Clinical Implementation of Automated Oxygen Titration in a Tertiary Care Hospital

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BACKGROUND: When treating acute respiratory failure, both hypoxemia and hyperoxemia should be avoided. S_{pO_2} should be monitored closely and O_2 flows adjusted accordingly. Achieving this goal might be easier with automated O_2 titration compared with manual titration of fixed-flow O_2. We evaluated the feasibility of using an automated O_2 titration device in subjects treated for acute hypoxemic respiratory failure in a tertiary care hospital. METHODS: Health-care workers received education and training about oxygen therapy, and were familiarized with an automated O_2 titration device (FreeO$_2$). A coordinator was available from 8:00 AM to 5:00 PM during weekdays to provide technical assistance. The ability of the device to maintain S_{pO_2} within the prescribed therapeutic window was recorded. Basic clinical information was recorded. RESULTS: Subjects were enrolled from November 2020 to August 2022. We trained 508 health-care workers on the use of automated O_2 titration, which was finally used on 872 occasions in 763 subjects, distributed on the respiratory, COVID-19, and thoracic surgery wards, and in the emergency department. Clinical information could be retrieved for 609 subjects (80%) who were on the system for a median (interquartile range) of 3 (2-6) d, which represented 2,567 subject-days of clinical experience with the device. In the 82 subjects (14%) for whom this information was available, the system maintained S_{pO_2} within the prescribed targets 89% of the time. Ninety-six subjects experienced clinical deterioration as defined by the need to be transferred to the ICU and/or requirement of high flow nasal oxygen but none of these events were judged to be related to the O_2 device. CONCLUSIONS: Automated O_2 titration could be successfully implemented in hospitalized subjects with hypoxemic respiratory failure from various causes. This experience should foster further improvement of the device and recommendations for an optimized utilization. *Key words: respiratory failure; oxygen supplementation; automated oxygen titration; hypoxemia; hyperoxemia; oxygen saturation.* [Respir Care 2024;69(9):1081–1091. © 2024 Daedalus Enterprises]

Introduction

Oxygen supplementation is ubiquitous in hospitalized patients with hypoxemic respiratory failure. Traditionally, the main concern of clinicians was to alleviate hypoxemia with little concern for hyperoxemia, except in the neonatal population[1] and in COPD, where avoidance of hyperoxia to protect against respiratory acidosis was recommended.[2] However, the appreciation that hyperoxemia may also be harmful in other conditions, such as sepsis and myocardial infarction, and after emergency surgery,[3] has led to recommendations that S_{pO_2} should be maintained within therapeutic zones that vary according to the cause of respiratory failure. For example, the British Thoracic Society has proposed S_{pO_2} targets of 94 to 98% for patients who are the most acutely ill or 88 to 92% in those at risk of hypercapnic respiratory failure.[4] Although guidelines for oxygen therapy are not uniform,[4-8] their implications are that S_{pO_2} should be monitored closely and O_2 flows adjusted frequently to maintain patients within a relatively narrow therapeutic window. Achieving this goal with manual O_2 titration is labor intensive and often not feasible in the context of routine care.[9] As such, it is common that patients are found outside the desired range of S_{pO_2}, both in the hypoxemic and hyperoxemic ranges.[10-12]

Automated O_2 titration with devices that are based on closed-loop algorithms has been developed with the objective of maintaining S_{pO_2} by providing continuous adjustment of O_2 flow in the context of fluctuating oxygen requirements.[13,14] These devices have been shown to increase the proportion of time spent in the desired S_{pO_2} range in various clinical situations, including hospitalized subjects with COPD

exacerbation,[11,14] subjects in the emergency department,[12] subjects after surgery,[15,16] and subjects in COVID-19–related hypoxemic respiratory failure.[17] Automated O_2 titration has also been shown to be effective in situations in which rapid adjustments of O_2 flows is required, for example, during exercise.[18-20] It might also accelerate weaning from oxygen and hospital discharge,[11,12,21] with potential reduction in hospitalization costs.[22] Automated O_2 titration has been implemented with high-flow nasal cannula, showing efficacy of the system to maintain S_{pO_2} within the desired target zone during walking exercise in patients with COPD and in the context of hypoxemic respiratory failure.[23,24] By reducing the requirement for direct contacts between hospital workers and patients because the O_2 flows are automatically adjusted, the risk of transmission of contagious disease is reduced.[25] This is an important consideration given the scarcity of hospital workers, overloaded health-care systems, and the high risk of hospital transmission of pathogens[25,26] among health-care workers during the recent pandemic.[27] The cumulative experience with automated O_2 titration has been obtained in the research context, data also needs to be obtained in the clinical setting. We evaluated the feasibility of using this technology in the clinical care of subjects treated for acute hypoxemic respiratory failure in a tertiary care hospital.

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QUICK LOOK

Current knowledge

It is recommended that S_{pO_2} be closely monitored to avoid hypoxemia and hyperoxia when treating patients with acute respiratory failure. Maintaining S_{pO_2} within a relatively narrow therapeutic window may be challenging with manual O_2 titration, the standard of care in oxygen therapy. Automated O_2 titration systems are currently being developed to reach this objective but their use is mostly limited to research settings.

What this paper contributes to our knowledge

Automated O_2 titration was implemented safely in the clinical care of subjects treated for hypoxemic respiratory failure in a tertiary care hospital. We also found that the ability of automated O_2 titration to maintain S_{pO_2} within the desired range in various diseases may also apply to "real life" clinical situations.

Methods

In 2019, a multidisciplinary committee advised hospital administrators on the possibility of implementing automated O_2 titration within the context of clinical care. In 2020, 30 automated O_2 titration devices were acquired by the hospital to treat patients in the emergency department or the hospital wards with various forms of hypoxemic respiratory failure, including COPD exacerbation, exacerbation of interstitial lung disease, viral (COVID-19) or bacterial pneumonia, and heart failure. This was done in the context of a prospective observational technological evaluation that took place between September 2020 and August 2022 at the Institut universitaire de cardiologie et de pneumologie de Québec, a 330-bed tertiary care, university-affiliated hospital with specialization in cardiology and respiratory medicine. When possible, clinical information, including etiology of respiratory failure, duration of O_2 therapy, and hospital length of stay were noted. Prospectively collecting clinical data on the participants was exempted from ethics committee review by the institution because this was considered to be part of routine clinical care. The permission to use the clinical data anonymously for a scientific report was granted by the medical director of the hospital with a waiver of consent from the institutional ethics review board, when considering that this evaluation was done in the context of clinical care. The manufacturer had no role in data collection, interpretation, and presentation.

The automated O_2 titration device used in this technological evaluation (FreeO_2, Oxynov, Québec City, Canada) relies on continuous S_{pO_2} recording to feed a closed-loop algorithm, which allows automatic O_2 flow titration to maintain S_{pO_2} within a target window prescribed by the clinician.[13] The device is coupled with a finger sensor linked to an embedded pulse oximeter (OEM III Module, Nonin Medical, Plymouth, Minnesota). The automated O_2 titration device has 3 operating modes, the closed-loop mode being the primary operating mode, whereby O_2 flow is changed based on measurement of S_{pO_2}. In the closed-loop mode, O_2 flow is automatically titrated based on the difference

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Table 1. Composition and the Role of the Members of the Multidisciplinary Team

Member	Role
Respiratory physicians	Patient safety
	O_2 prescription rules
Nurses, respiratory therapists	Elaborating nurse practice rules
	Standardizing practices with regard to O_2 therapy
	Initiating O_2 therapy
	Surveillance and patient follow-up
	O_2 weaning
Physiotherapists	Patient mobilization
	Ensuring appropriate oxygenation during mobilization
Patient representative	Patient comfort and safety
Project coordinator	Teaching hospital workers
	Overseeing the use of automated O_2 titration in the hospital
	Addressing any questions and/or concerns about the device

between the real-time S_{pO_2} and the target value by using a proprietary proportional integral algorithm with an O_2 flow command adjustment rate of once per second to achieve or maintain a pre-set S_{pO_2} level. O_2 flow is limited to 0.1 to 20.0 L/min. O_2 flow may increase or decrease so as to maintain a stable S_{pO_2}. The constant-flow mode is comparable with a standard O_2 regulator, with the device only providing fixed O_2 flow as set by the attending physician, between 0.1 and 20.0 L/min. In the acquisition mode, the device only monitors the oximeter readings (S_{pO_2}, breathing frequency, and heart rate) without any oxygen being provided. Data are visible on the front screen and captured in the device memory, from which it can be retrieved as long as the corresponding subject has been appropriately identified in the system (name, date of birth) when initiating therapy. However, this was not mandatory to initiate treatment with O_2 titration device, and this step was often overlooked by health-care workers.

The implementation of automated O_2 titration in clinical care of the hospital followed a multistep process to acclimate hospital workers to its use. A multidisciplinary implementation committee composed of nurses, respiratory therapists, physicians, a physiotherapist, and a patient representative oversaw the implementation of the devices and made recommendations about use (Table 1). A coordinator (PAB), helped by a senior nursing consultant (GPR) and one physician (FL), trained hospital workers (nurses, respiratory therapists, physicians) in various aspects of oxygen therapy and about the use of automated O_2 titration. Training sessions were planned to be done in person but due to infection control measures in the COVID-19 pandemic, they were delivered remotely. The teaching material remained available for subsequent consultation if needed. The main topics covered were the following: (i) update on oxygen therapy, including the importance of avoiding hypoxemia and hyperoxemia; (ii) prescribing oxygen with lower and upper S_{pO_2} boundaries in a specific patient population and revision of the current guidelines; and (iii) practical use of automated O_2 titration, including monitoring of subjects with the device, accurate patient selection, accurate S_{pO_2} target, and potential issues associated with improper use of the device. A key learning objective was the detection of clinical deterioration with automated O_2 titration. With fixed O_2 flow, clinical deteriorations are detected when S_{pO_2} worsens. With automated O_2 titration, S_{pO_2} remains stable during disease instability. This is due to the intrinsic ability of automated O_2 titration to maintain S_{pO_2} within the target zone as long as the maximum O_2 flow allowed by the device is not surpassed. With automated O_2 titration, clinical deteriorations, rather, are detected when requirements for O_2 flow increase to maintain the target S_{pO_2}, which is a major change of practice for health-care workers.

The coordinator (PAB) oversaw the use of automated O_2 titration from 8:00 AM to 5:00 PM during weekdays to address any concerns or technical questions with its use. In addition, 4 advanced practice nurses were available to accompany the hospital workers in the early weeks of the project when familiarity with the system had to be developed. A clinical protocol was developed by advanced practice nurses and respiratory therapists to address practical issues with the use of automated O_2 titration (Table 2). This document covered the following topics: (i) contraindications to automated O_2 titration, (ii) initiation of the device, (iii) setting of the clinical parameters of the device according to the clinical situation, (iv) how to mobilize subjects on the device, (v) clinical surveillance for nurses and respiratory therapists of patients on automated O_2 titration, and (vi) weaning from automated O_2 titration.

Patients admitted to the emergency department, respiratory and thoracic surgery wards, or COVID-19 unit with a diagnosis of hypoxemic respiratory failure were potentially eligible to be treated with automated O_2 titration when a device was available. Patients with one or more of the following characteristics were not considered for automated O_2 titration: (i) requirement for >8 L/min of O_2 to obtain a S_{pO_2} of $\geq 92\%$ on the respiratory ward or emergency department or > 6 L/min of O_2 to obtain an S_{pO_2} of $\geq 90\%$ on the COVID-19 unit; (ii) requirement for noninvasive ventilation, high-flow nasal cannula, imminent endotracheal intubation, or cardiac arrest; (iii) impossibility of measuring S_{pO_2} (poor peripheral perfusion, Raynaud, scleroderma); or (iv) agitation and/or absence of collaboration. We did not collect information about patients who were not considered for automated O_2 titration.

The proposed S_{pO_2} targets were 88 to 90% for COPD and 90 to 92% for other causes of hypoxemia but the final

Table 2. Clinical Care Protocol for the Installation of Automated O_2 Titration

Protocol	Result
Rule out contraindications	Requirement for > 8 L/min of O_2 to maintain $S_{pO_2} \geq 92\%$ or > 6 L/min of O_2 to maintain $S_{pO_2} \geq 90\%$ on the COVID-19 unit
	Noninvasive ventilation
	Imminent intubation or cardiac arrest
	High-flow nasal oxygen
	Unable to measure S_{pO_2}
	CO poisoning
	Agitation and/or confusion and/or delirium or non-collaborative patient
How to initiate automated O_2 titration	Proper connection of the device to wall O_2
	Verify O_2 prescription with S_{pO_2} targets
	Choose interface (nasal prongs or mask)
	Ensure appropriate S_{pO_2} signal
	Ensure patient comfort
Setting the clinical parameters of the device	Set oxygenation mode
	Set target S_{pO_2} according to prescription
	Set maximum O_2 flow (10 L/min or according to clinical situation)
	Set maximum O_2 flow alarm (8 L/min)
	Set minimum S_{pO_2} alarm (85%)
	Set breathing frequency alarm (according to clinical situation)
Mobilizing patient within the clinical unit	Change the O_2 source from the wall to O_2 cylinders
Clinical surveillance for nurses	Parameters to be monitored: breathing frequency, S_{pO_2} and O_2 flows, trends in O_2 flows and S_{pO_2}
	Verify S_{pO_2} probe and O_2 interface
	Verify alarms
	Frequency: every 1 h at initiation and then every 4 h in the emergency department or in the COVID-19 unit; twice a day plus as needed on the regular ward
	Contact treating physician when sustained increase in O_2 flow $\geq$ 3 L/min from baseline or in case of clinical deterioration
Clinical surveillance for respiratory therapists	Parameters to be monitored: breathing frequency, S_{pO_2} and O_2 flows, trends in O_2 flows and S_{pO_2}
	Verify S_{pO_2} probe and O_2 interface
	Verify alarms
	Frequency: at initiation, when administering nebulized medication, during routine visit
Weaning of O_2	Initiate weaning when O_2 flow $\leq$ 1 L/min
	Place the automated O_2 titration device in surveillance mode
	Ensure S_{pO_2} remains $\geq$ the lower S_{pO_2} target

decision belonged to the physician. These S_{pO_2} targets are lower than typically recommended[4-8]; they were selected based on our findings that the built-in oximeter that was used with the automated O_2 titration device (OEM III Module; Nonin Medical) systematically underestimates arterial oxygen saturation (S_{aO_2})[28] and with the objective of avoiding hypoxemia and hyperoxemia. Weaning from automated O_2 titration was proposed when O_2 flow was $\leq$ 1 L/min. O_2 flow, S_{pO_2}, and breathing frequency alarms were set at 8 L/min, 85%, and 40 breaths/min, respectively. The use of nasal cannula was recommended when O_2 flows were < 5 L/min; oxygen masks (OxyMask [Medline, Northfield, Illinois] or a simple O_2 mask) were used when O_2 flows were $\geq$ 5 L/min or if it was more comfortable. Health-care workers had the opportunity to answer a short anonymous survey about their experience with automated O_2 titration. The survey was available for one day, covering the 3 working shifts. The following questions were asked: (i) would you consider using an automated O_2 titration device for your patients on oxygen, rarely, occasionally, or often; (ii) did you receive sufficient technical support for the use of automated O_2 titration, yes or no; and (iii) on a 0 to 10 scale, 0 being completely useless and 10 being the most useful, how do you rate the clinical utility of automated O_2 titration?

We report data to support the feasibility of using an automated O_2 titration device in clinical practice, including the number of subjects for each hospital site (respiratory ward, COVID-19 unit, emergency department, thoracic surgery), etiology of respiratory failure, duration on automated O_2 titration, hospital length of stay, S_{pO_2} targets, and S_{pO_2} data. Clinical deterioration, defined as the need for high-flow nasal oxygen and/or transfer to the ICU, was recorded. Whether this was associated with the use of automated O_2 titration or to progression of the underlying disease was documented from the medical chart or by discussing with

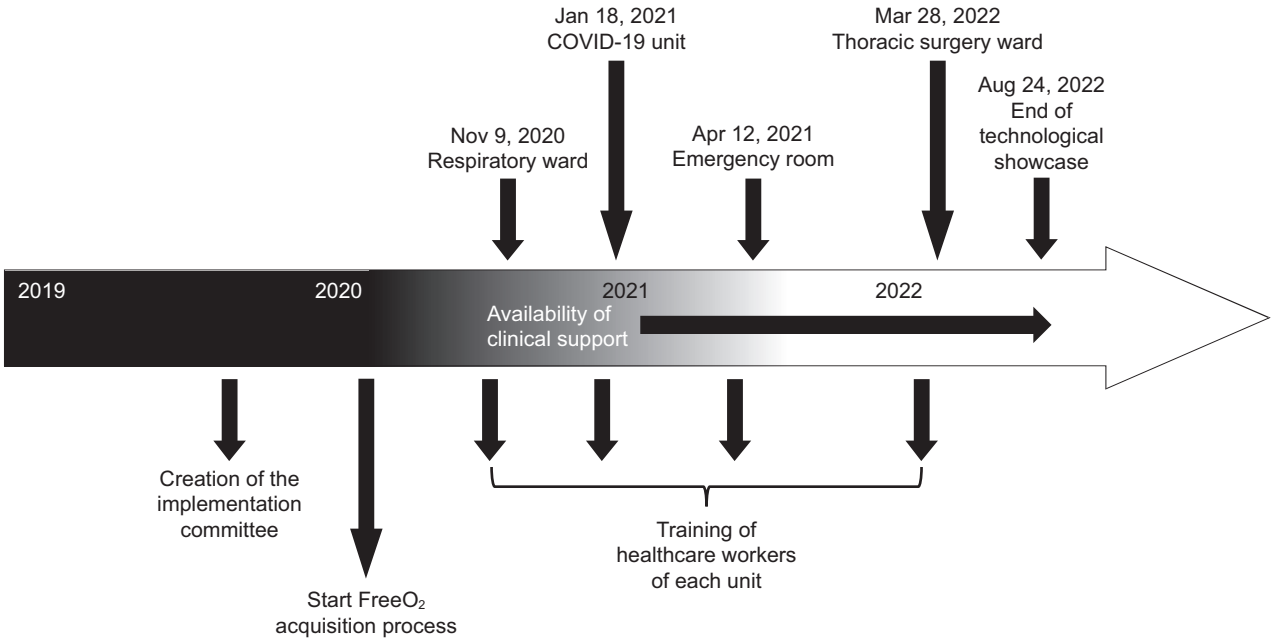

Fig. 1. Chronology of the implementation of the automated O_2 titration device.

the attending physician. We did not pre-specify the number of participants; this was determined by the duration of the project and by the availability of O_2 titration devices. Some subjects were treated twice during the same hospitalization; when this happened, we only reported the first use. Categorical variables are presented as absolute or relative frequencies and were analyzed by using the Fisher exact test. Continuous variables are expressed as mean ± SD or as median (interquartile range [IQR]) according to the variable distribution. The between-group comparison for continuous variables was to perform a one-way analysis of variance. The normality assumption was verified with the Shapiro-Wilk tests by using residuals from the statistical model. The Brown and Forsythe variation of the Levene test statistic was used to verify the homogeneity of variances. Length of hospital stay was log-transformed to fulfill the normality and variance assumptions. We used the Wilcoxon rank-sum test to compare groups when the normality and variance assumptions were rejected. Statistical significance was present with a 2-tailed $P < .05$. Analyses were performed by using SAS version 9.4 (SAS Institute Inc, Cary, North Carolina).

Results

The automated O_2 titration system began to be used on the respiratory ward in November 2020, on the COVID-19 unit in January 2021, in the emergency department on April 2021, and, finally, on the thoracic surgery ward on March 2022, with the last subject enrolled on August 24, 2022 (Fig. 1). A total of 508 health-care workers were trained to the use of automated O_2 titration, including 399 nurses and respiratory therapists, 16 physiotherapists, 28 nurse assistants, 27 physicians (14 emergency physicians and 13 pulmonologists), and 38 medical residents. The flow of subjects is presented in Figure 2. O_2 therapy was administered with the automated O_2 titration device on 872 occasions in 763 subjects distributed on the respiratory, COVID-19, and thoracic surgery wards, and in the emergency department (Fig. 3). Of this number, we could retrieve clinical information on 609 subjects who were in the system for a median (IQR) of 3 (2-6) d, which represented 2,567 patient-days of clinical experience with the device. The characteristics of these subjects are presented in Table 3. The mean ± SD age of the subjects was 72 ± 12 y, median (IQR) hospital length of stay was 9 (6-15) d. Automated O_2 titration was started at a median (IQR) of 0 (0-1) d after hospitalization, most subjects being previously treated with fixed-flow O_2 at 2 L/min (IQR: 1–3 L/min).

Three hundred two subjects of 609 subjects (49.6%) were weaned from oxygen while being on automated O_2 titration, the remaining individuals had a few hours of fixed-flow O_2 at low flows before O_2 therapy was stopped. Due to disease worsening or instability, 42 subjects (7.0%) had to be transferred to the ICU and 81 subjects (13.3%) had to be treated with high-flow nasal cannula, including 54 who received this therapy outside the ICU. Thus, a total of 96 subjects (15.8%) reached the definition of clinical worsening. Under those circumstances, automated O_2 titration was stopped according to the clinical care protocol. Attending physicians attributed these events to deterioration of the underlying condition and not to the use of the automated O_2 titration device. With earlier versions of the software, the system was

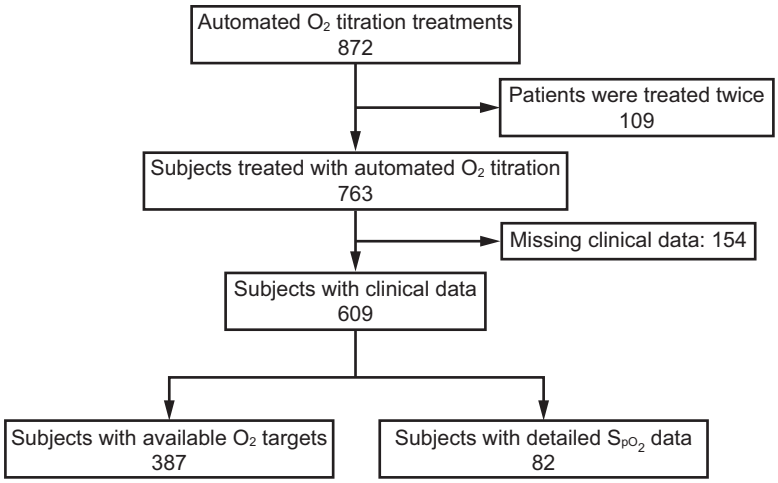

Fig. 2. Flow chart.

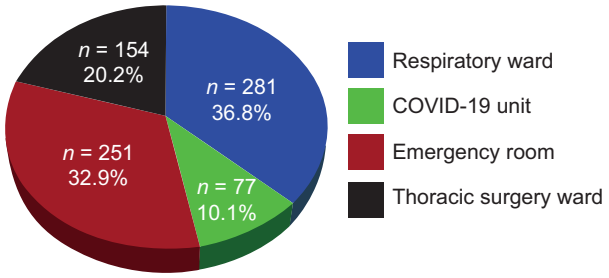

Fig. 3. Distribution of subjects on the automated O_2 titration device.

occasionally unstable and would stop automatically adjusting O_2 flows for unclear reasons. When this occurred, the system automatically reverted to the constant-flow mode, delivering a O_2 flow based on the analysis of the last 15 min of treatment. This functionality, which is also activated when the S_{pO_2} signal is interrupted or of poor quality, was created for safety purposes. These situations were immediately reported to the manufacturer and the software updated version 1.2.6, which was found to be reliable and working as expected.

S_{pO_2} targets prescribed by clinicians were generally in agreement with those proposed by the implementation committee (Table 4). Based on the analysis of 387 subjects for whom the information could be retrieved from the device memory, the S_{pO_2} target was 88% to 90% in 306 subjects (79%), whereas S_{pO_2} target $\geq$ 93% was used in 8 subjects (2.1%). The ability of automated O_2 titration to maintain S_{pO_2} within the desired range could be assessed in 82 subjects for whom detailed S_{pO_2} data could be retrieved from the device memory, 38 from the respiratory ward, 9 from the COVID-19 unit, and 35 from the emergency department. Baseline characteristics of these 82 subjects were similar to those of the 527 subjects for whom the oxygenation data were not available (Table 3). As can be seen in Table 5, the subjects were maintained within the S_{pO_2} target zone for 89% of the time. Hypoxemia (S_{pO_2} < 85%) occurred in < 5% of recording time, whereas hyperoxemia (S_{pO_2} $\geq$ 98%) was found < 1% of recording time. Thirty-six of 508 health-care workers (7.1%) who used the automated O_2 titration device filled out the survey about its utilization. Twenty-two of 36 health-care workers (61%) would often consider using automated O_2 titration for patients on O_2 therapy, 10 of 36 (28%) would do so occasionally, whereas 4 of 36 (11%) reported that they would rarely use it. Twenty-eight of 36 respondents (78%) considered that the technical support was sufficient and that they felt comfortable with the use of the device. The respondents gave the following device utility scores on a scale of 0 to 10: 5 (n = 2), 6 (n = 1), 7 (n = 5), 8 (n = 10), 9 (n = 5), and 10 (n = 13), with a mean ± SD utility rating score for automated O_2 titration of 8.5 ± 1.5.

Discussion

We report our clinical experience with the feasibility of using an automated O_2 titration device in subjects with acute respiratory failure requiring O_2 therapy as a part of their routine clinical care. The cumulative data during this evaluation extends previous clinical trials in showing that the ability of automated O_2 titration to maintain S_{pO_2} within the desired range in various diseases[10-12,14-17] may also apply to "real-life" clinical situations. Clinical worsening, defined as the requirement for high-flow nasal oxygen and/or transfer to the ICU, in 96 subjects (15.8%) was attributed to progression of the underlying disease. Although not a unanimous choice among 36 health-care workers who responded to a short survey, the automated O_2 titration device was felt to be useful and a positive experience was reported by the majority of users. This evaluation of the use of automated O_2 titration in routine clinical care provided several learning opportunities that helped to address some frequently overlooked practical

Table 3. Subject Characteristics

Characteristic	All Subjects ($N = 609$)	Subjects With Oxygenation Data ($n = 82$)	Subjects Without Oxygenation Data ($n = 527$)	P
Age, y	72.4 ± 12.1	74.0 ± 11.4	72.1 ± 12.2	.20
Men/women, *n*	303/306	41/41	262/265	> .99
Admission diagnosis, *n* (%)				
Pneumonia (including COVID-19)	355 (58.3)	45 (54.9)	310 (58.8)	
COPD and/or asthma exacerbation	131 (21.5)	20 (24.4)	111 (21.1)	
Pulmonary vascular disease	19 (3.1)	2 (2.4)	17 (3.2)	.74
Other respiratory diseases	48 (7.9)	5 (6.1)	43 (8.2)	
Cardiovascular disease	56 (9.2)	10 (12.2)	46 (8.7)	
Hospital admission to initiation of automated O_2 titration, h	0 (0–1)	0 (0–1)	0 (0–1)	.16
O_2 flow, L/min	2 (1–3)	2 (1–3)	2 (1–3)	.52
Hospital length of stay, d	9 (6–15)	10 (6–16)	9 (5–15)	.29
Clinical deterioration, *n* (%)*	96 (15.8)	16 (19.5)	80 (15.2)	.33

Data are mean ± SD or median (interquartile range) unless otherwise noted.
* Clinical deterioration is the requirement for high-flow nasal cannula and/or transfer to the ICU.

Table 4. Prescribed S_{pO_2} Targets in 387 Subjects on the Respiratory Ward, COVID-19 Unit, and Emergency Department

S_{pO_2} Target	Respiratory Ward ($n = 178$)	COVID-19 Unit ($n = 59$)	Emergency Department ($n = 150$)
88-90 %	154 (86.5)	42 (71.2)	110 (73.3)
91-92 %	23 (12.9)	16 (27.1)	34 (22.7)
≥ 93%	1 (0.6)	1 (1.7)	6 (4.0)

Data are *n* (%).

issues related to (i) oxygenation measurements with pulse oximetry and definition of optimal oxygenation with corresponding S_{pO_2} targets; (ii) organizational factors, including health-care workers training and supervision with the use of automated O_2 titration; (iii) optimal utilization of automated O_2 titration systems, and (iv) limitations in the accuracy of S_{pO_2} readings with currently available oximeters.

This technological evaluation provided an opportunity for nurses, physicians, respiratory therapists, and researchers from our institution to reflect and discuss various aspects of O_2 therapy. The use of an automated O_2 titration device, which forces clinicians to consider S_{pO_2} targets adapted to the clinical situation, may be helpful in implementing the recommendations that S_{pO_2} should be maintained in pre-specified therapeutic windows, avoiding both hypoxemia and hyperoxemia. Despite clear recommendations about the benefits of prescribing oxygen according to target ranges, clinical implementation of this approach is challenging and required numerous trainings, discussions, and feedback from clinicians. For example, in a recent audit of O_2 therapy conducted in New Zealand, S_{pO_2} targets could be found in only 60% of hospitalized patients.[29]

S_{pO_2} monitoring with the automated O_2 titration device made us even more aware of the fluctuations in O_2 needs in patients with acute respiratory failure, especially in patients with COVID-19, something that is not typically addressed by only intermittent (and often infrequent) S_{pO_2} measurements. Automated O_2 titration in response to S_{pO_2} fluctuations was more effective than manual O_2 titration to maintain subjects in the desirable S_{pO_2} range as previously reported in a variety of clinical situations, such as in trauma subjects who are critically injured,[10] in subjects admitted to the emergency department,[12] after thoracic or abdominal surgery,[15] those with COPD exacerbation,[11,14] during exercise in subjects with chronic lung diseases,[19] and in the pediatric population.[30] Typically, S_{pO_2} is maintained in the therapeutic zone 80% of the time with automated O_2 titration compared with 40 to 55% of the time with manual O_2 titration.[10-12,14-17] When considering the importance of avoiding both hyperoxemia and hypoxemia,[31] the goal of maintaining subjects within a safe S_{pO_2} target zone is an argument in favor of automated O_2 adjustment when caring for subjects with hypoxemic respiratory failure.

Our goal was to test the clinical implementation of an automated O_2 titration device and not to make recommendations about O_2 targets in specific conditions, and our experience should be interpreted in this context. The suggested S_{pO_2} targets from the implementation committee (88 to 90% in the subjects with COPD, 90 to 92% in other situations) were lower than typically recommended, particularly in subjects other than those with COPD, with targets ranging between 90 and 98% have been recently proposed.[4-8] The S_{pO_2} targets that were used took into consideration a study from our center that provided evidence that S_{pO_2} readings from the built-in Nonin oximeter, systematically underestimate S_{aO_2} and are lower than those of other oximeters.[28] In this study, it was found that S_{pO_2} readings

Table 5. S_{pO_2} Data in 82 Admissions on the Respiratory Ward, COVID-19 Unit, and Emergency Department

Parameter	Respiratory Ward ($n = 38$)	COVID-19 Unit ($n = 9$)	Emergency Department ($n = 35$)
Recording time, h	27.5 (10.1–78.8)	29.1 (20.9–49.2)	5.4 (3.4–10.3)
Recording time with S_{pO_2} signal, %	89.3 ± 8.7	95.9 ± 2.4	92.3 ± 9.9
Mean O_2 flow, L/min	2.4 ± 1.7	2.0 ± 0.6	2.3 ± 2.2
Mean S_{pO_2}, %	89.2 ± 1.2	90.0 ± 0.9	89.8 ± 1.8
Time in the S_{pO_2} target zone, %	88.7 ± 1.0	89.5 ± 0.9	89.4 ± 1.7
Time with S_{pO_2}, %			
<85%	4.0 ± 3.3	1.2 ± 0.8	3.2 ± 5.1
≥98%	0.5 ± 1.2	0.1 ± 0.1	1.2 ± 2.6
<3-5% of the S_{pO_2} target	4.7 ± 3.2	3.2 ± 1.8	5.5 ± 6.7
>3-5% of the S_{pO_2} target	11.5 ± 8.3	9.3 ± 6.2	7.9 ± 8.1

Data are median (interquartile range) or mean ± SD.

were, on average, 3% to 4% lower with the Nonin oximeter than with the Philips (Mississauga, Canada), Nellcor (Medtronic, Canada), or Masimo (Irvine, California) oximeters.[28] One advantage of the Nonin oximeter is that an S_{pO_2} target of 90% allowed detection of all the hypoxemic episodes, whereas other tested pulse oximeters only detected 11 to 37% of these occurrences.[28]

We, therefore, were confident that proposing S_{pO_2} targets of 88% in COPD and 90% in other diseases with the system that was used in this technological evaluation would protect against hypoxemia and hyperoxemia while avoiding the risk of worsening hypercapnia in COPD and ensuring the safety of subjects.[28] Although no blood gas data are available in the present report, a recent study from our group supports this practice by showing the an S_{pO_2} target of 90% with the Nonin oximeter is appropriate to protect against hypoxemia and hyperoxemia.[32] Another consideration is that using higher targets could delay weaning of O_2 and, therefore, unduly prolong the hospital stay, a situation that is more likely to occur when using an oximeter that systematically underestimates S_{pO_2}. Some clinicians showed some reluctance with our proposal for S_{pO_2} targets early in the technological evaluation, but, as clinical experience was gained and with appropriate teaching, most of them became comfortable with their use as shown in Table 4. The proposed S_{pO_2} targets were applied primarily in people with light skin pigmentation who constitute the vast majority of the population treated in our hospital, an important consideration given the possibility to overestimate S_{aO_2} with pulse oximetry in people with dark skin pigmentation.[33]

In theory, automated O_2 titration, which allows for multiple adjustments of O_2 flows, should be safer than relying on the current practice, in which it is challenging for healthcare workers to precisely titrate O_2 flows.[9] However, we acknowledge that confirmation of this theory would require a formal randomized clinical trial. In patients with hypercapnic respiratory failure, the avoidance of hyperoxemia, which was infrequently observed (Table 5), should reduce the risk of worsening respiratory acidosis.

For automated O_2 titration to be used safely, the premise that S_{pO_2} is an accurate surrogate of S_{aO_2} should be fulfilled and, unfortunately, this is not always the case.[28,34,35] Indeed, oximetry readings should be viewed as approximating S_{aO_2} rather than considered as an accurate vital sign. Although imprecision of oximetry readings was reported years ago,[34,35] this finding was largely unheeded by the medical community, with potential clinical consequences. For example, using an oximeter that systematically underestimates S_{aO_2} may lead to unduly high O_2 flows if the S_{pO_2} target is not adjusted accordingly.[32] In people with dark skin pigmentation, overestimation of S_{aO_2} by pulse oximetry may lead to the occurrence of undetected hypoxemia and the risk of undertreatment based on certain S_{pO_2} thresholds.[33] Low perfusion and motion artifact may also compromise reliable S_{pO_2} readings and thus any valid estimation of S_{aO_2}.[35] These limitations are not specific to automated O_2 titration devices because they apply to any situations in which O_2 therapy is governed by S_{pO_2} readings. What remains to be seen is to what extent imprecision of oximetry readings influence clinical outcomes; but, increased hospital mortality has been associated with the presence of undetected hypoxemia.[36] While we are awaiting better oximeter accuracy, the understanding of current limitations of pulse oximetry should help to provide safer medical care.[37]

When this project was conceived in 2019, we did not foresee the use of an automated O_2 titration device in subjects hospitalized with severe COVID-19 pneumonia. It turned out that such a system was useful in this circumstance because of the ability to continuously adjust O_2 flows without direct contact between the subjects and the nurses and respiratory therapists. This offered added safety for the subjects and for hospital workers, likely reducing the risk of transmission of contagious disease.[27] Another advantage of automated O_2 adjustment was the

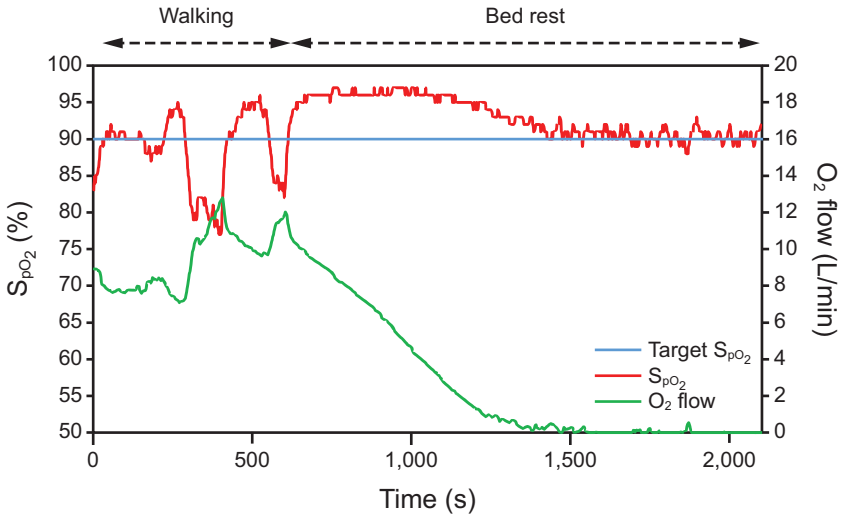

Fig. 4. Relationship between S_{pO_2} and O_2 flow in one subject who was treated with the automated O_2 titration device while transitioning from walking in the corridor to bed rest. Target S_{pO_2} was set at 90%. During walking, a sudden fall in S_{pO_2}, down to 80% provoked a rapid rise in O_2 flow aiming to return S_{pO_2} in the target zone. An overshoot in S_{pO_2} up to 95% was noted. Returning to bed resulted in reduced O_2 needs as seen by a progressive decline in O_2 flow down to 0 L/min over a 10-min period while S_{pO_2} remained at the target value of 90%.

reduction in the use of personal protective equipment, which was a major issue early in the pandemic due to scarcity. Our experience with automated oxygen titration is consistent with that of Danish investigators who reported a similarly positive experience in 20 subjects hospitalized with COVID-19 and with mild-to-moderate hypoxemic respiratory failure.[17]

Implementing new technology in clinical practice is challenging. Changing medical practice is a slow process, and there are multiple barriers to the adoption rate of health-care solutions.[38,39] The importance of education and continued support and feedback for the medical team cannot be overemphasized. We also observed some clinical situations during which the behavior of the system was difficult to understand by the clinical team. On some occasions, subjects with COPD required relatively high O_2 flows (4-6 L/min) to maintain target S_{pO_2}. These situations were uncomfortable for clinicians who are generally trained to avoid high O_2 flows in COPD without appreciating that it is hyperoxemia and not high O_2 flows per se that are responsible for worsening hypercapnia. In this context, the use of automated O_2 titration may offer additional protection to subjects because as long as S_{pO_2} is maintained within a safe therapeutic window, hyperoxemia and worsening hypercapnia should not occur.

Some clinical situations were difficult to comprehend because of the time lag between oxygenation status (S_{pO_2}) and incremental (or decremental) adjustments in O_2 flows. One such situation is illustrated in Figure 4. A recovering subject resumed mild physical activities during which O_2 desaturation was observed. This provoked a dip in S_{pO_2} to which the automated O_2 titration device responded by increasing O_2 flow. On return to rest, S_{pO_2} remained higher than the target value for some time while O_2 flows progressively returned to lower values. For example, at 1,000 s, an O_2 flow of 4 L/min could appear unexpected because the S_{pO_2} was above the target. In this situation, instantaneous reading of the physiologic parameters displayed on the automated O_2 titration device, showing O_2 flows that were higher than expected from the S_{pO_2} value could have mistakenly led to the conclusion that the device was not operating as intended, whereas this was simply a reflection of a time lag between the S_{pO_2} correction and the O_2 flow response. Inspecting the S_{pO_2} and O_2 flow trend report from the device is crucial to understand the nature of the situation. Another example that requires some experience with the device is when the required O_2 flow is low (approximately or < 1 L/min) and the patient is almost ready to be weaned from oxygen. Small fluctuations in S_{pO_2} related to physical activities could induce a transient increase in O_2 flow, which may prevent or slow O_2 discontinuation. This situation may generally be resolved by simply stopping oxygen and monitoring the patient to ensure that S_{pO_2} remains adequate.

There are limitations to the present report that should be considered in interpreting the findings and their generalizability. The most obvious is that data were available only for a fraction of the subjects. There was a shortage of resources to collect detailed information in a systematic fashion as we are accustomed to in clinical research. For example, detailed S_{pO_2} data could only be retrieved for 13% of subjects because many were not appropriately identified in the device, which made it impossible to match recorded oxygenation data with the corresponding subjects. Although the availability of detailed S_{pO_2} data in only a small portion of the subjects raises questions about the

external validity of the findings, we were reassured that the proportion of time spent within the S_{pO_2} targets was similar to that previously observed in other clinical circumstances.[10-12,14-17] Only a small number of nurses and respiratory therapists responded to the survey about the utilization of automated O_2 titration. Therefore, its interpretation should be done cautiously. For example, it is possible that only those who had a positive experience with the device took the time to answer the survey. Lastly, the decision to use or not use the automated O_2 titration system was made by the clinical team; we do not have data to estimate the proportion of hospitalized patients who require oxygen therapy treated with the device.

Conclusions

We found that automated O_2 titration could be implemented safely in the context of routine clinical care in subjects with hypoxemic respiratory failure of various etiology. Based on this clinical experience and analysis of pilot data that suggest the possibility to reduce hospital length of stay with automated O_2 titration,[11] we encourage the conduct of randomized clinical trials that test the impact of automated O_2 titration on hospital length of stay compared with the standard care in subjects with acute hypoxemia.

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