Analysis of the fraction of delivered oxygen by noninvasive ventilation devices working as invasive ventilators in pandemic times

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Short Report

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Abstract

Purpose: In the context of the COVID-19 pandemic, mandatory ventilation with noninvasive ventilation (NIV) devices is a valid option when intensive care/anesthesia ventilators are unavailable. The fraction of delivered oxygen (FDO_2) by NIV devices in intubated patients is unknown.

Method: We simulated intubated patients with normal and sick lungs. NIV was used in pressure control mode with protective lung ventilatory settings. O_2 flow was added into the NIV circuit in incremental steps of 1 L/min (from 1 to 15 L). The FDO_2 in breathing gases was measured by a paramagnetic O_2 sensor placed behind the endotracheal tube. Three NIV circuit options were analyzed: 1) leak at HME filter close to the patient, 2) anesthesia Bain circuit with leak distal to the patient, and 3) leak throughout a non-rebreathing valve near the patient.

Results: FDO_2 increased proportional to the supplemental O_2 flow in all NIV options and in both kinds of patients. The range of FDO_2 came from 0.25 to 0.98 in both, healthy and sick lungs. At 5 L/min, FDO_2 was 0.53±0.04 and 0.47±0.02 in option 1 and 0.53±0.04 and 0.47±0.02 in option 2 for healthy and sick lungs, respectively. In option 3, 5 L/min of O_2 reached 0.84±0.08 in healthy and 0.74±0.09 in sick lungs.

Conclusions: In all setups, FDO_2 was proportional to the administered O_2 flow and it covered the range of FDO_2 values commonly observed in ventilated patients.

Introduction

Respiratory failure induced by the SARS-CoV-2 virus is a key feature in most patients with COVID-19 [1,2]. The high contagiousness of the virus (Ro = 2.2-3.5) [3] increases the number of people infected exponentially, explaining why health systems collapsed all over the world. The problem is particularly severe in intensive care units (ICU) where beds and ventilators could be fully occupied with COVID-19 cases that require invasive ventilation longer than usual. In such critical scenario even anesthesia workstations have been utilized to ventilate COVID-19 patients, limiting the number of this crucial equipment in the operating rooms.

The use of noninvasive ventilation (NIV) devices in-lieu of invasive ICU ventilators has been recently suggested in the context of the COVID-19 pandemic [4]. Noninvasive ventilation was proposed as a second line strategy when ventilators and/or anesthesia machines are not available and patients need ventilatory support for acute respiratory failure or for general anesthesia. This is clearly an emergency situation for the pandemic that is not appropriated for normal circumstances. The FDA approved NIV devices to be used in intubated patients at the time of writing of this manuscript (https://www.fda.gov/medical-devices/letters-health-care-providers/ventilator-supply mitigation-strategies-letter-health-care-providers. Accessed April 20, 2020).

There are many comparative advantages and disadvantages between NIV devices when compared to ICU and anesthesia workstations [5]. Perhaps the main limitation of NIV is the difficulty to get precise fraction of delivered oxygen (FDO_2), therefore, specific O_2 flow/ FDO_2 tables are needed to adjust the oxygen therapy. Such information was described in two studies that simulated NIV in spontaneous breathing patients using masks [6,7]. However, these data are only approximations because the FDO_2 is easily modify by unintended leaks around poor-fitting masks and the patient's minute ventilation. In intubated patients with cuffed endotracheal tubes, NIV devices work with an intended air-leak in the ventilatory circuit but without any additional “unintended” leaks like with facial interfaces. Thus, for most of the NIV devices, the FDO_2 delivered to patients undergoing mandatory ventilation is unknown.

The main objective of this brief report was to analyze the FDO_2 supplied by NIV devices working as invasive ventilators. The analysis was performed in a bench study at this first step, simulating patients with healthy and sick lungs using different NIV circuit configurations at different supplemental O_2 flows. End-point of the analysis was the measurement of FDO_2 at the airways opening. The primary outcome was to describe the FDO_2 obtained at different additional O_2 flow for different NIV circuit dispositions.

The IRB of the Hospital Privado de Comunidad, Mar del Plata, Argentina approved the use of clinical data recorded in three anesthetized patients to illustrate the results of simulations (waiver for patients’ written informed consent).

Methods

NIV devices working as an invasive ventilator

To operate as an invasive ICU ventilator the NIV device must have the following features:

- To allow pressure control and/or S/T modes.
- The NIV device must reach an inspiratory positive airway pressure (IPAP) ≥ 30 cmH_2O and an expiratory positive airway pressure (EPAP) ≥ 10 cmH_2
- An obligated gas leak port to washout CO_2 from the single limb NIV circuit.
- An external O_2 source supply. We have administered O_2 through a port placed between the single-limb circuit and the NIV device.
- A heat and moisture exchange (HME) antibacterial/antiviral filter must be placed between the endotracheal tube (ETT) and the NIV circuit. The HME prevents SARS-CoV-2 virus dispersion and keeps humidity of inhaled gas.

Three NIV circuit configurations were proposed to implement ventilation in intubated patients (Figure 1) [4]. **These** are circuit configurations described for such altered standard of care that must be only used in the context of COVID-19 pandemic. The first option is the standard circuit configuration that has a leak at the HME filter, nearest to the patient. The second one is a modified Bain system ideated to perform

general anesthesia, which has the advantage to keep heat and humidity in the breathing gases [8]. The circuit has double coaxial tubes one inside the other. The outer tube is connected to the NIV device and delivers inspired gases to the patient while the inner tube transports expired gases to the ambient (leak closer to the NIV equipment). The third option has a non-rebreathing valve like Ruben or Duckbill (similar to those found in Ambu® resuscitation bags) [9], which delivers gases to the patient and then eliminates gases to the ambient throughout a PEEP valve. This atypical circuit option has the theoretical advantage to deliver more O_2 and to decrease CO_2 re-breathing.

Simulations

The analysis was done in the Simulation Center of the Buenos Aires Association of Anesthesia, Analgesia and Reanimation. Data was collected by the ASL 5000 Breathing Simulator (IngMar Medical, Pittsburgh, USA), which was connected to the NIV device (Stellar 150, ResMed Inc., Sydney, Australia) by a cuffed nº 8 endotracheal tube. This device can be used for noninvasive and invasive ventilation according to manufacturer's specifications. Respiratory mechanics and CO_2-O_2 signals were obtained with sensors placed at the airways opening (S5 device, GE Healthcare/Datex-Ohmeda, Helsinki, Finland). The O_2 was measured by paramagnetic sensor with an accuracy < 2% of reading, rise time < 260 milliseconds and measurement range between 0 to 100% [9,10]. Sensors were calibrated before protocol as described by the manufacturer. Data was recorded by the software Datex Collect (GE Healthcare/Datex-Ohmeda, Helsinki, Finland) in a laptop and was analyzed off-line.

We simulated two kinds of patients based on lung mechanics. One patient with healthy lungs, with a respiratory compliance of 50 mL/cmH_2O and airways resistance of 5 cmH_2O/L/s, while ventilated with an inspiratory positive airways pressure (IPAP) of 22 cmH_2O, an expiratory positive airways pressure (EPAP) of 8 cmH_2O, a respiratory rate of 15 bpm and an inspiratory time of 0.9 seconds. The other simulated patient with compromised lungs, a respiratory compliance of 30 mL/cmH_2O, an airways resistance of 12 cmH_2O/L/s while ventilated with an IPAP of 28 cmH_2O, an EPAP of 14 cmH_2O, a respiratory rate of 25 bpm and an inspiratory time of 0.9 seconds.

Protocol

In each simulated patient and for all three NIV circuit configurations (Figure 1) we have tested with an increased O_2 supply, from 1 to 10 L/min in incremental steps of 1 L/min, to a final maximum flow of 15 L/min. Each step of O_2 flow was maintained by 3 minutes separated by a washout period of another 3 minutes to reach a stable condition. Simulation was repeated three times in different days by different operators. Data is presented as mean ± SD.

Data of anesthetized patients

Preliminary data recorded in three American Society of Anesthesiologists Classification 1 patients undergoing laparoscopic procedures was used to illustrate the results of simulations. In these patients,

the ventilatory settings and the recording system (S5 device with Datex Collect software both, GE Healthcare/Datex-Ohmeda, Helsinki, Finland) were similar than the simulations for healthy lungs.

Results

Simulations

Main results of simulations are described in table 1. FDO_2 increased proportionally to the external O_2 flow in all setups and for both, healthy and compromised lungs. Option 1 and 2 presented similar FDO_2 with increment in supplementary O_2 flow. The highest FDO_2 was observed with the non-rebreathing valve that reached > 0.90 with an O_2 flow ≥ 10 L/min in both kinds of lungs. The simulation in the patient with compromised lungs showed slightly less FDO_2 than the healthy one in all NIV circuit dispositions.

Table 1: Fraction of delivered O2 reached at different O2 flow for the three NIV circuit dispositions in healthy and sick lungs.

O_2 Flow (L/min)	Healthy lungs			Sick lungs		
	Option 1 (leak at HME)	Option 2 (Bain)	Option 3 (N-R valve)	Option 1 (leak at HME)	Option 2 (Bain)	Option 3 (N-R valve)
1	0.27 ± 0.01	0.26 ± 0.01	0.35 ± 0.04	0.26 ± 0.01	0.25 ± 0.01	0.32 ± 0.02
2	0.31 ± 0.01	0.31 ± 0.02	0.52 ± 0.12	0.31 ± 0.01	0.29 ± 0.01	0.42 ± 0.04
3	0.34 ± 0.01	0.36 ± 0.02	0.69 ± 0.08	0.35 ± 0.01	0.32 ± 0.01	0.54 ± 0.08
4	0.41 ± 0.02	0.45 ± 0.03	0.78 ± 0.13	0.40 ± 0.01	0.37 ± 0.02	0.64 ± 0.10
5	0.53 ± 0.04	0.49 ± 0.04	0.84 ± 0.08	0.47 ± 0.02	0.41 ± 0.02	0.74 ± 0.09
6	0.58 ± 0.08	0.54 ± 0.06	0.89 ± 0.08	0.51 ± 0.01	0.45 ± 0.03	0.80 ± 0.10
7	0.63 ± 0.09	0.59 ± 0.06	0.91 ± 0.06	0.55 ± 0.01	0.49 ± 0.03	0.89 ± 0.05
8	0.70 ± 0.10	0.63 ± 0.08	0.93 ± 0.05	0.61 ± 0.03	0.54 ± 0.04	0.93 ± 0.04
9	0.75 ± 0.12	0.67 ± 0.09	0.94 ± 0.05	0.67 ± 0.05	0.57 ± 0.05	0.95 ± 0.03
10	0.81 ± 0.14	0.74 ± 0.09	0.95 ± 0.03	0.73 ± 0.05	0.61 ± 0.04	0.97 ± 0.01
15	0.88 ± 0.09	0.85 ± 0.08	0.97 ± 0.02	0.83 ± 0.05	0.77 ± 0.08	0.98 ± 0.01

HME = heat and moisture exchange antibacterial/antiviral filter. Bain = anesthesia Bain circuit. N-R = non-rebreathing valve.

Data of anesthetized patients

We included data of 3 healthy adult patients undergoing laparoscopic surgery with general anesthesia (1 male/2 females, age 45 ± 15 years old, weight 69 ± 12 kg and height 165 ± 17 cm). Table 2 showed the FiO_2 reached at 5, 10 and 15 L/min with the three types of NIV circuits studied. Data was quite similar to the values obtained during simulations of patients with healthy lungs. The highest FDO_2 was reached by the non-rebreathing valve at all supplemental O_2 flows just like with the simulations.

Table 2: Fraction of delivered O_2 at different supplemental O_2 flow in real anesthetized patients.

O_2 Flow (L/min)	Anesthetized patients		
	Option 1 (leak at HME)	Option 2 (Bain)	Option 3 (N-R valve)
5	0.49 ± 0.04	0.46 ± 0.06	0.80 ± 0.07
10	0.75 ± 0.05	0.72 ± 0.08	0.89 ± 0.02
15	0.84 ± 0.02	0.80 ± 0.02	0.91 ± 0.01

HME = heat and moisture exchange antibacterial/antiviral filter. Bain = anesthesia Bain circuit. N-R = non-rebreathing valve.

Figure 2 showed the temporal series of the main output variables (flow, pressure, capnography and oxigraphy) in one patient using the setup described in option 2. The patient was undergoing a laparoscopic surgery with an IPAP of 21 cmH_2O and EPAP of 10 cmH_2O. Airways pressure was maintained at the set pressures without any CO_2 rebreathing. The lack of CO_2 rebreathing was confirmed by capnography because the CO_2 signal reached zero at the end of expiration.

Figure 3 depicted an increase in FDO_2 caused by incremental O_2 flow in other patient using the option 1 with a fixed ventilatory pattern. The upper figure shows the kinetics of O_2 during the increase in O_2 flow from 0 to 5 L/min. Both, the fraction of O_2 at end-inspiration and end-expiration reached a new equilibrium in a few breaths.

Figure 4 shows the increase in FDO_2 for each NIV circuit options analyzed when O_2 flow was increased in steps of 5 L/min. Data was collected in the same patient with the same ventilatory settings than simulation of healthy lungs. Results are similar to the ones observed during the simulations; where the setup using the non-rebreathing valve showed the highest FDO_2 values when compared to options 1 and 2.

Discussion

Our results describe the range of FDO_2 reached by three different NIV circuit configurations in simulated intubated patients with healthy and compromised lungs. The FDO_2 was related to the administered O_2 flow in all setups and reached the highest value with the use of a non-rebreathing valve. This data gives information about how much O_2 can be delivered by NIV devices when using for mandatory invasive ventilation.

The values of FDO_2 obtained by simulations (Table 1) corresponded to the data observed in anesthetized patients at similar ventilatory settings and supplemental O_2 flow (Table 2). However, the FDO_2 values we found are much higher than those simulations reported during spontaneous breathing using facial interfaces [6,7]. These differences are probably due to the unintended leaks commonly observed around masks that do not happen in patients with sealed circuit and cuffed endotracheal tube. The leaks throughout the mask are compensated by the NIV device increasing flow to maintain the set pressures. This effect dilutes the O_2 and changes FDO_2 within the NIV circuit because the supplemental O_2 flow keeps constant.

The lower FDO_2 observed in sick lungs compared with healthy lungs could be explained by the high IPAP and EPAP used in the former. These results fit with the description of Schwartz et al. [6] and Thys et al. [7] using bench models and volunteers. The authors found that selecting high pressures increase not only the flow through the leak but also the NIV flow to compensate such leaks. The final result is the dilution of O_2 within the NIV circuit and the consequent reduction in the FDO_2.

The NIV circuit with the unidirectional, non-rebreathing valve showed the highest FDO_2. This is because such valve allows unidirectional flow during the respiratory cycle phases. The “leak” is closed during inspiration and fresh gases reach the patient. Then, the expired gases rich in CO_2 tend to scape outside through the valve during expiration. The combination of these effects is a lower dilution of O_2 within the single circuit of NIV. Thus, this NIV circuit disposition must be used in those cases when high FDO_2 is necessary like in patients with severe respiratory failure or during one-lung anesthesia. The main disadvantage of this NIV circuit disposition is the additional expiratory work imposed by the non-rebreathing and PEEP valves. This is a problem during assisted ventilation (S/T mode) that can be easily resolved by changing to circuit options 1 or 2 at the very moment when a patient is ready to re-start spontaneous breathing.

Limitations

We have simulated changes in FDO_2 caused by increments in the O_2 flow supply, keeping constant all the other ventilatory variables. Such variables like IPAP/EPAP values, placement of circuit leak, place of supplemental O_2 administration, respiratory rate, inspiratory time, etc. could affect the FDO_2 in NIV devices used as invasive ventilators. Due to the urgency to get alternative ventilatory options during the COVID-19 pandemic, we believe that the information we generated, while limited to changes in additional O_2 flow, it may prove useful to intensive care health-providers and anesthesiologists at this stage. Further studies should be done to get more information on the topic.

Conclusion

This study gives clinical information to manage FDO_2 when NIV devices are used for mandatory ventilation in intubated patients. The range of FDO_2 reached by all NIV circuit options covers the range of

values used in our ventilated patients with intensive care/anesthesia ventilators. Our results should not be transferred to patients in spontaneous assisted ventilation and surely new studies should be done to cover this issue.

Declarations

Informed Consent:

The IRB of the Hospital Privado de Comunidad, Mar del Plata, Argentina approved the use of clinical data recorded in three anesthetized patients to illustrate the results of simulations (waiver for patients' written informed consent).

Fundings: The study was supported by local resources of the Simulation Center of Buenos Aires Association of Anesthesia, Analgesia y Reanimation, Buenos Aires, Argentina.

Conflict of Interest Statement: No potential conflicts of interest exist.

Availability of data: on request.

Authors' contributions: Gerardo Tusman: Literature search, data collection, study design, manuscript preparation, review manuscript. Emiliano Gogniat: Literature search, data collection, review manuscript. Gustavo A. Plotnikow: Literature search, data collection, review manuscript. Marcelo D. Campos: Literature search, data collection, study design, manuscript preparation, review manuscript.

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Figures

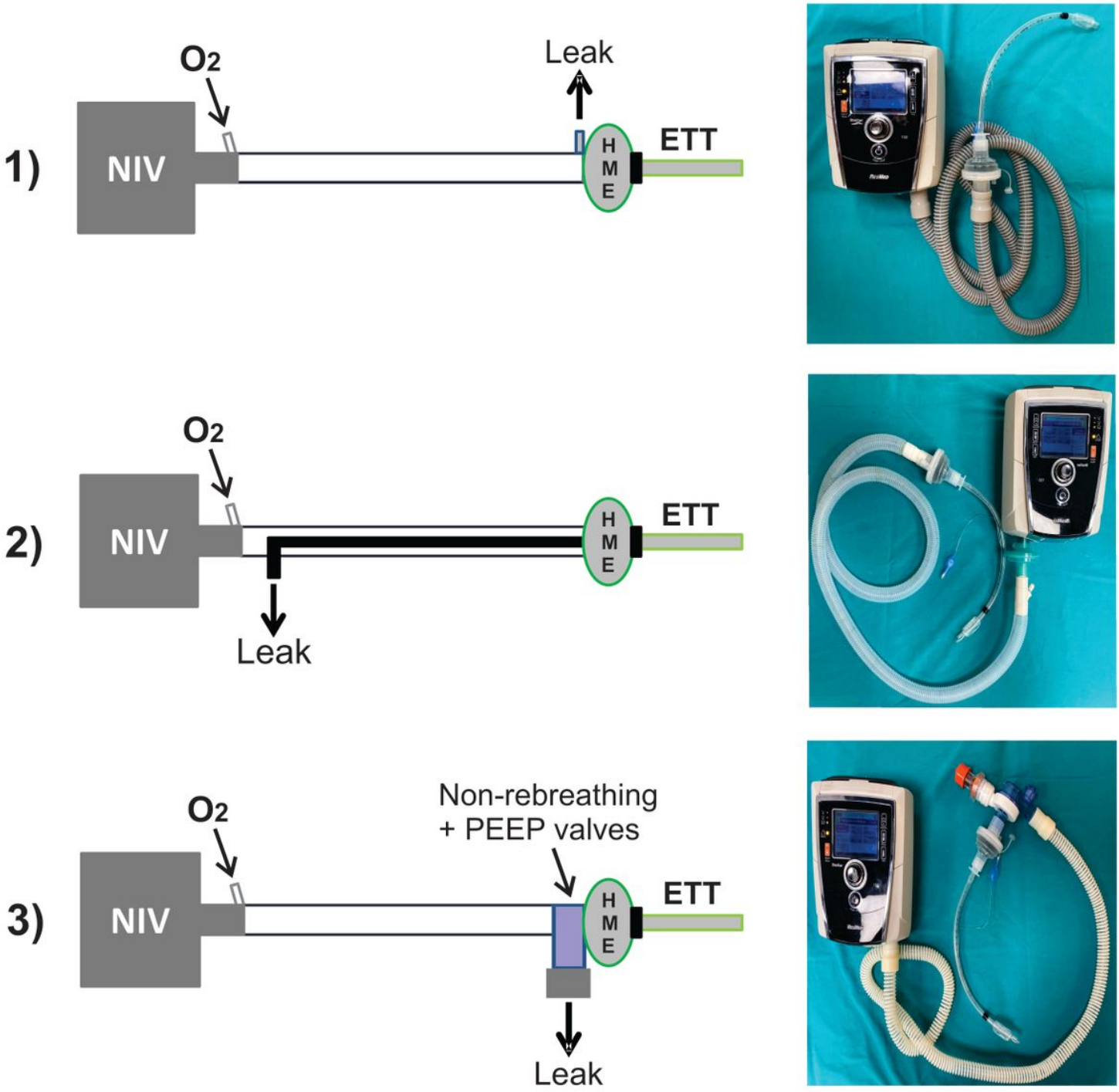

Figure 1

Three NIV circuit configurations to perform mandatory ventilation were studied. In option 1 the leak is placed distal to the NIV device, at the heat and moisture exchange (HME) filter. The second option is a modified anesthesia Bain coaxial circuit, where inspired gases go through the external limb and the expired gases are eliminated by the internal coaxial tube. The third option has a non-rebreathing unidirectional valve. Such valve is placed behind the HME where all the exhaust gases come outside the circuit through a PEEP valve. In all options, supplemental oxygen (O2) is administered between the NIV device and its single circuit.

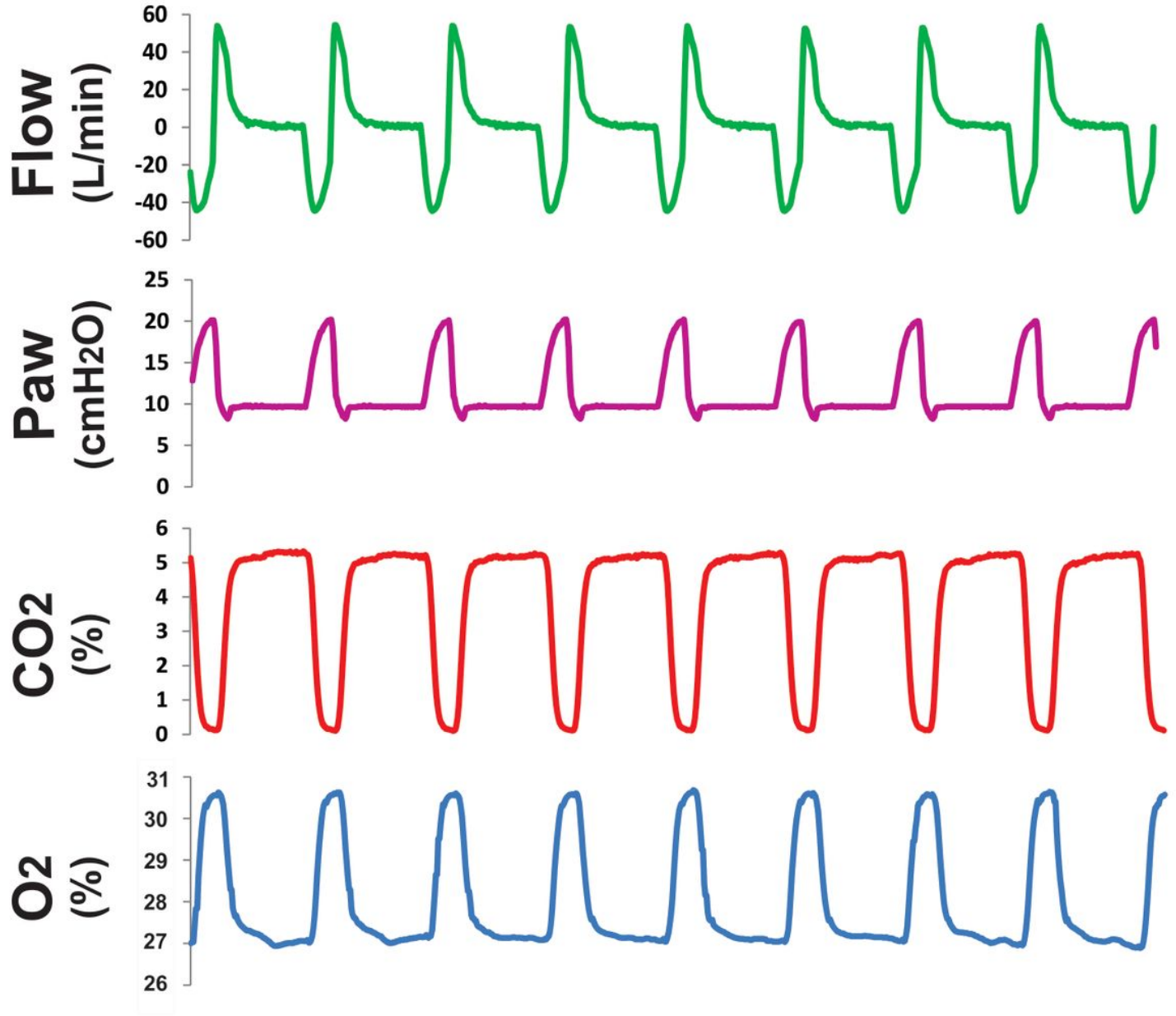

Figure 2

Flow, pressure, capnography (CO2) and oxygraphy (O2) temporal series were collected in a patient undergoing general anesthesia using a Bain circuit (Option 2). Note that oxygraphy is a mirror image of capnography.

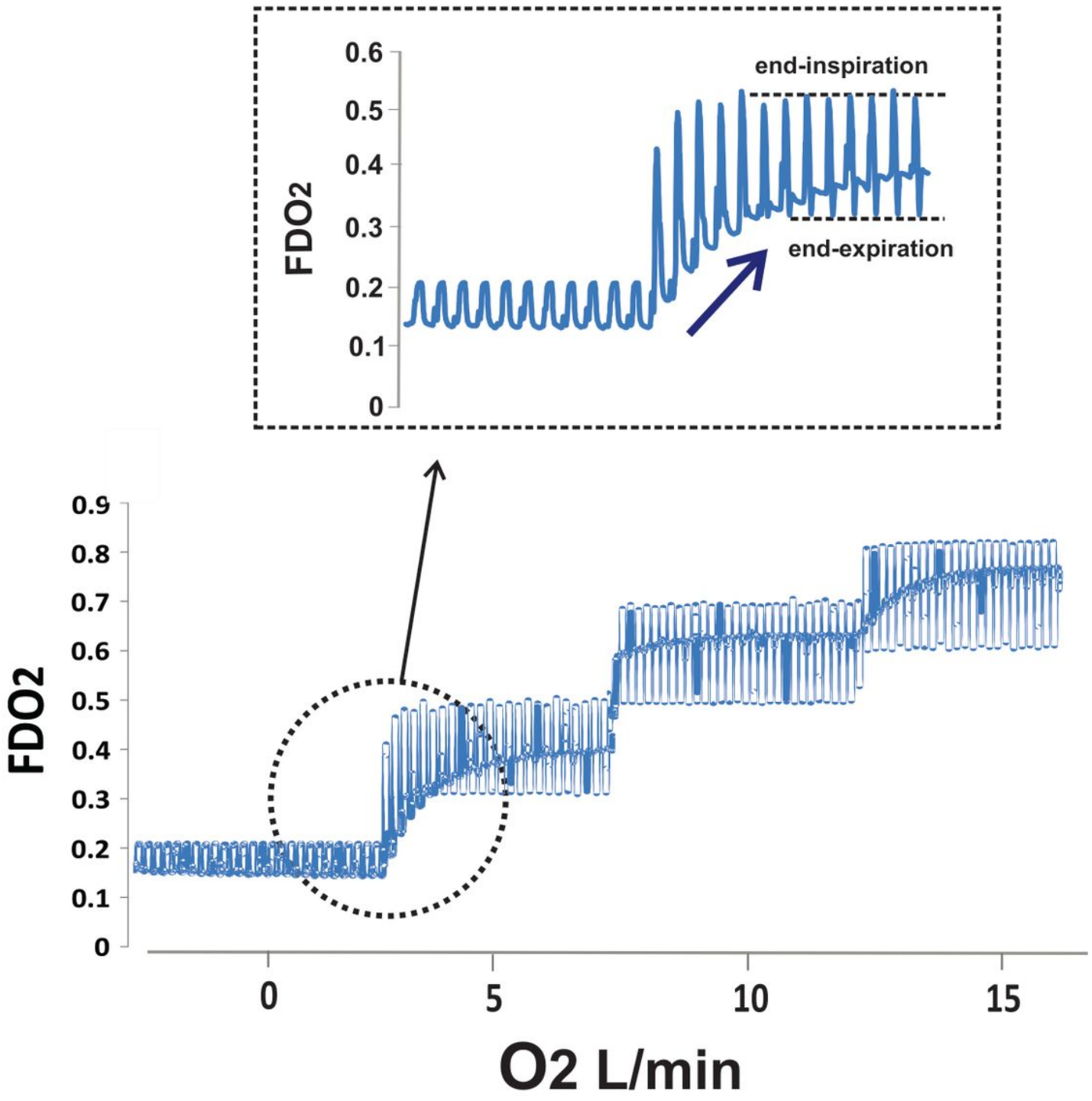

Figure 3

Supplemental O2 flow was changed in one anesthetized patient during fixed ventilation using option 1 (leak at HME filter). Ventilatory settings was similar to the one simulated in a healthy patient. The figure on the top depicts how fast the fraction of O2 at end-inspiration and end-expiration reached stable values after the addition of 5 L/min of O2.

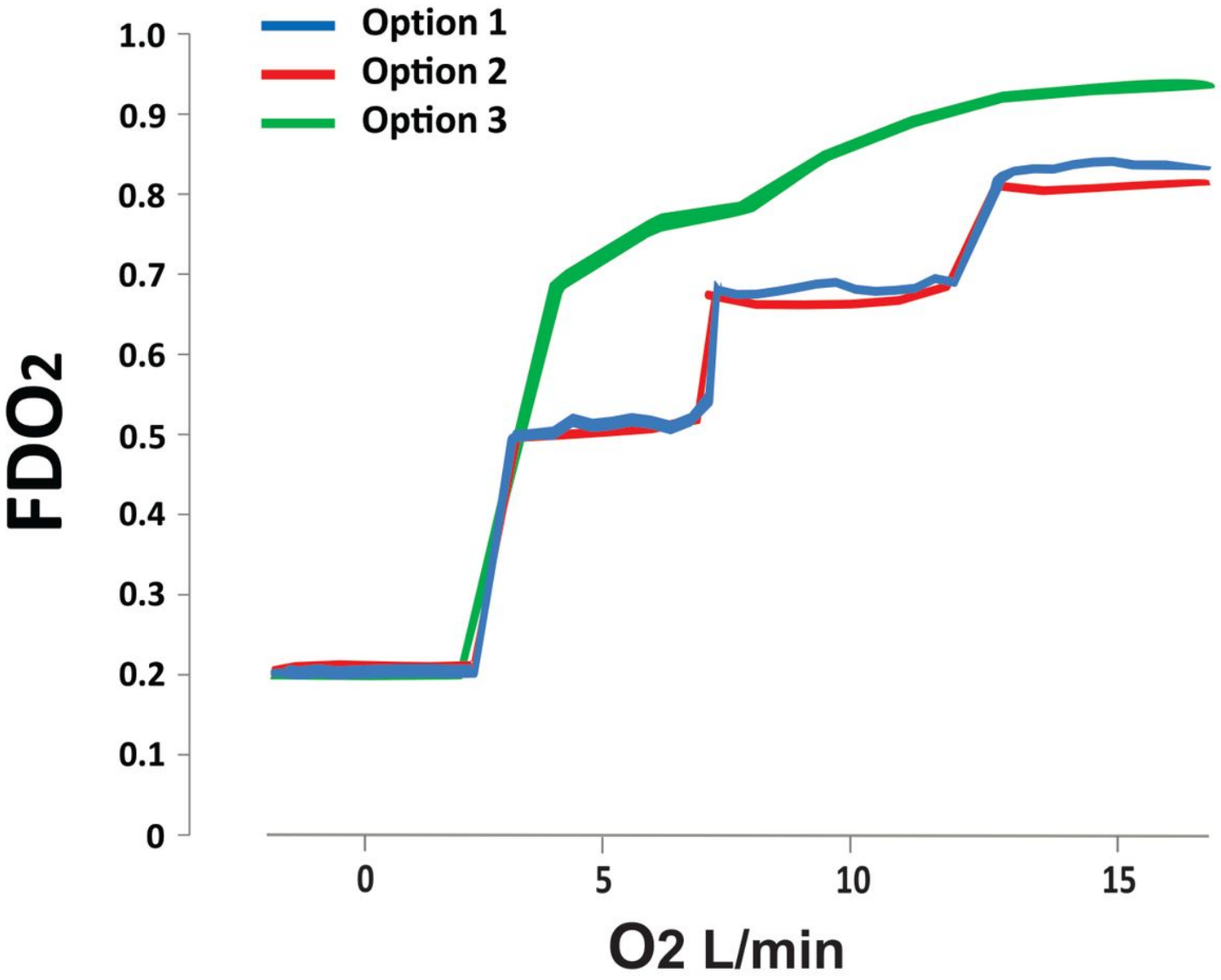

Figure 4

Each NIV circuit analyzed belongs to an anesthetized patient ventilated with the same setting than the simulation performed in healthy lungs. Supplemental O2 was increased in three steps. Blue = option 1, distal leak at HME. Red = option 2, anesthesia Bain circuit. Green = option 3, non-rebreathing valve.