEP pressure. The 4-mm orifice significantly ($P < .001$) increased the PEP pressure at flows > 5 L/min. The 6-mm orifice significantly ($P < .001$) increased the PEP pressure at flows > 15 L/min. The 8-mm, 9-mm, and 10-mm orifices did not significantly increase the PEP pressure at any of the tested flows. So, as with the tubing diameter, the PEP bottle's air-escape orifice must be ≥ 8 mm to make a threshold-resistor PEP bottle system.

Discussion

If the tubing is < 8 mm inner diameter, the PEP bottle pressure is affected by tubing length and diameter. The Hagen-Poiseuille law for laminar flow states that if flow and tube length are constant and diameter decreases, the pressure increases. If flow and diameter are constant and length increases, the pressure increases.[19] The tubes with inner diameter ≤ 7 mm showed pressure changes in agreement with the Hagen-Poiseuille law: when length increased and/or diameter decreased, then pressure increased. The tubes ≥ 8-mm inner diameter did not increase the PEP pressure above the 10 cm H_2O water-column pressure, at any of the tested tube lengths or flows. So, an inner diameter of ≥ 8 mm is necessary to obtain independence between the PEP pressure and the tubing length and flow, so that the PEP pressure is generated only by the water column. Tubing diameter < 8 mm makes the system behave as a fixed-orifice resistor rather than a threshold resistor.

Sehlin et al[20] found a mean PEP pressure of 11.7 cm H_2O in healthy volunteers, with a 10-cm H_2O water column and a 42-cm long, 10-mm inner-diameter tube. However, they did not mention the diameter of the air-escape orifice of their PEP device.

Christensen et al[18] evaluated various PEP setups, including a PEP bottle, and found that, with a 22-mm inner diameter, 100-cm long tube, the PEP pressure was equal to the water column (in the pressure range 5–20 cm H_2O). Our results confirm their finding that with an adequate tube diameter, the PEP pressure is created only by the

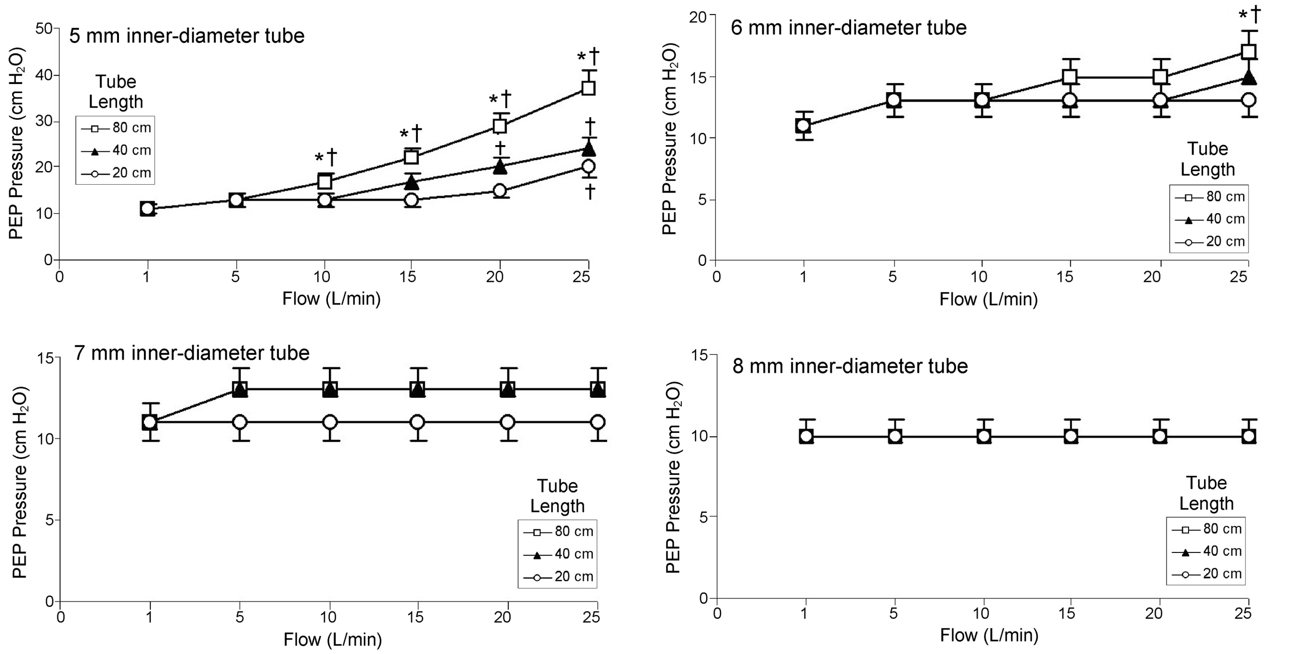

Fig. 3. Flow versus pressure in the tube, with 4 tube diameters and 3 tube lengths. With the 5-mm inner-diameter tube: * indicates a significant PEP (positive-expiratory-pressure therapy) pressure difference between the 20-cm and 40-cm tube lengths with a given flow; and † indicates a significant PEP-pressure difference between different flows with a given tube length. With the 6-mm inner-diameter tube: * indicates a significant PEP-pressure difference between the 20-cm and 40-cm tube lengths with a given flow; and † indicates a significant PEP-pressure difference between different flows with the 80-cm tube length. With the 7-mm inner-diameter tube there was a nonsignificant increase in the PEP pressure with the 40-cm and 80-cm tube lengths, and no increase with the 20-cm tube. With the 8-mm inner-diameter tube there was no difference in the PEP pressure with any of the tube lengths at any of the flows.

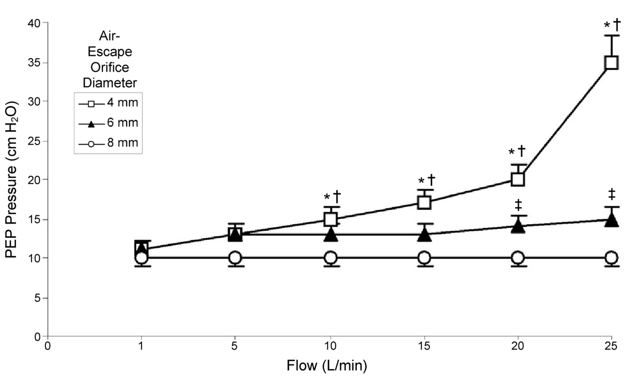

Fig. 4. Flow versus pressure with 3 different air-escape-orifice diameters. * indicates a significant PEP (positive-expiratory-pressure therapy) pressure difference between the orifice diameters (4 mm, 6 mm, and 8 mm) with a given flow. † indicates a significant PEP-pressure difference between different flows at orifice diameter 4 mm. ‡ indicates a significant PEP-pressure difference between flows ≥ 20 L/min and ≤ 15 L/min with orifice diameter 6 mm.

water-column resistance, and is independent of the flow. To our knowledge, the present study is the first to find that the minimum tubing diameter is 8 mm.

A PEP bottle is supposed to be a threshold-resistor system that provides a constant pressure at any flow.[2,18] At clinically realistic flows, if the tube diameter is < 8 mm, the tube increases the PEP pressure and makes the PEP bottle system a fixed-orifice resistor. However, if the tube is ≥ 8 mm, the flow does not affect the PEP pressure, up to tube length 80 cm. We do not know if tube length > 80 cm would increase the PEP pressure, but we see no reason the tube would need to be longer than 80 cm. The PEP bottle's air-escape orifice also has to be ≥ 8 mm or it will increase the PEP pressure above the water-column pressure.

Constructing a PEP bottle with too-narrow a tube or too-small an air-escape orifice will generate a PEP pressure higher than the water-column pressure, and probably higher than the pressure recommended by the American Association for Respiratory Care[17] (10–20 cm H_2O). In our setup, tubing diameter < 8 mm generated pressure greater than the water-column pressure (mean increase of 400% above the intended 10 cm H_2O water-column pressure), and above the recommended pressure.

The main limitation of this study is that it was a laboratory study. We used an experimental model with precise, constant flows, which are not necessarily reproducible in humans, who have a wide range of expiratory flow. Measurement in human subjects is also affected by equipment imprecision.

Supranormal airway resistance (as in patients with chronic obstructive pulmonary disease) increases the work of breathing, and an inadequate PEP therapy system (ie, pressure above the recommended) would further increase it.[23] According to Scano and co-workers,[24] the work of breathing can be defined as the product of the muscular breathing pressure and the change in lung volume. During basal ventilation at rest, the work of breathing in healthy individuals is approximately 0.069 W, but it can be 10–12 times higher in patients with chronic obstructive pulmonary disease,[25] many of whom use PEP therapy. Thus, an incorrectly constructed PEP bottle could increase the work of breathing too much[24] and cause ventilatory muscle fatigue.[26,27]

Conclusions

The inner diameter of both the tube and the air-escape orifice must be $\geq$ 8 mm to make the PEP bottle a threshold-resistor system. If the tube's inner diameter or air-escape orifice is $<$ 8 mm, the PEP pressure will be greater than the water-column pressure and will probably be greater than the recommended pressure. More studies are needed to evaluate the alveolar repercussions of various PEP bottle pressure devices.

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