A novel Venturi system to generate high flow with titratable FiO₂

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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 FiO₂ 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 FiO₂.

The system allowed to modify FiO₂ 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 cmH₂O.

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 (QO₂), it is possible to achieve a much higher flow of a mixture of gas (Qtot), at a variable FiO₂. For each Venturi system, it is hence possible to calculate the flow of gas entrained (Qentr) for a given QO₂, where the ratio

$$R_{vent} = \frac{Q_{entr}}{Q_{O₂}}$$

For example, Rvent = 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 (Qtot) depends on QO₂ and Rvent according to the following formula:

$$Q_{tot} = Q_{entr} + Q_{O₂} = Q_{O₂} + Q_{O₂} \cdot R_{vent}$$  \hspace{1cm} [1]

The FiO₂ of Qtot (if the gas entrained is air) equals

$$FiO₂ = \frac{(Q_{entr} \cdot 0.21) + Q_{O₂}}{Q_{tot}}$$  \hspace{1cm} [2]

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

$$FiO₂ = \frac{1 + (R_{vent} \cdot 0.21)}{1 + R_{vent}}$$
Hence, if $R_{\text{vent}}$ does not change, varying $Q_{\text{OO}}$ to the nozzle will not vary the FiO$_2$ of $Q_{\text{tot}}$, but only $Q_{\text{tot}}$ itself.

$R_{\text{vent}}$ 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, $R_{\text{vent}}$ tends to decrease for low $Q_{\text{OO}}$, due to the loss of entrainment at lower gas speeds. A typical behavior of a Venturi system is displayed in Figure 1.

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 $Q_{\text{OO}}$, 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 Juer-gen K. Kranz GmbH) and values were averaged to obtain the measured FiO$_2$ ($\text{FiO}_2,\text{meas}$). Theoretical FiO$_2$ ($\text{FiO}_2,\text{th}$) was calculated as:

$$\text{FiO}_2,\text{th} = \frac{Q_{\text{O2}} + (Q_{\text{tot}} - Q_{\text{O2}}) \cdot 0.21}{Q_{\text{tot}}}$$

and compared with $\text{FiO}_2,\text{meas}$ to verify internal data consistency.

For each condition $R_{\text{vent}}$ was calculated as:

$$R_{\text{vent}} = \frac{Q_{\text{tot}} - Q_{\text{O2}}}{Q_{\text{tot}}}$$

Results

As expected $\text{FiO}_2,\text{meas}$ and $\text{FiO}_2,\text{th}$ were tightly correlated (Fig. 3).
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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 EasyVEE 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.
Disclosures
Conflict of interest: Both authors are coinventors on patents and receive consultancy fees from Flow-Meter SPA (Levate, BG, Italy) for a matter related to the topic of the article. Financial support: None.

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