

BMJ Open Cost-effectiveness of FreeO₂ in patients with chronic obstructive pulmonary disease hospitalised for acute exacerbations: analysis of a pilot study in Quebec

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ABSTRACT

Objective Conduct a cost-effectiveness analysis of FreeO₂ technology versus manual oxygen-titration technology for patients with chronic obstructive pulmonary disease (COPD) hospitalised for acute exacerbations.

Setting Tertiary acute care hospital in Quebec, Canada.

Participants 47 patients with COPD hospitalised for acute exacerbations.

Intervention An automated oxygen-titration and oxygen-weaning technology.

Methods and outcomes The costs for hospitalisation and follow-up for 180 days were calculated using a microcosting approach and included the cost of FreeO₂ technology.

Incremental cost-effectiveness ratios (ICERs) were calculated using bootstrap resampling with 5000 replications. The main effect variable was the percentage of time spent at the target oxygen saturation (SpO₂). The other two effect variables were the time spent in hyperoxia (target SpO₂+5%) and in severe hypoxaemia (SpO₂<85%). The resamplings were based on data from a randomised controlled trial with 47 patients with COPD hospitalised for acute exacerbations.

Results FreeO₂ generated savings of 20.7% of the per-patient costs at 180 days (ie, −\$C2959.71). This decrease is nevertheless not significant at the 95% threshold (P=0.13), but the effect variables all improved (P<0.001). The improvement in the time spent at the target SpO₂ was 56.3%. The ICERs indicate that FreeO₂ technology is more cost-effective than manual oxygen titration with a savings of −\$C96.91 per percentage point of time spent at the target SpO₂ (95% CI −301.26 to 116.96).

Conclusion FreeO₂ technology could significantly enhance the efficiency of the health system by reducing per-patient costs at 180 days. A study with a larger patient sample needs to be carried out to confirm these preliminary results.

Trial registration number NCT01393015; Post-results.

INTRODUCTION

Context

Chronic obstructive pulmonary disease (COPD) is an umbrella term used to describe chronic lung diseases that obstruct airflow from the lungs.¹ According to

Strengths and limitations of this study

- A microcosting (or bottom-up) approach with bootstrap resampling was used to assess the cost-effectiveness of FreeO₂ for patients with COPD.
- Various cost-effectiveness analyses were conducted, showing robust results.
- The size of the sample used is small and a larger study should be conducted to confirm the cost-effectiveness of FreeO₂.

WHO, COPD is actually the fifth leading cause of mortality worldwide and could move into third place by 2030.¹ A recent study conducted in Canada also shows that the number of patients with COPD could increase by 150% in 2030 compared with 2010.² Among the elderly aged 75 years or older, the increase could be as high as 220%.² The prevalence of COPD in Canada was 4.3% for individuals aged 35 years or older in 2010,³ and COPD exacerbation was the leading cause of hospitalisation among chronic diseases with an average length of stay of about 10 days.^{4 5} There is considerable heterogeneity in the economic burden and prevalence of COPD, but the trend is an increase related to population growth and ageing.⁶ Depending on the study, the estimated costs of an episode of exacerbation varied widely, ranging from US\$88 for simple medication to US\$7757 or more for hospitalisation.^{7 8} In the USA, the hospitalisation costs for a principal diagnosis of COPD are estimated at US\$6.1 billion per year⁸ and can be as much as several tens of billions of dollars per year when secondary diagnoses of COPD and absenteeism costs are included.⁹

Inadequate oxygenation (hyperoxia or hypoxaemia) increases the risks of medical complications and can, in certain cases, lead to increased mortality among patients with COPD.^{10 11} It is therefore essential to optimise oxygen therapy to bolster patient safety and the quality of care provided.¹² From this perspective, certain studies have demonstrated shortcomings in oxygen administration to patients,¹³ despite the recommendations of many medical societies,^{14 15} in particular, the fact that certain patients with COPD received excessive oxygen flows.^{16 17} It also appears that the current system for administering oxygen—the float-ball flowmeter, in use for more than a century—can have serious limitations that urgently call for more effective and practical solutions. In the hospital setting, several studies showed poor compliance with recommendations. Cousins *et al.*¹³ review included the analysis of 29 papers evaluating oxygen prescription in the general medical or respiratory ward. Overall, the literature suggests that the practice of prescribing oxygen therapy is poor for prescription, administration and monitoring, and that specific interventions may improve the practices. One study demonstrated that the rate of compliance with oxygen prescriptions increased after educational interventions (eg, audit, audit presentation, groups of discussion, modification of the prescription chart, stickers); however, few years later, the benefits of the intervention on the rate of adequate prescription were lost.¹⁸ Automated oxygen-titration systems have been recently developed in an attempt to resolve this problem.^{19–21} The FreeO₂ system, in particular, was designed to automatically titrate, every second, the oxygen flow delivered to patients as they breathe spontaneously. The flow adjustment is based on the target for saturated pulse oxygen (SpO₂) set by the clinician. Its main objective is to reduce hyperoxia and hypoxaemia, automatically perform patient oxygen weaning while reducing caregiver workload, and improve monitoring.^{19 22}

By better managing patient oxygen needs through automated oxygen titration and weaning, the FreeO₂ system could reduce the risks of medical complications and promote shorter duration of oxygen therapy and hospital stays so that patients could more rapidly resume to their normal quality of life and their normal activities. To date, only two studies on this technology involving hospitalised patients have been conducted: one with patients with COPD hospitalised for acute exacerbations²²; the other with patients admitted to emergency departments for acute respiratory distress.²³ Neither of these studies assessed the cost-effectiveness of the FreeO₂ system.

Objective

The objective of this study was to assess the cost-effectiveness ratio of FreeO₂ technology based on data from a randomised controlled study comparing automated and manual oxygen titration in patients with COPD hospitalised for acute exacerbations.²²

METHODS

We conducted a cost-effectiveness analysis using bootstrapping (data resampling)²⁴ and the criteria in the Consolidated Health Economic Evaluation Reporting Standards checklist.²⁵ The analysis perspective was hospital costs to Quebec's healthcare system over 180 days subsequent to the initial hospitalisation. A microcosting (or bottom-up) approach was used to collect data.

Target population

We used the same database as the first study on FreeO₂ with patients with COPD.²² That study—conducted between 2011 and 2015—was a randomised clinical trial of 50 patients over the age of 40 hospitalised for acute exacerbations. The patients were randomly separated into two groups of 25. Only one of the two oxygen-titration methods (FreeO₂ or manual) was used for the patients in each group during their hospital stay. Two patients in the FreeO₂ group and one in the control group withdrew during the study. Our study therefore included 23 patients in the FreeO₂ group and 24 in the control group. Note that patients were on FreeO₂ (or manual) until weaning of oxygen therapy. In this study, some patients (not all) used FreeO₂ during mobilisation (ie, walk in the corridors).

Interventions assessed

We compared the FreeO₂ system (OxyNov, Quebec, QC, Canada)—the new automated oxygen-titration technology—to manual oxygen titration using the standard flowmeter (Western Medica, Westlake, Ohio, USA) currently in use at the Institut Universitaire de Cardiologie et de Pneumologie de Québec—Université Laval (IUCPQ-UL). The FreeO₂ system automatically adjusts oxygen flow delivered through a nasal cannula or a simple mask according to an algorithm based on the patient's physiological data, in particular, the patient's SpO₂, which is continually measured. As a result, FreeO₂ provides continuous monitoring of respiratory parameters in spontaneously breathing patients.¹⁹ In contrast, manual oxygen titration was conducted by nurses each time the target SpO₂ was not reached based on local protocols.

Principal outcome indicator

We used the incremental cost-effectiveness ratio (ICER)²⁴ to assess the cost-effectiveness of FreeO₂ technology. This ratio corresponds to the difference in costs (ΔC) divided by the difference in effects (ΔE) of two interventions, namely: $ICER = (Cost_{FreeO_2} - Cost_{Manual}) / (Effect_{FreeO_2} - Effect_{Manual})$.

Effectiveness measurement

Given the clear recommendations for oxygenation targets for patients with COPD,¹⁴ the main effectiveness variable was the proportion of time spent by the patient at the target SpO₂ ($\pm 2\%$). The data were systematically measured in both two groups by an oximeter transducer placed on the patient's finger. We also conducted analyses with two other effectiveness variables: percentage of



time spent in hyperoxia and percentage of time spent in severe hypoxaemia. Hyperoxia was deemed to be when the patient's SpO₂ was five percentage points above the target and severe hypoxaemia when the patient's SpO₂ was <85%.

Cost estimates

This study included all the costs related to the patients' hospitalisation on inclusion, as well as rehospitalisation costs at 180 days. These costs were broken down into two categories: clinical costs and compressible costs for clinical support activities. The clinical costs included remuneration for physicians and nursing staff as well as all other costs for medications, consumables, diagnostic tests and miscellaneous items. The compressible costs for clinical support activities included costs to support clinical activities and that can be affected by the duration and nature of the clinical activities (eg, diet, laundry, archives and supernumerary staff). The incompressible costs for clinical support activities (eg, safety services, general management and computer science) were excluded. Costs for depreciation and using the technology were included in the calculations based on information provided by the manufacturer. All costs are expressed in 2015 Canadian dollars (\$C). The data were collected in current dollars and then actualised using the Consumer Price Index provided by Statistics Canada.²⁶

Data collection

The data were collected from the pilot study's clinical database,²² examination of patient clinical records and IUCPQ-UL financial databases, as well as discussions with healthcare staff to provide us with information about some resources used to deliver various clinical activities to hospitalised patients with COPD (see the details in online supplementary appendix 1).

Model selection

Various bootstrap resampling techniques with 5000 replications were used. This choice was dictated by the small size of our sample (ie, n=47). We conducted both univariate and multivariate bootstrap analyses. The explanatory variables used for the multivariate bootstrap corresponded to the intervention assessed (ie, whether FreeO₂ technology was used or not) and several variables in the literature for accounting for the length and frequency of hospitalisations for exacerbations in patients with COPD (ie, for the cost variable), as well as to account for the intervention's effectiveness (ie, effectiveness variables). These variables of control were the age of the patient, the forced expiratory volume in per cent, hypercapnia, diabetes, diabetes or smoking, number of hospitalisation 12 months preinclusion and number of emergency department visits 12 months preinclusion.²⁷⁻³²

Statistical analysis

For continuous and normally distributed variables, Student's t-tests were conducted between groups. Wilcoxon rank sum tests were performed for data that

did not fulfil the normality assumption. Categorical variables were compared using X² exact tests. Four ICER calculations were made: manual, non-parametric bootstrap, univariate parametric bootstrap and multivariate parametric bootstrap. For the parametric bootstraps, Spearman's correlation tests were carried out in order to choose an estimation method: seemingly unrelated regression (SUR) or ordinary least squares. The ICER was calculated using the ratios of the coefficients obtained in the simulations with bootstrap resampling. In the case of the non-parametric bootstrap, once the data had been resampled and the averages of the cost and effectiveness variables for each group calculated, we calculated the ICER using the usual equation: $bsICER = (1/B) \times \sum_{b=1, B} bsICER_b$.^{33 34} To correct for estimate bias, we subtracted the bootstrap result from twice the ICER calculated manually: $bsICER_{bc} = 2 \times ICER - bsICER$. Any results at the threshold of 95% were considered statistically significant.

To visually present our results, we generated joint-distribution diagrams and cost-effectiveness acceptability curves. The cost-effectiveness acceptability curves provided for comparing cost-effectiveness ratios for various cost thresholds per unit of gain on a probabilistic basis.³⁵

RESULTS

Descriptive statistics

Table 1 provides the details of the cost data. Table 2 gives the main characteristics of the study participants. Table 1 breaks the clinical costs down into major categories, whereas the compressible costs for clinical support activities were organised in a single category (see online supplementary table A1 for details about the compressible costs). Table 1 indicates that hospitalisation expenditures on inclusion represent the major portion of total expenditures (55.7%), followed by rehospitalisation expenditures (44.3%). In the case of rehospitalisations, up to five rehospitalisation episodes per patient were observed in the 180 days subsequent to patient inclusion. It should be noted that the FreeO₂ technology was used solely for the initial hospitalisation; patients received only manual titration when rehospitalised.

The control group generated more costs than the FreeO₂ group (ie, a mean difference of \$C2959.71, equivalent to a 20.7% reduction) and none of the patients in the FreeO₂ group required intensive care. In addition, the per-patient depreciation cost for the FreeO₂ technology is relatively low despite the fact that we used the upper limit of the manufacturer's suggested price (ie, \$C12 000+annual operating costs).

Table 2 indicates that while there was a strong per-patient cost difference between the two groups, it was nevertheless not statistically significant (P=0.13). In contrast, in the case of effectiveness variables, the patients in the FreeO₂ group spent significantly more time at the target SpO₂ and less time spent in hyperoxia

**Table 1** Cost structure per patient and by sector of activity (2015 \$C)

Group	Overall (n=47)	Control (n=24)	FreeO ₂ (n=23)
Emergency	261.48	257.71	265.40
Nursing			
Medicine units	2422.04	2627.99	2 207.14
Intensive care	157.90	309.23	0.00
Outpatient consultations	1.01	1.35	0.65
Day medicine	3.45	6.76	0.00
Subtotal	2584.41	2945.33	2207.79
Medical imaging and nuclear medicine	207.55	259.08	153.79
Laboratories	354.30	418.25	287.57
Pharmacy			
Labour	235.94	278.89	191.12
Supplies	378.23	461.38	291.48
Subtotal	614.17	740.27	482.60
Endoscopy	99.74	80.63	119.68
Occupational therapy	57.10	83.23	29.83
Physiotherapy	139.89	145.00	134.55
Social services	92.27	81.08	103.95
Respiratory physiology	11.94	13.87	9.92
Respiratory therapy	564.71	687.60	436.47
Compressible costs for clinical support activities	968.72	1127.36	803.18
Specialist costs			
Pneumology	820.39	904.39	732.74
Other specialties	260.70	290.73	229.37
Subtotal	1081.09	1195.12	962.11
FreeO ₂ depreciation	26.41	–	53.97
O ₂ flowmeter depreciation	0.15	0.30	–
O ₂ use	76.99	105.27	47.48
Hospitalisation subtotal	7140.91	8 140.10	6098.30
Rehospitalisation costs			
Direct and indirect	4814.13	5156.31	4457.09
Medical specialists	862.65	969.67	750.97
Subtotal	5676.78	6125.98	5208.06
Total costs	12817.69	14 266.08	11 306.36

Source: data expressed as mean. Calculations provided by the authors and Direction de la performance clinique et organisationnelle, Institut Universitaire de Cardiologie et de Pneumologie de Québec— Université Laval.

and hypoxaemia ($P<0.001$). In addition, we noted that the control-group patients spent more days hospitalised than the patients in the FreeO₂ group. Similarly, the patients in the FreeO₂ group spent, on average, fewer days on oxygen than those in the control group. This made it possible to save about \$C57.79 on average per patient in oxygen costs, which is more than the per-patient depreciation cost for the FreeO₂ system. Lastly, the patients did not appear to present any statistically significant differences in terms of clinical or demographic characteristics on inclusion.

Incremental cost-effectiveness ratio

Manual calculation

To note that to calculate an ICER, means are used and not medians. These values for the effectiveness variables are provided in online supplementary table A2. The ICER calculation is $(\$C11\ 306.36 - \$C14\ 266.08) / (81.19 - 51.94) = -\$C101.21$ per percentage point of additional time spent at the target SpO₂. This ratio indicates that FreeO₂ technology allows Quebec's healthcare system to save \$C101.21 per percentage point of additional time spent at the target SpO₂. In other terms, compliance

**Table 2** Descriptive statistics per treatment group

	Control (n=24)	FreeO ₂ (n=23)	P value
Total expenditures (2015 \$C)	10 269.79* (6448.28 to 17 785.93)	5678.99* (4457.01 to 11 101.05)	0.13
Time spent at the target SpO ₂ (%)	48.19* (39.86 to 64.87)	83.83* (72.77 to 92.74)	0.00
Time spent in hyperoxia (%)	6.33* (3.02 to 10.46)	0.82* (0.20 to 2.06)	0.00
Time spent in hypoxaemia (%)	1.32* (0.16 to 2.65)	0.08* (0.04 to 0.18)	0.00
Length of hospitalisation (days)	7.5* (6.0 to 11.0)	6.0* (5.0 to 8.0)	0.08
Length of rehospitalisation (days)†	0.5* (0.0 to 13.0)	0.0* (0.0 to 7.17)	0.47
Length of rehospitalisation (days)‡	13.5* (5.43 to 21.0)	20.0* (6.73 to 27.33)	0.37
Total number of rehospitalisation at 180 days	21	9	0.09
Rate of rehospitalisation at 180 days (%)§	50.00 (51.07)	34.78 (48.70)	0.29
One rehospitalisation at 180 days (%)	25.00 (9.03)	30.43 (9.81)	0.69
Two or more rehospitalisations at 180 days (%)	25.00 (9.03)	4.35 (4.35)	0.05
Duration of oxygen therapy (days)	5.5* (3.0 to 6.0)	4.0* (2.26 to 5.0)	0.12
Oxygen consumption (L/min)	0.69* (0.58 to 1.31)	0.56* (0.33 to 0.76)	0.05
Total oxygen consumption (L)	6192.0* (2687.4 to 10969.4)	3600.0* (1553.2 to 4426.3)	0.05
FEV1 on inclusion (% predicted)	35.5* (30.7 to 43.7)	32.0* (27.3 to 41.5)	0.34
Diabetic (%)	37.50 (49.45)	26.09 (44.90)	0.40
Active smoker (%)	25.00 (44.23)	47.83 (51.08)	0.10
Diabetic or active smoker (%)	58.33 (50.36)	65.22 (48.70)	0.62
Hypercapnia (PaCO ₂ >45 mm Hg) on inclusion (%)	54.17 (50.90)	34.78 (48.70)	0.18
Respiratory rate on inclusion (bpm)	21.38 (2.26)	21.83 (2.87)	0.55
Female (%)	50.00 (51.07)	43.48 (50.69)	0.65
Age (years)	73.17 (8.62)	71.17 (8.33)	0.42
Body mass index (kg/m ²)	26.97 (5.63)	27.06 (6.34)	0.96
No. of hospitalisations in the 12 months preinclusion	0.0* (0.0 to 1.0)	0.0* (0.0 to 1.0)	0.52
No. of emergency department visits in the 12 months preinclusion	1.0* (0.0 to 2.0)	1.0* (0.0 to 1.0)	0.97
Hospitalised in the month preinclusion (%)	12.50 (33.78)	8.70 (28.81)	0.67

Data expresses as mean with SD in parentheses, unless otherwise specified.

*Median and 95% CI in parentheses.

†Total number of days of rehospitalisation out of 180 days divided by the total number of patients (rehospitalised or not).

‡Length of rehospitalisation solely for rehospitalised patients.

§Percentage of the total of patients in that group that has one or more rehospitalisations in the 180 days.

FEV1, forced expiratory volume in 1 s.

with oxygen-therapy recommendations is possible with FreeO₂ without incurring additional costs, and using the technology will very probably yield lower costs. On a per-COPD-patient basis, that is equal to an average of 29.25 percentage points of additional time spent at the target SpO₂ and a savings of \$C2959.71 with FreeO₂.

We used various bootstrap methods to calculate SD and CIs in order to estimate by how much the ratio might vary.

Bootstrap calculations

We calculated an ICER associated with the generated sample for each bootstrap resampling. The final ICER corresponds to the average of all the ICERs for each of the 5000 replications. In the case of the parametric bootstrap, all of our Spearman's correlation results indicate a

correlation between the cost variable and our three effectiveness variables (see online supplementary table A3). We therefore opted for an SUR model to calculate the difference between the average costs and average effects (see online supplementary table A4).

Table 3 summarises the ICERs obtained for each calculation method. Each time, the different ICERs were of relatively similar orders of magnitude. Given that multivariate bootstrapping provides for correcting differences related to patient characteristics, the results associated with this method serve as reference points. Consequently, an ICER of -\$C96.91 per percentage point of additional time spent at the target SpO₂ was observed. This outcome is not statistically significant at the threshold of 95%. That

Table 3 Incremental cost-effectiveness ratios (ICERs)

		ICER	ICER corrected for bias	Normal CI	Percentile CI (95%)	Normal CI (corrected for bias)
Target	Simple	-101.21	-	-	-	-
	Non-parametric BS	-104.55	-97.87	(-107.88 to -101.21)	(-352.59 to 120.26)	(-101.21 to -94.53)
	Univariate parametric BS	-96.58	-105.84	(-99.77 to -93.38)	(-312.78 to 144.74)	(-109.03 to -102.65)
	Multivariate parametric BS	-96.91	-105.51	(-99.84 to -93.99)	(-301.26 to 116.96)	(-108.43 to -102.59)
Hyper	Simple	-369.22	-	-	-	-
	Non-parametric BS	-395.93	-342.51	(-408.95 to -382.91)	(-1380.61 to 467.07)	(-355.53 to -329.49)
	Univariate parametric BS	-379.03	-359.41	(-391.94 to -366.12)	(-1,294.23 to 537.07)	(-372.32 to -346.50)
	Multivariate parametric BS	-411.09	-327.35	(-424.28 to -397.91)	(-1,442.43 to 437.01)	(-340.54 to -314.16)
Hypox	Simple	-1565.46	-	-	-	-
	Non-parametric BS	-1709.95	-1420.97	(-1766.64 to -1653.25)	(-6265.24 to 1894.99)	(-1477.67 to -1364.27)
	Univariate parametric BS	-1661.46	-1469.46	(-1718.62 to -1604.29)	(-5,911.79 to 2367.25)	(-1526.62 to -1412.30)
	Multivariate parametric BS	-2250.04	-880.88	(-4841.99 to 341.92)	(-17 091.61 to 6560.38)	(-3472.84 to 1711.01)

Target, percentage of time spent at the target SpO₂.

BS, bootstrap; Hyper, percentage of time spent in hyperoxia (SpO₂+5% above the target); Hypox, percentage of time spent in hypoxaemia (SpO₂<85%).

notwithstanding, when bias correction is applied with the normal CI, the ICER becomes significant. Similar results have been observed with the ICER associated with hyperoxia, but not for hypoxaemia, which indicates greater heterogeneity for this variable.

Joint-distribution diagrams and cost-effectiveness acceptability curves

As can be seen in the joint-distribution diagrams, the large majority of bootstrap points are located in the negative part of the incremental cost (figures 1–3 for multivariate parametric bootstrap; online supplementary figures A1–A6 for non-parametric and univariate parametric bootstrap). In the case of the diagrams with the percentage of time spent in hyperoxia (Hyper) or percentage of time spent in

hypoxaemia (Hypox), the incremental target appears as a negative variation because the objective here of achieving better oxygen titration is to reduce these time percentages.

In examining the cost-effectiveness acceptability curve for the percentage of time spent at the target SpO₂, it can be seen that the FreeO₂ system has a probability of over 80% of being cost-effective given a zero willingness to pay (figure 1). For a willingness to pay of \$C100 per percentage point gained at the target SpO₂, the probability is 96%. The FreeO₂ system is, moreover, 100% cost-effective with a willingness to pay of only \$C200 per additional percentage point of time spent at the target SpO₂. In the case of hyperoxia and hypoxaemia, the cost-effectiveness probabilities associated with a zero willingness to pay are higher, namely, 85% and 90%, respectively.

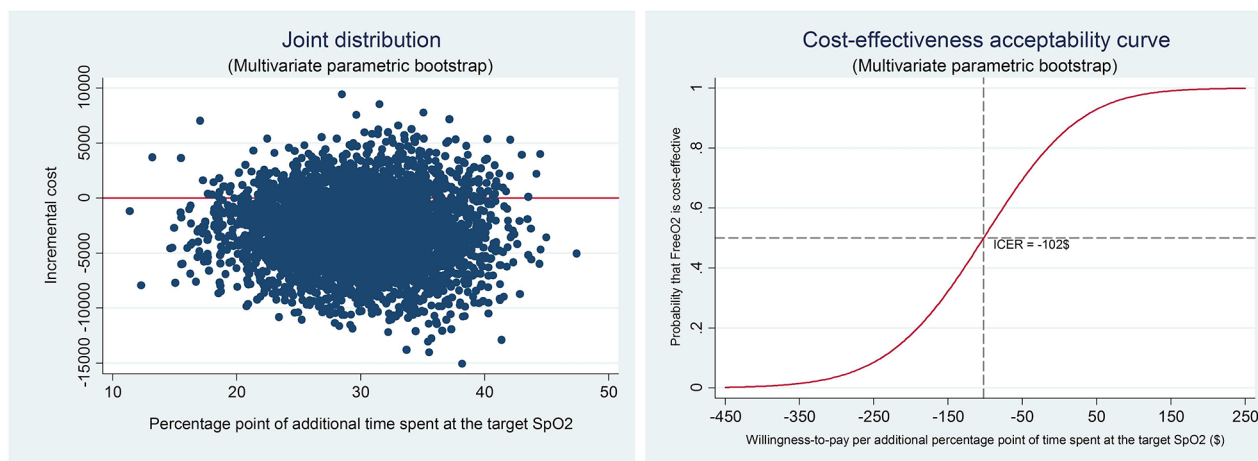


Figure 1 Joint distribution and incremental cost-effectiveness acceptability curve for time spent at the target SpO₂ (multivariate parametric bootstrap). ICER, incremental cost-effectiveness ratio.

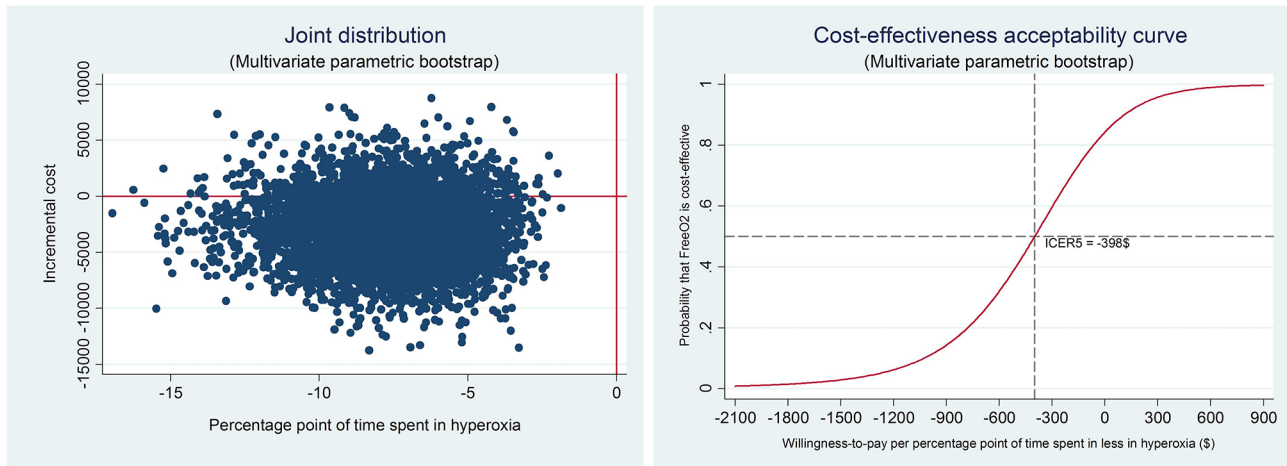


Figure 2 Joint distribution and incremental cost-effectiveness acceptability curve for time spent in hyperoxia (multivariate parametric bootstrap). ICER, incremental cost-effectiveness ratio.

DISCUSSION

General observation

This study examined the cost-effectiveness ratio of the new FreeO₂ oxygen-titration technology in patients with COPD hospitalised for acute exacerbations. The comparison with conventional manual oxygen-titration indicates that FreeO₂ technology is more cost-effective. Nevertheless, the study was conducted on a small sample, and the definitely large difference observed in the per-patient costs was not statistically significant. A study on a larger patient sample would quite probably confirm a reduction of >20% in the per-patient costs observed over 180 days. In fact, the savings achieved for a patient with COPD hospitalised for acute exacerbations averaged \$C2960 herein. Consequently, it can be concluded that the relatively high cost of the FreeO₂ automated titration system (ie, 100 times higher than the manual system) as well as its shorter life cycle, are not economic issues given the savings and health outcomes that it yields. From the clinical standpoint, FreeO₂ technology indeed offers a definite advantage over conventional manual titration because it can

maintain patients at the right target SpO₂ longer, thereby reducing the risks of hypoxaemia and hyperoxia.

Despite the small size of our sample, our results remain stable and indicate that the FreeO₂ system is in all probability cost-effective (ie, probability higher than 80% for a zero willingness to pay). The ICERs could nevertheless vary marginally with new underlying assumptions related to the cost of the technology and depreciation time. To illustrate, varying the depreciation of the FreeO₂ device from 7 to 5 years yields an ICER of -\$C100.47 per additional percentage point of time spent at the target SpO₂. Moreover, based on our calculations while keeping all the other variables constant, the FreeO₂ system would have to cost \$C607 619.65 to yield the same ICER as a conventional manual titration device. A simple return-on-investment calculation also indicates that acquiring a FreeO₂ device maintained over 7 years would pay for itself in <3 months, that is, after only eight to nine hospitalised patients.

As in all cost studies, it is difficult to generalise our results to other countries. Indeed, manufacturers can

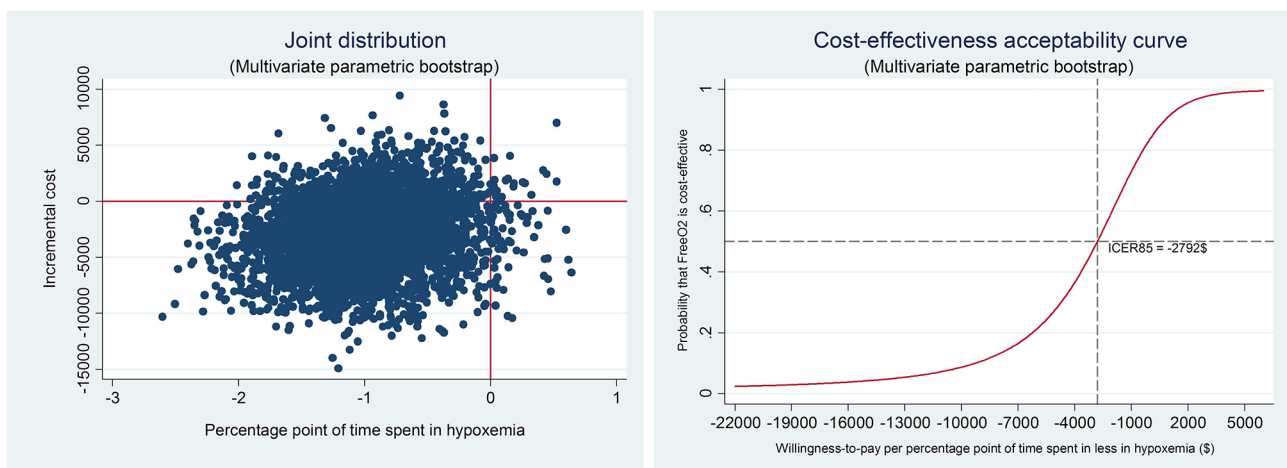


Figure 3 Joint distribution and incremental cost-effectiveness acceptability curve for time spent in hypoxaemia (multivariate parametric bootstrap). ICER, incremental cost-effectiveness ratio.



have very different cost structures and prices. Nevertheless, since the main cost factors in our study were hospitalisation and the number of rehospitalisations, it would appear likely that another such study conducted in a country with a healthcare system that shares many characteristics with Quebec's could yield similar results. For example, extrapolating the clinical data of the study conducted by Lellouche *et al*²² with patients with COPD in France could yield an ICER of -€48.41 (ie, \$C72.63 at an exchange rate of €1 for \$C1.5) per additional percentage point of time spent at the target SpO₂. Indeed, based on the cost guidelines in France,³⁶ the average cost at 180 days for a patient with COPD would be €6841.74. Applying a cost reduction of 20.7%, as in our study, for a gain of 29.25 percentage points at the target SpO₂, would give an ICER of -€48.41. Moreover, it should be noted that the length of hospitalisation for acute exacerbations is about the same in our study and in France.³⁷ In contrast, it would be more difficult to extrapolate results in the case of other countries, such as the USA, that have very different healthcare systems and often shorter hospital stays.³⁸

To the best of our knowledge, there are two other automated systems on the market for adjusting oxygen flow. One has an algorithm adapted to a premature population^{39 40} and is integrated into an intensive care ventilator. Because of its specificities, this system is not actually comparable to the FreeO₂ system. Moreover, we know of no cost-effectiveness studies on it. There is also an automated oxygen regulator marketed in Europe (O₂ Flow Regulator, Dima Italia LRS, Bologna, Italy), but there have been few clinical assessments of it and there are no data on it in a context of COPD acute exacerbations.²¹

Strengths and weaknesses

This study was the first to conduct a cost-effectiveness analysis of automated oxygen-titration technology. The study's main strength is that we were able to collect cost and effectiveness data for each of the patients using a bottom-up approach. As a result, we were able to very accurately measure individual variability, which allows us to be very confident about the degree of accuracy of our results. Another strength of our study is that we resampled a large number of times in order to reduce the bias related to its small size. Nevertheless, as an effect of a bottom-up approach, the initial sample showed high variability in the cost data, which led the bootstrap to simulate samples with value distributions containing a large number of extreme values. These extreme values broadened the CIs and consequently reduced the significance of the observed cost difference. One limitation of the study is thus the relatively small sample size of the population that may have influenced the results. The initial study was a pilot study and the cost-effectiveness outcomes used in the current study were not the primary outcomes in this pilot study. Larger randomised controlled studies will be required to confirm these results. Another limitation relates to some of the cost data collected. Specifically, we

had to assign costs based on the averages in available data for the remuneration of specialists other than pneumologists. Since these costs amounted only to a few hundred dollars, this limitation is very unlikely to affect our results. Moreover, rehospitalisation costs herein are biased against the FreeO₂ group insofar as all rehospitalised patients were systematically oxygenated with a conventional flowmeter and not with the FreeO₂ system. Considering the shorter hospital stays among patients oxygenated with FreeO₂, it is very likely that this group would have had shorter rehospitalisation stays if they had received oxygenation with FreeO₂ technology for their subsequent hospitalisations. Consequently, the cost reduction observed in our study might have been even greater.

CONCLUSION

In our study, we observed a 20.7% reduction in costs with FreeO₂ technology for an increased effectiveness of 56.3% at the target SpO₂ (ie, the percentage of time at the target increased from 51.94% to 81.19%). Automated oxygen titration with FreeO₂ therefore appears very cost-effective, and it would, in all probability, be very advantageous for the healthcare system to have this technology.

This technology delivers optimised oxygen therapy and allows patients with COPD to return home faster (which is the objective of all healthcare systems), and it yields substantial savings with patients with COPD hospitalised for acute exacerbations. The growing number of patients with COPD worldwide and in the Canadian population, in particular, must give pause for reflection on how to effectively manage such patients. A technology such as the FreeO₂ system could therefore prove very useful in achieving this objective. At IUCPQ-UL, that could potentially yield savings of about \$C1 468 000 per year (ie, \$C2960 for 496 hospitalised patients). In the case of Quebec, where hospitals operate on a fixed-budget basis, the savings generated will make it possible to fund other activities or treat a larger number of patients with the same number of beds.

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Contributors TGP, CRCK and FL conceived the study. TGP, PAB and VT collected the data. TGP, CRCK, SB, FM and FL participated to the analysis of data. TGP and CRCK conducted the bootstrap simulations. TGP and CRCK wrote the manuscript. All authors revised and approved the manuscript.

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Disclaimer The funding body did not influence the study design and analysis.

Competing interests FL is the coinventor of the FreeO₂ system and cofounder of Oxynov, the firm that developed and productionised the FreeO₂ system for marketing. The Fonds de Recherche en Santé du Québec contributes to Dr François Lellouche salary for research activities (clinical research scholar) and to the research assistant's salary (clinical research grant). FM holds a GlaxoSmithKline/Canadian Institutes of Health Research chair on COPD at Laval University. FM participates in Innovair, a company that owns shares in OxyNov, the owner of the FreeO₂ device.



Patient consent Obtained.

Ethics approval The RCT was approved by the Institutional Ethics Committee of the IUCPQ (# 20694), and a signed consent was obtained from each participant.

Provenance and peer review Not commissioned; externally peer reviewed.

Data sharing statement Data are available on request to the corresponding author.

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