A novel Venturi system to generate high flow with titratable FiO$_2$

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ABSTRACT

Venturi-based flow generators are commonly used for noninvasive continuous positive airway pressure (CPAP) of high-flow nasal oxygen (HFNO). The system is simple and allows to increase the total flow while decreasing the FiO$_2$ starting from a single oxygen source.
In this report we describe the characteristics and performance of a novel Venturi system (EasyVEE, Levate, BG, Italy), which allows to vary the size of the port through which ambient air is entrained, hence allowing a continuous modulation of FiO$_2$.
The system allowed to modify FiO$_2$ continuously between 35% and 80% and, consequently, a 1.5- to 4.5-fold increase of the total flow rate. A minimal decrease in entrainment performance was observed for positive end-expiratory pressure levels above 12.5 cmH$_2$O.
EasyVEE system appears to be a simple, flexible, and reliable solution to generate continuous flow for noninvasive respiratory support interfaces.

Keywords: CPAP, Noninvasive ventilation, Acute Respiratory Failure, Oxygen

Background and rationale

Noninvasive ventilatory support, based on free-flow continuous positive airway pressure (CPAP) delivered by helmet or face mask or high-flow nasal oxygen (HFNO), is increasingly used to treat patients with acute respiratory failure (1). During the recent Coronavirus-2019 (COVID-19) pandemic, the use of free-flow system massively spread also outside the intensive care units (2-5). The main advantage of free-flow systems is that an active mechanical ventilator is not required; a flow generator connected to the oxygen pipe or tank can feed a helmet or a face mask to provide CPAP through a positive end-expiratory pressure (PEEP) valve (6), or to nasal cannulas to provide HFNO (7). Flow generators can be either turbine-based or Venturi-based systems.

Venturi systems are based on the principle that a high-pressure gas (typically oxygen at 4 atm) is delivered through a small-bore nozzle, reaching a very high speed. Due to Bernoulli's law, once the high-speed gas moves into a larger conduit, it generates a decrease of the lateral pressure, which becomes subatmospheric and entrains another gas (air) from the external atmosphere. In this way, starting from a pure flow of oxygen (Q_{O2}), it is possible to achieve a much higher flow of a mixture of gas (Q_{tot}), at a variable FiO$_2$. For each Venturi system, it is hence possible to calculate the flow of gas entrained (Q_{entr}) for a given Q_{O2}, where the ratio $R_{vent} = \dfrac{Q_{entr}}{Q_{O2}}$.

For example, $R_{vent} = 3$ indicates that for each 1 L/min of oxygen flowing through the nozzle, three additional liters/minute of gas is entrained, resulting in a total flow of 4 L/min. The final flow (Q_{tot}) depends on Q_{O2} and R_{vent} according to the following formula:

$$Q_{tot} = Q_{entr} + Q_{O2} = Q_{O2} + Q_{O2} * R_{vent} \quad [1]$$

The FiO$_2$ of Q_{tot} (if the gas entrained is air) equals

$$FiO_2 = \frac{(Q_{entr} * 0.21) + Q_{O2}}{Q_{tot}} \quad [2]$$

which, combined with Equation [1] and simplified becomes:

$$FiO_2 = \frac{1 + (R_{vent} * 0.21)}{1 + R_{vent}}$$

Hence, if R_{vent} does not change, varying Q_{O2} to the nozzle will not vary the FiO_2 of Q_{tot}, but only Q_{tot} itself.

R_{vent} depends mainly not only on the diameter and shape of the nozzle orifice but also on the pressure downstream, as positive pressure decreases the entrainment ability of Venturi.

From a clinical standpoint, this is relevant, since when delivering free-flow CPAP using a Venturi system to generate the flow, any PEEP increase will cause an FiO_2 increase, which might be misinterpreted as a patient's response to PEEP. Finally R_{vent} tends to decrease for low Q_{O2}, due to the loss of entrainment at lower gas speeds. A typical behavior of a Venturi system is displayed in Figure 1.
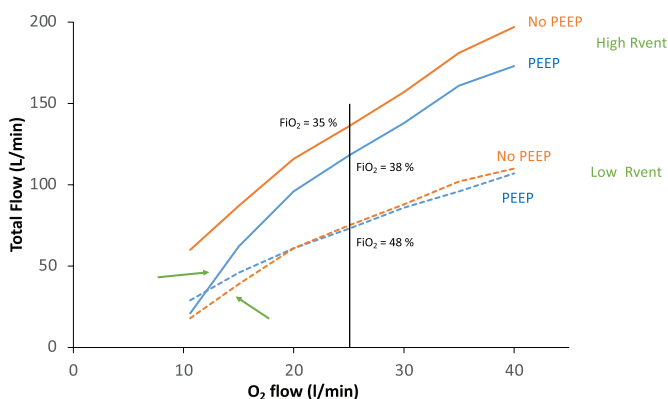

Fig. 1 - Characteristic behavior of Venturi systems with higher or lower entrainment of ambient air (expressed as the ratio between initial oxygen flow and entrained air, R_{vent}). For the same O_2 flow the Venturi with a higher entrainment will lead to a greater total flow, with lower FiO_2 (due to the greater amount of air in the final mixture) and vice versa. Notice that a PEEP increase may determine a decrease of the performance of the same Venturi (as the positive pressure decreases the entrainment capabilities). Finally, in the low range of O_2 flow (green arrow), the R_{vent} of the Venturi can drop, leading to low total flow rates and higher FiO_2.

Description of the system

We herein describe and characterize a novel Venturi system (EasyVee flowmeter, Levate, Bergamo, Italy), coupled with a variable area oxygen flowmeter, connected to a high-pressure (4 bar) O_2 source. The Venturi nozzle (with a diameter of 1.1 mm) is characterized by a nominal R_{vent} of approximately 4.5 when operating without downstream pressure. A novel solution is that the size of the aspiration port (open to ambient air) can be modulated, by means of a nonius, from full opening to complete closure (Fig. 2). The excursion progresses continuously, but six precalibrated marks are put in order to facilitate Q_{entr} (and hence FiO_2) titration with the use of a table or an app.

Because of the size of the nozzle, the maximum achievable flow from a standard 4-bar oxygen wall port equals 38-40 L/min, even if the flow meter is opened to full scale. Therefore, when the nonius is completely closed to deliver pure oxygen (FiO_2 100%), the total flow might be inadequate
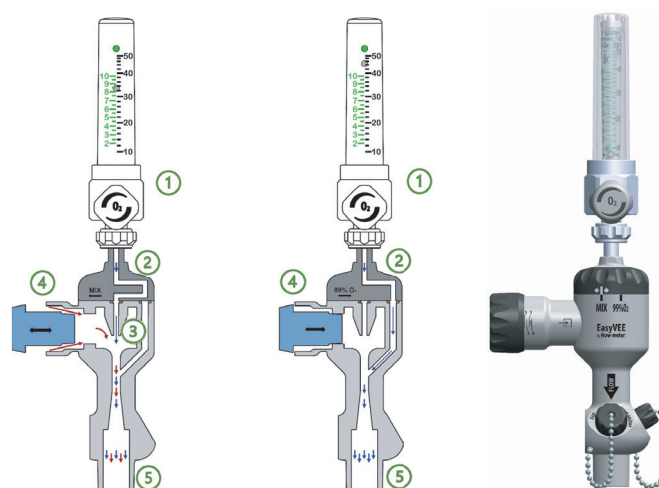

Fig. 2 - Representation of the novel Venturi. **Panel A:** The oxygen (blue) flow delivered by a variable surface flowmeter (1) is directed (2) through the small nozzle (3) where the high speed and subsequent enlargement of the section causes an entrainment of air from the ambient through a nonius (4), whose bore can be modulated, varying the final (5) $FiO2$ and total flow. **Panel B:** In the case of pure oxygen delivery, the Venturi nozzle is bypassed by a switch (2) and flow follows an auxiliary larger-bore path. **Panel C**: Image of the device.

to provide noninvasive CPAP support; a novel solution is the presence of a switch to bypass the Venturi nozzle, achieving up to 70 L/min oxygen flows.

Methods

In this bench study we evaluated the performance of the novel Venturi system, in terms of total flow generated and FiO_2 for different Q_{O2}, nonius position, and PEEP loads, to simulate different clinical scenarios. Total flow and FiO_2 were measured by VT Plus HF (Fluke Biomedical, USA). FiO_2 was measured additionally by PICK-O2 (Medizintechnik Juergen K. Kranz GmbH) and values were averaged to obtain the measured FiO_2 ($FiO_{2,meas}$). Theoretical FiO_2 ($FiO_{2,th}$) was calculated as:

$$FiO_{2,th} = \frac{Q_{O2} + \left(\dot{Q}_{tot} - Q_{O2}\right) \cdot 0.21}{Q_{tot}}$$

and compared with $FiO_{2,meas}$ to verify internal data consistency.

For each condition R_{vent} was calculated as:

$$R_{vent} = \frac{\left(\dot{Q}_{tot} - Q_{O2}\right)}{Q_{tot}}$$

Results

As expected $FiO_{2,meas}$ and $FiO_{2,th}$ were tightly correlated (Fig. 3).
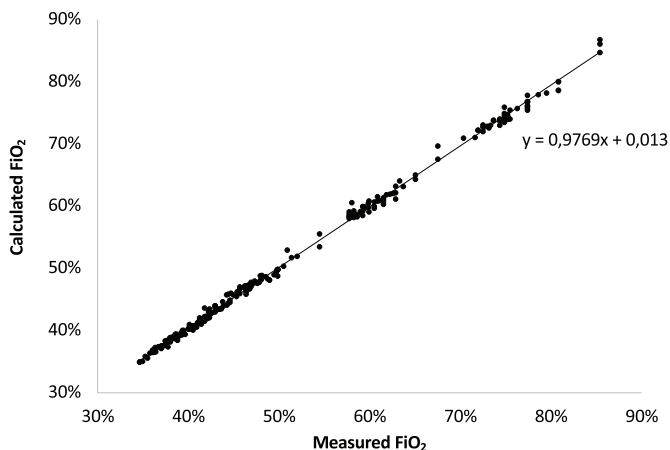
$$y = 0{,}9769x + 0{,}013$$

Fig. 3 - Tight correlation between the measured and theoretical FiO_2 of the final gas flow, with a slope very close to identity, reinforcing the internal consistency of the data.

Figure 4 shows the performance of the novel Venturi system for different Q_{O2} and position of the nonius, for a PEEP value of 7.5 cmH$_2$O. As expected, progressively closing the nonius leads to a decrease of the air entrained by the Venturi (decreasing R_{vent}) and hence Q_{tot} (upper panel), allowing to achieve higher FiO_2 (lower panel), in the range between 35% and 80%.

As shown in Figure 5, the performance of the novel Venturi system, measured as capacity to entrain air (R_{vent}), remained rather stable over a wide range of PEEP, showing a sensible impact only for PEEP levels above 12.5 cmH$_2$O, particularly if a low Q_{O2} is used (upper panel).

Discussion

In this report we described the pneumatic performance of the EasyVEE system, a Venturi flow generator equipped with an adjustable air entraining port and a single extended-range flowmeter. The novel system was very flexible, in generating high-flow gas mixture, with a simple control to titrate FiO_2 and a constant performance over a wide range of PEEP and Q_{O2}.

As mentioned, an adequate flow of fresh gas is necessary in order to efficiently deliver CPAP or HFNO. This is often achieved by Venturi systems, which drop the FiO_2 proportionally to their efficiency in gas entrainment. Standard Venturi systems are typically built with a fixed (not adjustable) port for air entrainment; therefore, a second flowmeter is needed to increase FiO_2 by addition of oxygen to the gas mixture generated by the Venturi. At variance from these, the EasyVEE foresees a progressive reduction of the air opening, so that the net result is an adjustable R_{vent} and an increase in FiO_2.

Another crucial point of the Venturi systems is the loss of performance for increasing back pressures, typically due to PEEP increase. In this respect, the Easy-VEE maintains a relatively constant performance over a wide range of PEEP levels, albeit the use of a direct FiO_2 measure or custom tables for the device is recommended to determine the exact FiO_2 after any therapeutic adjustment.

In conclusion the EasyVEE system appears to be a simple, flexible, and reliable solution to generate continuous flow for noninvasive respiratory support interfaces.
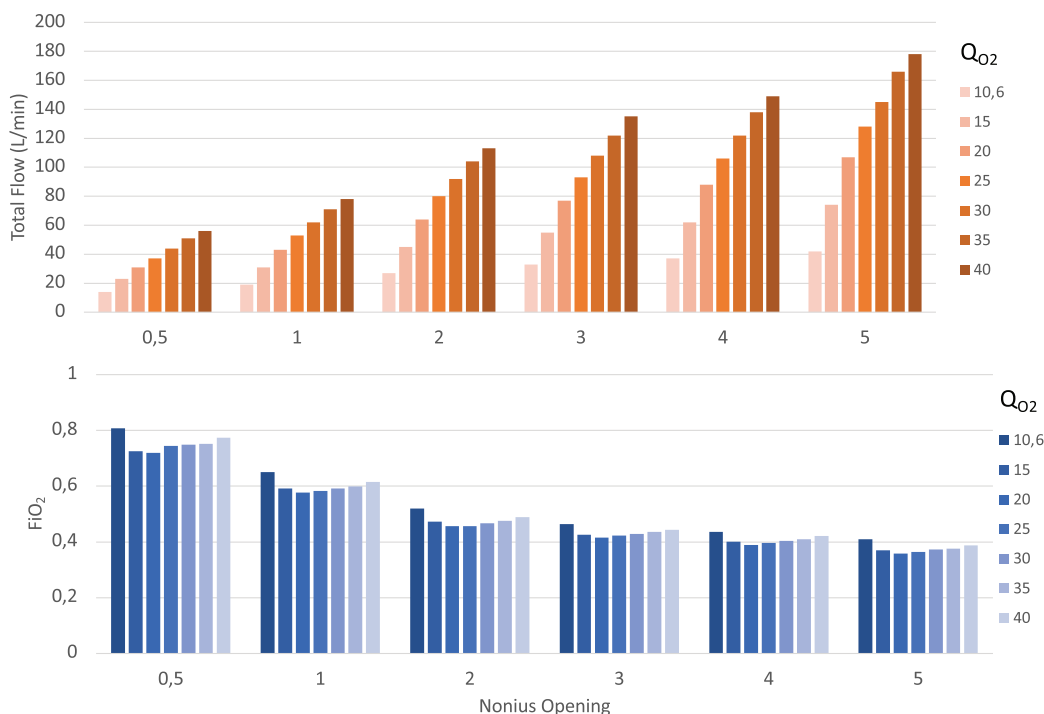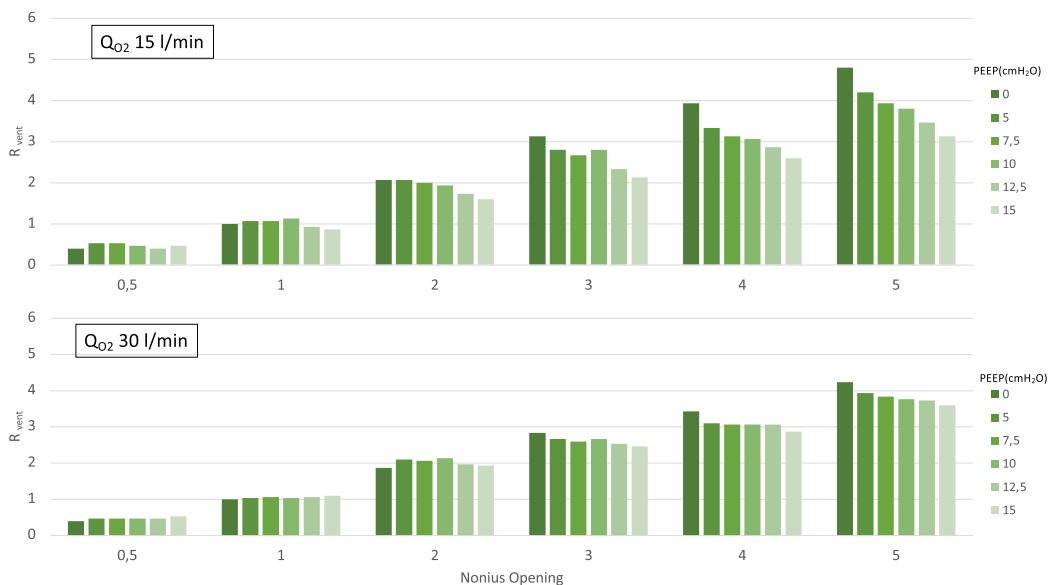

Fig. 4 - Total flow (upper panel) generated by the novel Venturi system depending on the O_2 flow (Q_{O2}) and nonius opening. As expected (lower panel) FiO_2 decreases for progressive openings of the nonius, allowing a fine titration between 35% and 80%. FiO_2 does not vary with Q_{O2}, allowing a separate titration of total flow and FiO_2.

Fig. 5 - Impact of positive end-expiratory pressure on the ability of Venturi to entrain air from the external environment. R_{vent} expresses the ratio between the O_2 flow (Q_{O_2}) and the flow of air entrained. For example, an $R_{vent} = 2$ indicates that a Q_{O_2} of 20 L/min will entrain 40 L/min from the environment, generating a total flow (Q_{tot}) of 60 L/min. In the novel system R_{vent} can be easily titrated acting on the nonius, but, conveniently, the value is stable irrespective of Q_{O_2} and PEEP (unless for extreme values).

Disclosures

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