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NON-INVASIVE VENTILATION

Non-invasive Ventilation: Effect of Vented and Non-vented Exhalation Systems on Inspiratory CO_2 and O_2 Concentrations, Ventilation, and Breathing Pattern

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Abstract

Introduction To increase CO_2 elimination and to reduce work of breathing in hypercapnic patients, non-invasive ventilation (NIV) can be applied via mask either with non-vented CO_2 exhalation systems or with vented systems with leak port. The effect of the exhalation system on CO_2 rebreathing in the mask and total gas exchange remains widely unknown. Aim of this study was to compare the exhalation systems in terms of inspiratory O_2 and CO_2 concentrations, breathing patterns and gas exchange.

Methods We prospectively examined 10 healthy subjects and 10 hypercapnic patients with both exhalation systems. O_2 and CO_2 were measured in the nose, in the mask, and in the ventilation circuit, and respiratory rate, tidal volume, and transcutaneous capnometry ($PtcCO_2$) were recorded during the experiments.

Results Using the non-vented system, CO_2 concentrations in the mask were significantly higher in both subject groups, and $PtcCO_2$ values in the patient group increased up to 3.6 mmHg compared to the vented system ($p = 0.011$). O_2 concentrations increased with higher O_2 flow rates, but were significantly lower in the vented settings in both groups. No effect in breathing pattern could be demonstrated during the measurement time.

Conclusion Using NIV, the chosen exhalation system influences CO_2 and O_2 concentrations under the mask, CO_2 rebreathing from the mask and could influence the effectiveness of the ventilation support with regards to hypercapnia treatment. To compensate for relevant hypoxia, the O_2 supplementation must be set up to a sufficient level under a vented system.

Keywords COPD · NIV · Respiratory physiology · Gas concentrations · Tube · Vented · Non-vented

Introduction

A variety of diseases can cause hypercapnic respiratory failure, leading to the indication of home non-invasive ventilation (NIV) [1]. This form of respiratory support is an important treatment option in patients with chronic obstructive pulmonary disease (COPD). Although improving gas exchange and normalization of partial arterial carbon dioxide pressure ($PaCO_2$) has been the proposed target parameter for ventilation control in COPD, the implication in terms of clinical benefits remains ambiguous [2]. The ventilation settings that lead to optimal treatment efficacy are still subject of ongoing research. In COPD patients with chronic hypercapnia, high inspiratory pressures and ventilator frequency set above the patient's normal resting respiratory rate, also known as high intensity NIV, appears to be the most effective method to improve blood gases [3–7]. To achieve optimal efficacy and adherence in the treatment of acute or chronic respiratory failure, different tube systems and masks are available [1, 8]. Concerning masks, a recent meta-analysis that assessed NIV efficacy found no different effects between oronasal and nasal masks for blood gases and tolerance and described oronasal masks as the most commonly used interfaces for home NIV [9]. However, there is still limited research on the effect on treatment efficacy and the reduction in $PACO_2$ using different NIV exhalation systems. The systems are classified as vented and

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non-vented variants. Vented systems operate with a single-tube and leakage system, with leak ports in the mask or between tube and mask. Non-vented systems operate with fully closed masks without leakage ports and a respiratory cycle-controlled exhalation valve, often used with a double tube system. Lung model studies indicated a reduction of dead space ventilation, when the exhalation port is localized in the mask, and that rebreathing from the mask depends on the volume of the mask [10, 11]. Some data exist on the influence of leakage flows on FiO_2. In a clinical experimental study, FiO_2 decreased by 6.3% due to the application of an artificial leakage in a single tube system with a controlled exhalation valve [12]. Studies in experimental models and healthy volunteers showed a relation between the oxygen concentration in the mask and the oxygen flow rate, the location of the leakage, the oxygen supply, and the ventilation pressure in vented systems [13–15].

Our clinical-experimental study was conducted to systematically compare CO_2 and O_2 concentrations under NIV with a vented and a non-vented system in order to estimate the influence of the used exhalation system on gas concentrations and patients` gas exchange.

Methods

This was a monocentric, randomized study with approval Nr 13/2014 of the ethics committee of University Witten/Herdecke, Germany. This study included 10 healthy subjects and 10 stable COPD patients. Informed consent was obtained from all individual participants. Anthropometric data were recorded, and spirometry and bodyplethysmography were performed for each participant according to the European Respiratory Society (ERS) and American Thoracic Society (ATS) guidelines [16, 17]. Inclusion criteria for the healthy participants were: age 18–80, anamnestically healthy lungs, non-smoker. Inclusion criteria for the patients were: age 18–80, diagnosis of COPD with prescribed NIV therapy.

Subjects and Device Settings

All subjects were measured during the day in a semi-recumbent position the same NIV device (VENTIlogicLS, Weinmann, Hamburg, Germany). The pressure was set according to the study procedure (see Table 1). Oxygen was supplied laterally to the ventilator via a safety valve. Flow rate and concentration of supplemented oxygen were monitored by a meter (Check O_2 plus; Invacare GmbH, Isny, Germany).

Patient Interfaces and Tube Systems

The same oronasal mask brand (Fig. 1) was used in all patients and subjects (JOYCE Fullface, Weinmann, Hamburg, Germany). The vented setting with exhalation valve at the mask was used with a single tube system, and the non-vented setting had no exhalation valve and a double-tube system.

Recording Devices

O_2 and CO_2 concentrations were recorded breath-by-breath using the ML206 fast gas analyzer (ADInstruments, Dunedin, NZ). In addition, blood gases were continuously monitored and recorded by transcutaneous capnometry (TOSCA, Radiometer, Krefeld, Germany), and tidal volume, respiratory rate and mask leakage were read and recorded from the ventilator. All parameters were continuously recorded using Powerlab, and LabChart V7 software (ADInstruments, Dunedin, NZ).

Measurement Points

O_2 and CO_2 concentrations were measured at 3 defined measurement points (MP) in the ventilation system. At measurement point 1 (M1) the gas concentration in the upper airways was measured. A thin plastic tube, which was connected to the probe of the gas analyzer, was inserted into the oxygen connection port of the mask. The tubing was secured with a tape above the upper labial lip, with the tip of the tubing protruding approximately 1 cm into the nostril.

Measurement point 2 (M2) measured the concentrations of the mixed air in the mask. The measuring tube was inserted into the mask in the same way as before, but fixed to the wall of the mask immediately behind the entry point.

Measurement point 3 (M3) measured the existing gas concentrations within the circuit system before they reach the patient. For this purpose, an adapter for pressure measurements was placed between the ventilator and the tubing system at the ventilator end, from which the gases were fed into the gas analyzer.

Procedure

The measurements with the tube systems (non-vented vs vented) were conducted in randomized order following a predesigned randomization list, starting either with the vented or the non-vented setup. For each tube system, three pressure levels (12/4, 16/4, 20/4 cmH2O) and for each pressure level three oxygen flow rates (0, 2, 5 l/min) were measured. The gas concentrations were recorded at all three measurement points (Table 1). After randomization, all subjects and patients underwent the measurements in the same sequence, starting with the lowest pressure level and with the lowest oxygen flow rate. This represented 54 partial readings per subject/patient.

Table 1 Study flow chart

System	IPAP/EPAP	O_2 flow (L)	MP		System	IPAP/EPAP	O_2 flow (L)	MP
Double-tube and non-vented mask	12/4	0	1	Randomized	Single-tube and vented mask	12/4	0	1
			2					2
			3					3
		2	1				2	1
			2					2
			3					3
		5	1				5	1
			2					2
			3					3
	16/4	0	1			16/4	0	1
			2					2
			3					3
		2	1				2	1
			2					2
			3					3
		5	1				5	1
			2					2
			3					3
	20/4	0	1			20/4	0	1
			2					2
			3					3
		2	1				2	1
			2					2
			3					3
		5	1				5	1
			2					2
			3					3

Data Analysis and Statistics

At the end of each partial reading, when the subject was breathing regularly and without agitation, 10 consecutive breaths were analyzed in a breath-by-breath manner. Descriptive statistics with means and standard deviations were calculated for all data obtained. Comparative statistics were performed using the Wilcoxon test for connected samples and the Mann–Whitney-U test for comparisons between COPD patients and healthy subjects. For the primary endpoint CO_2 and O_2 concentration at M1, a 2-sided significance level of 0.05 at a power of 90% was deemed a significant difference between the vented and the non-vented system.

Patients' Baseline Characteristics

Baseline anthropometric data and lung function data are presented in Table 2. The healthy subjects were considerably younger and had a higher BMI than the COPD patients. The COPD patients showed severe obstructive ventilation disorder and pulmonary hyperinflation.

Results

CO_2 Concentrations

The mean CO_2 concentrations in the mask were significantly higher with the non-vented system in both subject groups independent of the amount of oxygen supplementation and iPAP (CO_2 concentrations are presented in Table 3 and Fig. 2). Further details of the gas concentrations at each setting and MP are provided in the supplementary tables (Supplementary file 1 and 2).

O_2 Concentrations

The mean oxygen concentrations increased with increasing O_2 flow rate with the vented as well as with the non-vented

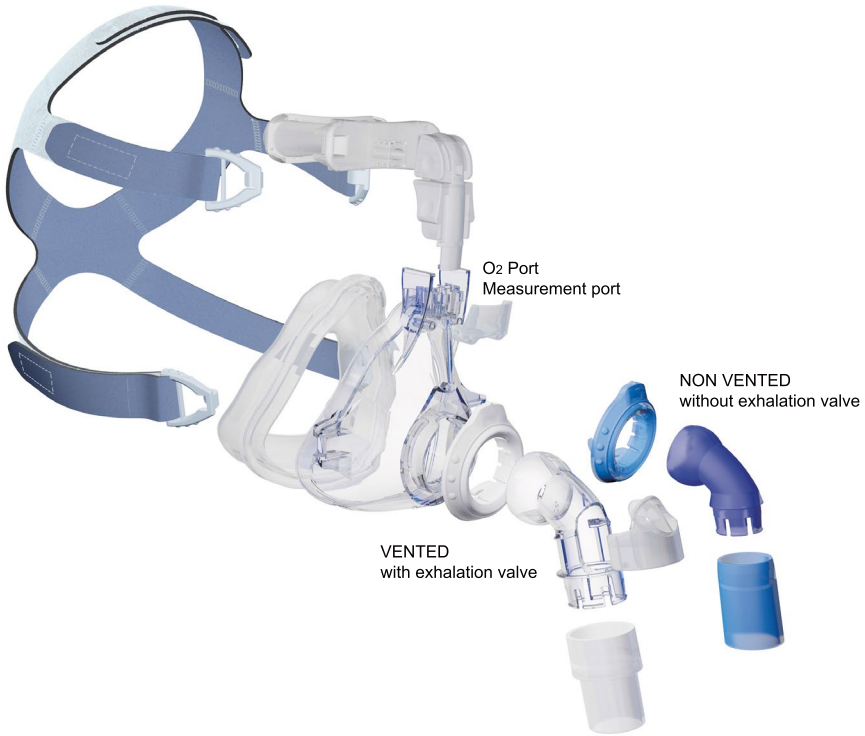

Fig. 1 Patient Interface with vented and non-vented valves

Table 2 Baseline characteristics

	COPD patients		Healthy subjects	
	Mean	SD	Mean	SD
Age (year)	60.5	10.9	31.9	9.7
Height (cm)	172.4	11.3	173.5	7.9
Weight (kg)	77.9	24.4	83.6	14.5
BMI (kg/m^2)	26.0	5.8	27.7	3.8
SpO_2	93.2	2.8	99.1	0.5
$PaCO_2$	46.2	5.6	32.3	3.6
FEV1 (l)	1.1	0.4	3.8	0.7
VC in (l)	2.4	0.8	4.5	0.7
RV (l)	4.5	1.6	1.7	0.0
TLC (l)	6.9	1.9	6.0	0.7
FEV1 (% predicted)	38.1	12.5	105.0	12.7
VC in (% predicted)	64. 7	11.6	101.3	6.7

system, over all measurement points, and in all subjects. However, with the vented system, the overall O_2 concentrations were lower. When disconnecting the oxygen supplement (0L/min), O_2 concentration was below 21% at both mask points (M1 and M2). The lowest measured value with 18.2 ± 0.8% was measured in patients in the vented setting with an iPAP of 20 cmH_2O (see Table 4, Fig. 3).

Transcutaneous Partial Pressure of Carbon Dioxide ($PtcCO_2$)

During the vented ventilation, the patient's $PtcCO_2$ values significantly decreased compared to the non-vented ventilation (mean value over all pressure modes: 43.7 ± 0.1 vs 46.7 ± 0.4; $p = 0.05$). The healthy subject's $PtcCO_2$ values were also lower during vented ventilation, but did not differ significantly (28.0 ± 1.3 vs 29.5 ± 1.1; $p = 0.19$), see Fig. 4.

Leakage and Breathing Pattern

The leakage flow was significantly higher using the vented system compared to non-vented (mean leakage of both mask measurement points, M1 and M2, and all settings in healthy subjects: 39.9 ± 11.3 ml vs. 1.7 ± 1.7 ml; $p < 0.001$; and patients: 41.0 ± 9.8 ml vs. 6.5 ± 6.9 ml; $p < 0.001$). The overall respiratory rate (rr) and the tidal volume (Vt) was not statistically different between the non-vented and vented setting (see Table 5).

Table 3 Mean CO_2 concentrations and differences in patients and healthy subjects at M1, M2 and M3

CO_2 concentration (%)	Non- vented		Vented		Diff		T test NV vs V
MP	Mean	SD	Mean	SD	Mean	SD	p
Patients							
M3	0.59	0.08	0.56	0.06	0.01	0.04	0.116
M2	2.88	0.56	1.54	0.41	1.34	0.77	< 0.0001
M1	3.09	0.55	2.45	0.55	0.64	0.68	< 0.0001
Healthy subjects							
M3	0.60	0.04	0.57	0.04	0.03	0.03	< 0.0001
M2	2.27	0.42	1.45	0.34	0.81	0.58	< 0.0001
M1	2.37	0.56	1.90	0.36	0.47	0.53	< 0.0001

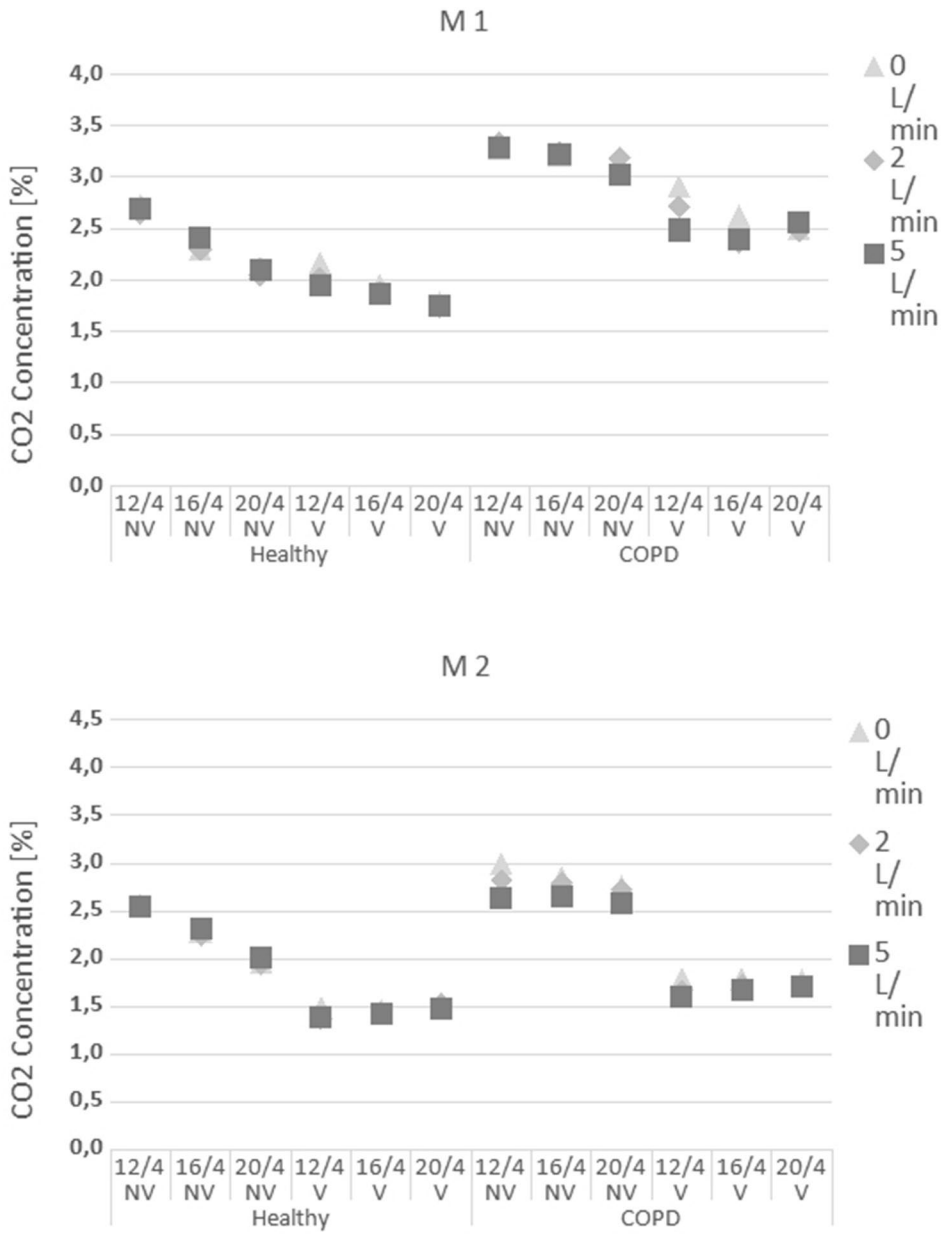

Fig. 2 CO_2 concentrations at M1 and M2

Table 4 Mean O_2 concentrations and Differences in Patients and Healthy Subjects at M1, M2 and M3

O_2 concentration (%)		Non- vented		Vented		Diff		T test NV vs V
MP	O2	Mean	SD	Mean	SD	Mean	SD	p
Patients								
M3	0	21.19	0.16	21.13	0.13	0.02	0.06	0.068
	2	26.06	1.19	24.09	0.64	1.92	1.06	< 0.0001
	5	33.85	0.71	28.46	0.55	5.40	0.95	< 0.0001
M2	0	18.64	0.71	20.04	0.55	− 1.40	0.95	< 0.0001
	2	23.20	1.18	22.72	0.57	0.47	1.39	0.072
	5	30.92	3.41	26.55	0.96	4.37	3.03	< 0.0001
M1	0	18.32	0.77	18.88	0.49	− 0.56	1.07	0.008
	2	22.68	0.89	21.74	0.86	0.94	0.98	< 0.0001
	5	30.18	3.33	26.03	1.37	4.14	2.58	< 0.0001
Healthy subjects								
M3	0	20.99	0.06	21.01	0.07	− 0.02	0.06	0.060
	2	25.88	1.62	23.48	0.59	2.41	1.66	< 0.0001
	5	34.16	0.51	27.50	0.44	6.66	0.47	< 0.0001
M2	0	19.32	0.51	19.92	0.44	− 0.60	0.47	< 0.0001
	2	24.75	1.14	22.95	0.70	1.78	0.78	< 0.0001
	5	34.61	4.73	28.06	2.24	6.65	3.87	< 0.0001
M1	0	19.03	0.65	19.55	0.41	− 0.52	0.66	0.0002
	2	24.59	1.04	22.99	1.18	1.60	1.14	< 0.0001
	5	33.48	3.70	28.16	2.29	5.32	2.91	< 0.0001

Discussion

CO_2 Concentrations

To our knowledge, the present study was the first to demonstrate an effect on CO_2 concentrations and subsequent lowering of $PtcCO_2$ values in hypercapnic COPD patients and in healthy subjects when comparing NIV with a vented exhalation system to a non-vented system. The higher leakage flow with the vented system and the subsequent reduction in CO_2 rebreathing could be regarded as the possible cause for lower CO_2 concentrations at the nares and in the mask. Other research supports the assumption, that the effect of CO_2 rebreathing from the mask could be the cause for the different results we were able to measure. A study on a lung model compared 19 different face masks [11]. Ventilation with face masks with expiratory ports over the nasal bridge reduced the total dynamic dead space from 42 to 28.5% of the tidal volume and thus to a level less then physiological dead space. There are only a few experimental data about a comparable $PaCO_2$ measurement during ventilation with active exhalation valve or passive exhalation port. Vianello et al. randomized amyotrophic lateral sclerosis (ALS) patients on tracheostomy ventilation to the aforementioned exhalation systems (each $n = 10$) [18]. $PaCO_2$ values did not significantly differ after 30 days, but tended to be lower with the passive exhalation port. Notably, this was not NIV via a mask and the underlying disease required much lower ventilator pressures. Surprisingly, the work of Storre et al. demonstrated an increase in $PaCO_2$ by 1.8 mmHg when an artificial leak was introduced into the circuit of the active and passive exhalation valves of NIV systems (pooled data) [12]. It was suggested, that the occurrence of leaks would cause decreasing minute ventilation demonstrated by increasing $PaCO_2$, which negatively impacted on oxygenation.

Our patient measurements yielded the opposite effect: with substantially higher leakage in the vented system, $PtcCO_2$ was up to 3.7 mmHg lower. The underlying mechanism of action seems to be a washout effect in the mask from the vented system leakage, with a subsequent reduction of CO_2 rebreathing. This mechanism has been described previously in relation with nasal high flow (NHF) in the nasopharynx [19] The reduction of CO_2 rebreathing was found to be dependent on the NHF rate; the association between the level of mask leakage and the measured CO_2 concentration in our study could be interpreted similarly. The reduction in CO_2 rebreathing can be thought of as a reduction of extraanatomical dead space within the mask, with the CO_2 concentration in the incoming airway being approximately 5% in healthy subjects. For the COPD patient with ventilation-perfusion mismatch, expiratory flow limitation, and increase in alveolar dead space, a small amount of dead space reduction may be important and can lead to an improvement in CO_2 exhalation.

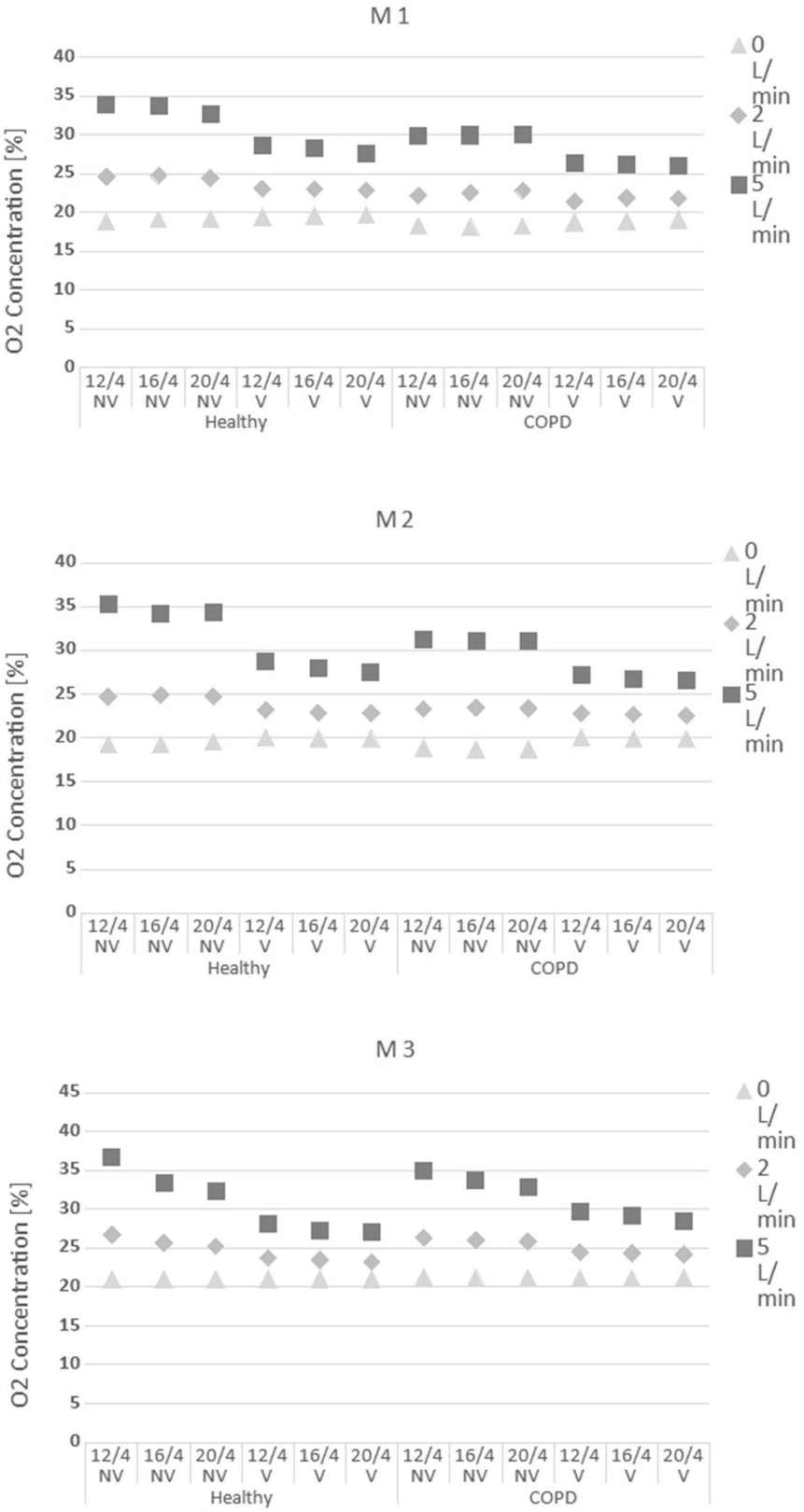

Fig. 3 O_2 Concentrations at M1, M2, and M3

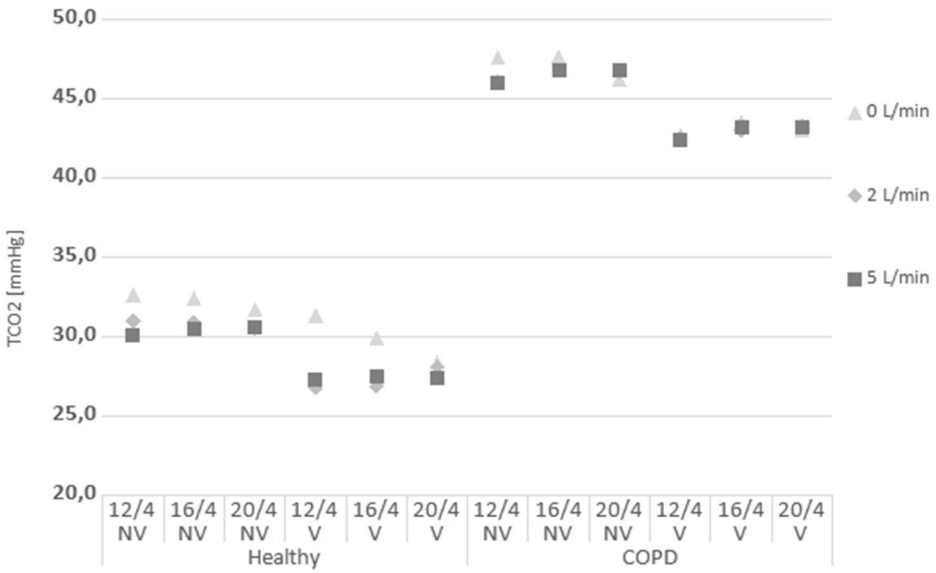

Fig. 4 Mean transcutaneous partial pressure of carbon dioxide (PtcCO2), non-vented (nV) vs. vented (V)

Table 5 Physiological device data in patients and healthy subjects independent of MP, non-vented vs vented

O2	iPAP	Non-Vented						Vented						Wilcoxon test non-vented vs vented		
		Respiratory rate (n/min)		Leckage (L/min)		Vt (ml)		Respiratory rate (n/min)		Leckage (L/min)		Vt (ml)		Respiratory rate	Leak	Vt
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	p	p	p
Patients																
0	12/4	16.8	3.0	4.3	5.0	277.3	68.5	16.6	2.4	38.2	8.5	295.2	54.5	0.799	0.005	0.799
0	16/4	15.9	2.4	5.4	6.6	315.4	56.0	15.4	1.7	41.6	11.5	322.2	64.4	0.169	0.005	0.799
0	20/4	15.5	2.0	6.0	6.9	342.5	67.1	14.7	1.3	43.5	10.8	362.0	87.7	0.139	0.005	0.386
2	12/4	16.7	2.6	4.9	5.6	260.6	70.5	15.4	1.7	39.0	8.2	290.6	74.0	0.386	0.005	0.959
2	16/4	15.9	2.3	5.5	6.1	292.4	70.3	15.1	1.6	39.9	8.6	297.4	78.4	0.241	0.005	0.646
2	20/4	15.1	1.9	5.7	7.3	335.1	90.1	14.5	1.3	42.2	9.2	340.7	75.8	0.203	0.005	0.878
5	12/4	17.5	3.0	5.9	5.6	232.5	52.6	15.8	1.9	37.0	8.1	255.6	73.8	0.038	0.008	0.110
5	16/4	15.7	2.3	5.8	6.7	289.7	77.4	14.6	1.4	39.9	8.4	303.5	88.4	0.110	0.008	0.594
5	20/4	15.4	1.8	6.3	8.2	317.0	71.2	14.2	1.8	42.3	9.4	348.3	92.5	0.028	0.008	0.139
Healthy																
0	12/4	16.2	1.6	1.7	1.2	291.1	95.8	18.0	3.0	36.6	9.6	321.2	93.6	0.037	0.005	0.203
0	16/4	15.9	1.3	1.5	0.8	346.5	81.3	17.0	2.6	38.6	10.8	355.7	97.5	0.386	0.005	0.508
0	20/4	15.7	1.0	1.5	0.7	411.0	90.6	17.1	2.7	41.1	12.4	412.5	97.6	0.169	0.005	0.646
2	12/4	15.8	1.4	1.5	0.5	268.2	91.2	18.1	3.4	36.9	10.5	272.7	92.5	0.074	0.005	0.508
2	16/4	15.5	1.3	1.5	0.8	327.0	74.7	17.5	3.0	39.2	11.9	325.2	81.9	0.114	0.005	0.878
2	20/4	15.5	1.4	1.7	1.2	384.7	58.9	17.5	3.0	41.8	12.9	398.1	91.8	0.047	0.005	0.575
5	12/4	15.8	1.7	1.8	1.5	259.7	85.2	17.7	3.1	36.7	10.3	276.6	90.0	0.114	0.005	0.646
5	16/4	15.5	1.7	1.8	2.0	309.3	79.0	17.3	3.0	39.0	11.5	346.1	96.5	0.241	0.005	0.114
5	20/4	15.1	1.1	2.2	2.7	374.6	69.1	17.3	3.1	41.2	12.6	411.4	133.5	0.037	0.005	0.333

The concept of high intensity NIV with inspiratory pressure levels above 20 mbar has been developed to achieve an effective reduction of $PaCO_2$ in severe hypercapnic COPD patients [5]. The elevation of pressure from 12 to 20 cmH_2O in our study however revealed only a small decrease in CO_2 concentrations at the nose (M1) or in the mask (M2) (3.28% vs. 3.02%; non-vented, $5LO_2$/Min.) The choice of the exhalation system, on the other hand, made a difference in CO_2 concentrations and patient`s $PtcCO_2$ values.

O_2 Concentrations

FiO_2 was lower in both subject groups with the vented system applied, with a difference at M1 of 5.5% in healthy subjects, and 3.8% in COPD patients under 5L/Min oxygen insufflation and iPAP of 16. Storre et al. demonstrated a difference of 3.2% between an active and a passive exhalation valve, and of 5.7% with and without an introduced artificial leak and active exhalation valve [12]. So in our work, the drop in FiO_2 when using a vented versus a non-vented system was quite comparable. In contrast, the passive exhalation valve and the artificial leak of Storre were located in the ventilator circuit and not in the mask, and the FiO_2 measurement was taken between the mask and the circuit, whereas in our study the FiO_2 measurements were obtained inside of the mask and in the nasal cavity. With $5LO_2$/min of supplemented oxygen we found the lowest FiO_2 with 27.5% (healthy) or 26.1% (COPD) using the vented system, and Storre found 27.6% in the setting with active exhalation valve and artificial leak. A study using a lung model also demonstrated a FiO_2 of 27.6% under an O_2 insufflation rate of 6 L/min and a leakage of 34.5 L/min at an airway pressure of 5 cmH_2O [20]. Another study in a lung model showed a FiO_2 of 31 ± 1% with a mask leak, an O_2 insufflation rate of 5L/min, and an IPAP of 20 cmH_2O [14]; a study with vented test setups in three healthy volunteers at an IPAP of 20 cmH_2O and an O_2 insufflation rate of 6 L/min demonstrated a FiO_2 of 26% [13]. These comparable results despite different leakage systems, different experimental setups, and different models (lung model, subjects, patients) suggest a degree of predictability for the expected FiO_2 using a vented system, which might help in the individual selection of the O_2 insufflation rate under NIV. Prevention of critical arterial hypoxia with a $PaO_2 < 55$ mmHg to avoid stimulation of chemoreceptors and an increase in inspiratory neural drive is of concern for ventilated COPD patients.

Limitations

We did not investigate inspiratory pressures above 20 cmH_2O and did not asses the respiratory drive, for example by measuring diaphragmatic EMG or esophageal pressure. Our measurements were conducted in an experimental setting during daytime and were limited in time. A direct transfer of the measured concentration differences to the clinical routine of nocturnal NIV is not possible. Rather, it is a contribution to the understanding of nasopharyngeal washout during mask respiratory support, a point that has received little attention but may be of importance to COPD patients with hypercapnic respiratory failure. We also chose to focus on a single respirator and one vented and one non-vented system each because of the experimental effort involved. However, the masks and ventilation tubes we used must be considered to be representative of the respective system. Furthermore, we had the advantage of direct concentration measurement intra-nasally and within the mask, and by locating the leakage in the mask, we reduced the near-patient artificial dead space. Finally, the healthy subjects and the group of patients were not matched in terms of their anthropometric data. However, when comparing subjects and patients for the first time on the mentioned question, the concentration differences measured in both groups support the conclusions made.

Conclusion

The primary aim of NIV therapy in patients with COPD and chronic hypercapnia is to improve gas exchange and normalize partial arterial carbon dioxide pressure ($PaCO_2$). Although this has been the proposed target parameter for ventilation control, the ventilation settings that lead to optimal treatment efficacy are still subject of ongoing research. The data presented here indicate that, in addition to the ventilation modes, the choice of the mask exhalation system can also play an important role in effective $PaCO_2$ reduction. Compared to a non-vented system, a vented system may be beneficial in this respect, although a sufficiently high rate of oxygen insufflation must be ensured.

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Declarations

Conflict of interest KJ Franke, M Schroeder, U Domanski, and B Dewald have no financial or other potential conflicts of interest associated with this study. G Nilius has received research support from Fisher & Paykel Healthcare, Heinen und Löwenstein, ResMed and Weinmann; this has gone into department funds.

Ethical Approval The study was approved under Nr 13/2014 of the ethics committee of University Witten/Herdecke.

Informed Consent Informed consent was obtained from all individual participants. The study was already presented at the European Respiratory Society (KJ Franke, U Domanski, M Schroeder, B Stoehr, G Nilius. Non-invasive ventilation: Effect of a vented and a non-vented CO_2 exhalation system on O_2- and CO_2-concentration. European Respiratory Journal 2016 48: OA3533; https://doi.org/10.1183/13993003.congress-2016.OA3533).

References

1. Mehta S, Hill NS (2001) Noninvasive ventilation. Am J Respir Crit Care Med 163(2):540–577. https://doi.org/10.1164/ajrccm.163.2.990611
2. Macrea M, Oczkowski S, Rochwerg B et al (2020) Long-term noninvasive ventilation in chronic stable hypercapnic chronic obstructive pulmonary disease. An Official American Thoracic Society clinical practice guideline. Am J Respir Crit Care Med 202(4):e74–e87. https://doi.org/10.1164/rccm.202006-2382ST
3. Köhnlein T, Windisch W, Köhler D et al (2014) Non-invasive positive pressure ventilation for the treatment of severe stable chronic obstructive pulmonary disease: a prospective, multicentre, randomised, controlled clinical trial. Lancet Respir Med 2(9):698–705. https://doi.org/10.1016/S2213-2600(14)70153-5
4. Murphy PB, Rehal S, Arbane G et al (2017) Effect of home noninvasive ventilation with oxygen therapy vs oxygen therapy alone on hospital readmission or death after an acute COPD exacerbation: a randomized clinical trial. JAMA 317(21):2177–2186. https://doi.org/10.1001/jama.2017.4451
5. Dreher M, Storre JH, Schmoor C, Windisch W (2010) High-intensity versus low-intensity non-invasive ventilation in patients with stable hypercapnic COPD: a randomised crossover trial. Thorax 65(4):303–308. https://doi.org/10.1136/thx.2009.124263
6. Lukácsovits J, Carlucci A, Hill N et al (2012) Physiological changes during low- and high-intensity noninvasive ventilation. Eur Respir J 39(4):869–875. https://doi.org/10.1183/09031936.00056111
7. Schwarz SB, Magnet FS, Windisch W (2017) Why high-intensity NPPV is favourable to low-intensity NPPV: clinical and physiological reasons. COPD 14(4):389–395. https://doi.org/10.1080/15412555.2017.1318843
8. Windisch W, Dreher M, Geiseler J et al (2017) S2k-Leitlinie: Nichtinvasive und invasive Beatmung als Therapie der chronischen respiratorischen Insuffizienz – Revision 2017 [Guidelines for non-invasive and invasive home mechanical ventilation for treatment of chronic respiratory failure - update 2017]. Pneumologie 71(11):722–795. https://doi.org/10.1055/s-0043-118040
9. Lebret M, Léotard A, Pépin JL et al (2021) Nasal versus oronasal masks for home non-invasive ventilation in patients with chronic hypercapnia: a systematic review and individual participant data meta-analysis. Thorax 76(11):1108–1116. https://doi.org/10.1136/thoraxjnl-2020-215613
10. Schettino GP, Chatmongkolchart S, Hess DR, Kacmarek RM (2003) Position of exhalation port and mask design affect CO_2 rebreathing during noninvasive positive pressure ventilation. Crit Care Med 31(8):2178–2182. https://doi.org/10.1097/01.CCM.0000081309.71887.E9
11. Saatci E, Miller DM, Stell IM, Lee KC, Moxham J (2004) Dynamic dead space in face masks used with noninvasive ventilators: a lung model study. Eur Respir J 23(1):129–135. https://doi.org/10.1183/09031936.03.00039503
12. Storre JH, Huttmann SE, Ekkernkamp E et al (2014) Oxygen supplementation in noninvasive home mechanical ventilation: the crucial roles of CO_2 exhalation systems and leakages. Respir Care 59(1):113–120. https://doi.org/10.4187/respcare.02596
13. Thys F, Liistro G, Dozin O, Marion E, Rodenstein DO (2002) Determinants of Fi, O_2 with oxygen supplementation during noninvasive two-level positive pressure ventilation. Eur Respir J 19(4):653–657. https://doi.org/10.1183/09031936.02.00263102
14. Schwartz AR, Kacmarek RM, Hess DR (2004) Factors affecting oxygen delivery with bi-level positive airway pressure. Respir Care 49(3):270–275
15. Samolski D, Antón A, Güell R, Sanz F, Giner J, Casan P (2006) Inspired oxygen fraction achieved with a portable ventilator: determinant factors. Respir Med 100(9):1608–1613. https://doi.org/10.1016/j.rmed.2005.12.005
16. Miller MR, Hankinson J, Brusasco V et al (2005) Standardisation of spirometry. Eur Respir J 26(2):319–338. https://doi.org/10.1183/09031936.05.00034805
17. Wanger J, Clausen JL, Coates A et al (2005) Standardisation of the measurement of lung volumes. Eur Respir J 26(3):511–522. https://doi.org/10.1183/09031936.05.00035005
18. Vianello A, Arcaro G, Molena B et al (2018) Effect of a passive exhalation port on tracheostomy ventilation in amyotrophic lateral sclerosis patients: a randomized controlled trial. J Thorac Dis 10(2):1007–1014. https://doi.org/10.21037/jtd.2018.01.102
19. Möller W, Feng S, Domanski U et al (2017) Nasal high flow reduces dead space. J Appl Physiol 122(1):191–197. https://doi.org/10.1152/japplphysiol.00584.2016
20. Miyoshi E, Fujino Y, Uchiyama A, Mashimo T, Nishimura M (2005) Effects of gas leak on triggering function, humidification, and inspiratory oxygen fraction during noninvasive positive airway pressure ventilation. Chest 128(5):3691–3698. https://doi.org/10.1378/chest.128.5.3691