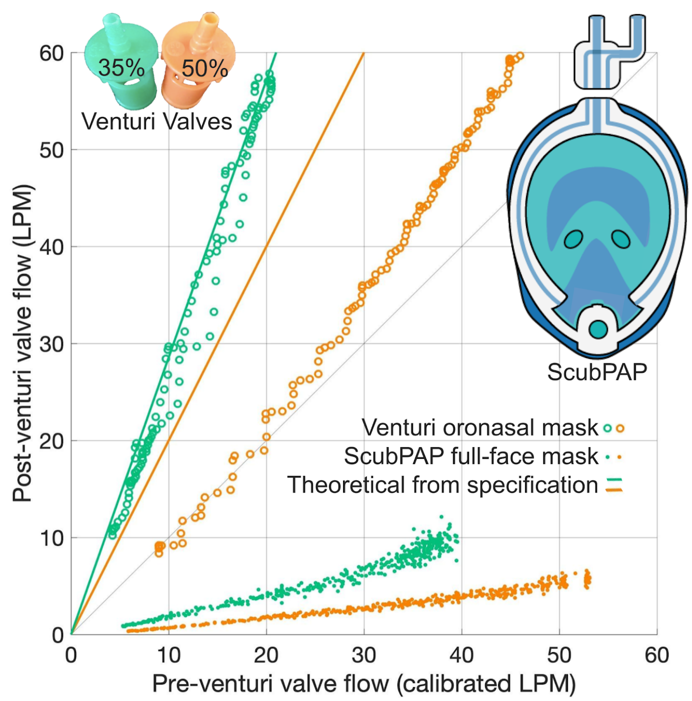
Title On the Use of Venturi Valves to Control Oxygen Supplementation During Positive Airway Pressure Support With ScubPAP Circuits

Introduction Many hospitals throughout the globe were unprepared for COVID-19 patient surges [1] and resorted to free and open source solutions [2] to palliate shortages of essential medical supplies and equipment. For example, snorkeling masks have been repurposed as personal protective equipment [3] or to provide oxygen therapy with positive pressure support [4]. Very little hard data (e.g. [5]), even outside peer-reviewed journals, are available to inform the last-resort use of such unauthorized devices.

Here we report a finding from our continuously evolving open research [6] on the use of snorkeling mask adaptations for oxygen and Continuous Positive Airway Pressure (CPAP) therapy (for which we propose the term ScubPAP). We extend Landry *et al.* [5]'s and show that venturi valves do not dilute the oxygen delivered to ScubPAP configurations clinically used in Italy [4] and Belgium [7] (personal communications). It suggests patients' FiO_2 can be much larger than specified by a given venturi valve and likely always close to 100%, with a risk to overestimate patients' PaO_2/FiO_2 ratio.

Method We estimated dilution of oxygen by measuring air flow before and after the venturi valve: larger post-venturi flows indicate the valve entrains room air into the circuit and dilutes input gases to concentrations corresponding to the pre-venturi flow (figure's x axis) divided by the post-venturi flow (figure's y axis). Our input circuit begins with a wall-mounted source of compressed medical air feeding to oxygen tubings, a 19mm-ID adapter, a rotameter (pre-venturi flow; Fischer & Porter 10A1735S, 8 to 97 LPM), standard 19mm-ID medical corrugated tubings, another 19mm-ID adapter, <1cm-long oxygen tubings, a venturi valve (specified to dilute to 35% or 50%; color coded according to the figure's top left picture), 19mm-ID corrugated tubings, a low-resistance digital flowmeter (post-venturi flow; Sensirion Sensirion SFM3000-200, 0 to 100 LPM) and 19mm-ID corrugated tubings, all connected in series.

This input circuit feeds to either the AirLife® oronasal mask specified for the venturi valve by Vyaire Medical (*venturi mask*) or a "Charlotte Valve" [4]-like thermoplastic-injected adapter [7] connected the Easybreath snorkeling full-face mask by Decathlon (*ScubPAP*, figure's top right picture, air flow channels in pale blue). Both masks are fitted on a realistic 3D-printed head model (figure's top right picture, deeper blue color). For the ScubPAP, air flows through the "inhalation port" of the adapter and the



Capacity of venturi valves to dilute gases through air entrainment
Above the diagonal, the valve entrains room air into the system, diluting input gases. Below the diagonal, there is no dilution as input gases are instead expelled from the valve.

central channel of the mask's opening on the *eye chamber*, then through the two openings into the oronasal chamber (both one-way valves removed). The one-way valve at the chin opening was inverted to force air outflow through the mask's side channels and the adapter's "exhalation port". The ScubPAP exhalation port feeds to the output circuit, beginning with 19mm-ID corrugated tubings followed by an anti-viral filter and a PEEP valve set at 20 mmH_2O, all connected in series. In an additional experimental condition, flow was reversed by switching the inhalation and exhalation ports.

For each condition, we acquired flow data while manually ramping up flow from the wall source in steps of <10 LPM, excluding data from the ramping down phase. We recorded digital flowmeter data using an Arduino UNO microcontroller, displaying acquisition time on a laptop screen. We digitized data from the rotameter through image processing of video footages of the experiment that also included the displayed acquisition time for synchronization. This digitization used a combination of in-house Python scripts using OpenSV libraries [8] and Matlab Scripts. The rotameter was calibrated to the digital flowmeter during post-processing from data acquired with no venturi valve.

Results The colored lines on the graph of the inserted figure show the theoretical expectation of perfect 35% (green) or 50% (orange) dilution of pre-venturi gas with entrained room air. For example, feeding 20 LPM to the 50% venturi valve would entrain 20 LPM of room air and produce a 40 LPM post-venturi flow. No entrainment (i.e. no dilution) would produce data falling on the diagonal unity line.

With the venturi mask (empty circles), data from the 35% venturi valve closely follows the prediction. Data from the 50% venturi valve indicates lower than expected dilution, but follows a line above and steeper than the diagonal of no dilution. Data acquired with the ScubPAP (solid dots) however all fall below the diagonal line, indicating that room air is not entrained in the circuit but rather that input air is expelled out of the venturi valve.

Discussion Our control condition shows that the venturi valves, when used with their specified mask, do dilute input gases to various concentrations. The lower than expected dilution of the 50% venturi valve might relate to the static "non-breathing" nature of our test system, but calls for replication as human error cannot be excluded. Connected to our ScubPAP circuits, venturi valve dilution fails and oxygen would be wasted. This may be due to the high flow resistance of the fully serial ScubPAP circuits tested here [6]. Landry *et al.* [5]'s showed proper venturi valve dilution of input oxygen, but with a likely less resistive ScubPAP circuit where input flow can by-pass the common inhalation/exhalation port mounted in parallel.. Another difference is the use of "breathing" human subjects, such that our experiment should be repeated with a dynamic "breathing" system, e.g. by connecting a lung simulator to the plastic head model. It should also be noted that other venturi valve designs may perform better under high resistance [4].

Other preliminary data from our ScubPAP Documentation Project [6] support the clinical functionality of the ScubPAP circuits tested here, i.e. sufficient inspiratory flow and positive airway pressure support. Though it remains to be directly assessed, the smaller dead space of our ScubPAP circuit configurations should make them less prone to the CO_2 rebreathing found by Landry *et al.* [5]. The price is a compromised capacity of venturi valves to control patients' FiO_2, likely delivering close to 100% FiO_2. The latter calls for more direct measures of oxygen dilution as in Landry *et al.* [5], given the important consequences on clinical decisions based on the PaO_2/FiO_2 ratio. An alternative solution could be to dilute oxygen by source mixing with compressed medical air [5,7].

Bibliography

1. Grasselli G, Pesenti A, Cecconi M. Critical Care Utilization for the COVID-19 Outbreak in Lombardy, Italy: Early Experience and Forecast During an Emergency Response. JAMA. 2020. doi:10.1001/jama.2020.4031

2. Maia Chagas A, Molloy JC, Prieto-Godino LL, Baden T. Leveraging open hardware to alleviate the burden of COVID-19 on global health systems. PLoS Biol. 2020;18: e3000730. doi:10.1371/journal.pbio.3000730

3. Kroo L, Kothari A, Hannebelle M, Herring G, Pollina T, Chang R, et al. Pneumask: Modified Full-Face Snorkel Masks as Reusable Personal Protective Equipment for Hospital Personnel. medRxiv. 2020. Available: https://www.medrxiv.org/content/10.1101/2020.04.24.20078907v1?rss=1

4. Easy – Covid19 ENG. In: Isinnova [Internet]. 19 Mar 2020 [cited 13 Aug 2020]. Available: https://www.isinnova.it/easy-covid19-eng/

5. Landry SA, Mann DL, Djumas L, Messineo L, Terrill PI, Thomson LDJ, et al. Laboratory performance of oronasal CPAP and adapted snorkel masks to entrain oxygen and CPAP. Respirology. 2020. doi:10.1111/resp.13922

6. Proulx S, Ruiz T, McClurg P, editors. The ScubPAP Documentation Project. Available: https://docs.google.com/document/d/1IIxzLe9wkgt4wh4kcznvBKmciGSwYmCgXIALS6mYUII/edit

7. Bonnier F. Connecteur AIRasme pour masques de plongée Décathlon : plans de confection. In: Hôpital Erasme [Internet]. 1 Apr 2020 [cited 14 Aug 2020]. Available: https://www.erasme.ulb.ac.be/fr/formulaires/connecteur-airasme-pour-masques-de-plongee-decathlon-plans-de-confection

8. BRADSKI, G. The OpenCV library. Dr Dobb's J Software Tools. 2000;25: 120–125. Available: https://ci.nii.ac.jp/naid/10028167478/