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EFFECTS OF COMBINED RESPIRATORY PHYSIOTHERAPY WITH HIGH-FLOW NASAL CANNULA AND VENTURI MASK IN SPINAL CORD INJURY: A SINGLE-SUBJECT RESEARCH STUDY AND LITERATURE REVIEW

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ABSTRACT

Background: The level of spinal cord injury affects the severity of respiratory impairment and the alteration of respiratory pattern and gas exchanges. Lesions at the C3-C5 level (phrenic nerve nucleus) cause disruption of descending input with paralysis of the main inspiratory muscle, often requiring tracheostomy and prolonged mechanical ventilation. Oxygen therapy is essential to switch from ventilatory support to removal of the endotracheal tube to correct residual difficulties in oxygenation management.

Case Presentation: A 58-year-old man had tracheostomy and tetraparesis as complication of tonsillectomy and adenoidectomy treatment for a history of obstructive sleep apnea. A respiratory rehabilitation program with protocol of oxygen therapy with high flow cannula alternated with a low-flow system by Venturi mask during daytime hours only was started. The patient was constantly monitored with capillary partial oxygen saturation to obtain adequate oxygenation (≥ 94%) and registered every 15 minutes in the clinical chart. There was gradual improvement of respiratory function. Oxygen by Venturi mask was gradually reduced due to improvement of partial pressure oxygen values. Over the course of days, the optimal results of respiratory parameters led to a gradual weaning from the Venturi mask until the complete discontinuation of the low-flow system during daytime and decreased of the high-flow fraction of inspired oxygen to the maximal tolerated level during nighttime.

Conclusions: Implementing a combined protocol of nighttime oxygen with high flow cannula and daytime Venturi mask improves intensive motor training of patients by promoting the acquisition of ability to perform chair/bed transitions and to be able to achieve standing and begin gait training. More research is needed whether or noted to determine the role of this promising approach in patients with severe SCI and in other critically ill patients.

KEYWORDS

Venturi mask, high flow nasal cannula, spinal cord disease, mechanical ventilation, respiratory rehabilitation

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LEARNING POINTS

- This is a presentation of a new respiratory training protocol of combined oxygen therapy by high flow cannula and Venturi mask in a patient with cervical spinal cord injury and respiratory failure.
- Due to this new respiratory training, from the weaning of ventilation devices the patient had greater independence and improved quality of life, with more intensive motor training in the gym, improvement of the motor program and the patient tolerance to training.
- Oxygen therapy with high flow cannula and Venturi mask could be valid and reliable combined respiratory training to improve the respiratory pattern in severely hypoxemic and hypercapnic patients, without adverse events.

INTRODUCTION

Spinal cord injury (SCI) is one of the causes of disability. SCI causes motor and multi-organ impairments (as cardiovascular, respiratory), with a reduced quality of life (QoL)[1]. Cervical SCI often requires prolonged mechanical ventilation due to paralysis of respiratory muscles leading to worsening lung vital capacity, severe impairment of clearance of tracheobronchial secretions, and a high incidence of respiratory complications, such as pneumonia or atelectasis. Respiratory failure is, therefore, the most common early complication and the leading cause of death in both the acute and chronic phases in SCI[1]. The level of SCI affects the severity of respiratory impairment and the alteration of respiratory pattern and gas exchanges. The more rostral the level of SCI and the more complete the injury, the more severe the respiratory impairment. Usually, the consequence is mechanical ventilation as well as endotracheal intubation and/or tracheostomy[2]. When weaning is possible, oxygen therapy is necessary to switch from ventilatory support to removal of the endotracheal tube to correct residual difficulties in oxygenation management[1]. The purpose of this paper is to present the results of a respiratory rehabilitation treatment of a patient with cervical SCI and respiratory failure, treated with combined oxygen therapy (O_2) administered by high flow cannula (HFC) and Venturi mask (VM).

CASE DESCRIPTION

A 58-year-old man, with a history of obstructive sleep apnea, underwent tonsillectomy and adenoidectomy and turbinate reduction in April 2023. He had no history of dysphagia and performed normal activities of daily living (ADL). After about a month, the surgical procedure was complicated by spondylodiscitis with meningoencephalitis. In June 2023, the patient underwent C2-C3 decompression surgery and implantation of a ventricular-peritoneal shunt for tetra-ventricular hydrocephalus, with slight clinical improvement. Subsequently the shunt was removed. In addition, following dysphagia and respiratory failure, percutaneous endoscopic gastrostomy (PEG) implantation and tracheostomy cannula were performed. After resolution of the meningoencephalitis, the patient was transferred to the Department of Unità Spinale Unipolare, Azienda Ospedaliera per l'Emergenza, Cannizzaro, for rehabilitation treatment. On admission, the patient was conscious, collaborating, with no apparent cognitive deficits, but with incomplete quadriplegia with lower limb tactile hypoesthesia and hypoalgesia. The patient required assistance for all ADLs, with an American spinal injury association (ASIA) scale classification[3] of C, level C4. His Barthel index was 0/100. The patient was also fitted with a neck brace. The onset of hypercapnia required O_2 therapy with HFC (Optiflow, Fisher and Paykel Healthcare) with a final O_2 of 8 l/min and volumes of 35 l/min for 24 hours. However, motor rehabilitation under these conditions was limited to passive movements in bed and confined to the few activities possible in the patient's room. To facilitate

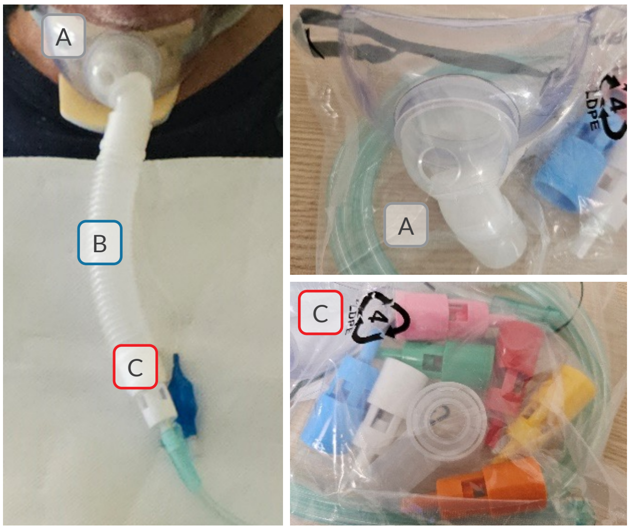

Figure 1. Venturi tracheotomy (A) nebulization mask with (B) sure flow tubing and one of the (C) colored adapters for different oxygen concentration flowing. The various Venturi valves provide a 'fixed' fraction of inspired oxygen (FiO_2) of 24-60%, depending on the size of the openings for oxygen and air, and based on oxygen delivery rate and the amount of airflow varies. Through a thin hole, oxygen flows in a high-speed jet and is diluted by atmospheric air that is drawn in through a side port. According to Bernoulli's theorem of fluid dynamics the total energy and flow rate (volume of fluid per unit time) must be constant at every point in the tube. Thus, the fluid velocity (kinetic energy) at the point of constriction of the pipe increases when the cross-sectional area (pressure/potential energy) decreases: this is the so-called Venturi effect. On the other hand, gravity, the pressure gradient, fluid viscosity and other variables remain constant (Bernoulli's theorem). In the end, the final oxygen concentration delivered to the patient may be lower than the FiO_2 depending on the patient's ventilatory requirements[1,2].

Figure 2. Oxygen therapy with high flow cannula (HFC). The system is characterized by a device (A) that receives oxygen and water, heats, and humidifies the gas and delivers it to the patient through a (B) heated single-branch inspiratory circuit (to avoid heat loss and condensation) and through a large-diameter nasal cannula (C). O_2 therapy with HFC generates an air-oxygen mixture that allows a high fraction of 21-100% of inspired oxygen (FiO_2), provides a constant FiO_2 and creates air flow rates/volumes of up to 60 l/min by reducing oxygen dilution. The heated humidification generates positive end-expiratory pressure by hindering expiratory flow, facilitates clearance of secretions, prevents alveolar collapse and atelectasis lung recruitment, improves alveolar ventilation, reduces bronchospasm, and improves airway mucosal function by attenuating mucociliary clearance, supporting epithelial integrity and removing physiological nasopharyngeal dead space[10]. In our patient the O_2 therapy with HFC was started at 8 PM and stopped at 8 AM.

recovery and to allow the patient to use the wheelchair outside the room, it was decided to carry out a combination of O_2 therapies by high and low flow systems.

Protocol: A protocol of O_2 therapy with high-flow by cannula (O_2-HFC) with a fraction of inspired oxygen (FiO_2) initially of 0.44 (O_2 8 l/min) and a flow of 35 l/min alternated with a low-flow system by Venturi mask (O_2-VM, FIAB S.p.A., model OS/60K), at the same FiO_2 levels (35% O_2 8 l/min) during daytime hours only was followed *(Fig. 1 and 2)*. Every morning an arterial blood gas (ABG) - at about 8 AM - an objective tool with an unbiased evaluation of partial pressure of oxygen values (PaO_2), partial pressure of carbon dioxide ($PaCO_2$) and pH in arterial blood[4], was applied before stopped O_2-HFC, and then the O_2-VM protocol was started. Arterial blood gas was recorded every thirty minutes for the first two hours, then every 2-3 hours based on the clinical conditions in the first days of training. The patient was constantly monitored with capillary partial oxygen saturation (SpO_2) to obtain adequate oxygenation ($SpO_2 \geq 94\%$). Then, an ABG was performed about every 4-6 hours from starting the VM-protocol, based on SpO_2 *(Fig. 3)*, and 8 PM, before starting O_2-HFC. Therefore, the O_2 therapy with HFC started at 8 PM and stopped at 8 AM.

Results: Respiratory training with combined oxygen therapy administered by high flows via a tracheostomy cannula during the nighttime (from 8 PM to 8 AM) and by low flows with a VM in the daytime (from 8 AM to 8 PM), allowed to achieve the following results:

- Gradual weaning from high flows and oxygen therapy during daytime.
- Reaching eupnea with an artificial filter for tracheostomy cannula (cupped) during daytime with good respiratory compensation.
- Reduction in the overnight FiO_2 with O_2-HFC, from 44% to 31%.
- The O_2-HFC weaning allowed more intensive motor training and increased the patient's tolerance to training, improving the motor program.
- The patient from bedridden posture was able to tolerate the sitting position, to start chair/bed transitions with caregiver supervision, to achieve standing position and starting overground gait training, also with a robotic device for training gait ability (Lokomat, Hocoma AG).

DISCUSSION

This is the first case of a patient with cervical SCI and respiratory failure that was treated with a combined respiratory training of oxygen therapy administered by high flows via a tracheostomy cannula during night and by low flows with a VM in the daytime. This training led to a gradual weaning from high flows during the daytime, as well as a weaning from daytime oxygen therapy and a reduction in the overnight FiO_2 with O_2-HFC. As shown in *Table 1*, over the course of days, the optimal results of PaO_2 parameters obtained led to a gradual weaning from the VM until the complete discontinuation of the low-flow system during the daytime and decrease of the high-flow FiO_2 to the maximal tolerated level of FiO_2 31% O_2 4 l/ min, only during the nighttime. Because the patient continued to have obstructive sleep apnea syndrome (OSAS), an attempt to an overnight O_2-VM at FiO_2 31% 6 l/min was made, but failed because of hypercapnia, requiring the use of O_2-HFC therapy. Subsequently, the combination of O_2 treatment with nighttime HFC and daytime VM, improved the patient's tolerance to training and his endurance increased. The O_2-HFC weaning allowed more intensive motor training in the gym, improving the motor program. Furthermore, after gradual weaning training the patient has been maintained in eupnea and with an artificial filter for tracheostomy cannula, cupped (due to persistent inability to manage secretions) with good respiratory compensation. Better motor outcomes were then achieved: the patient was able to make chair/bed transitions with caregiver supervision, achieving upright position and starting overground gait training, also without the use of robotics. As far as we know, only results of comparative studies between the two methods are currently available. In a randomized controlled trial by Maggiore et al.

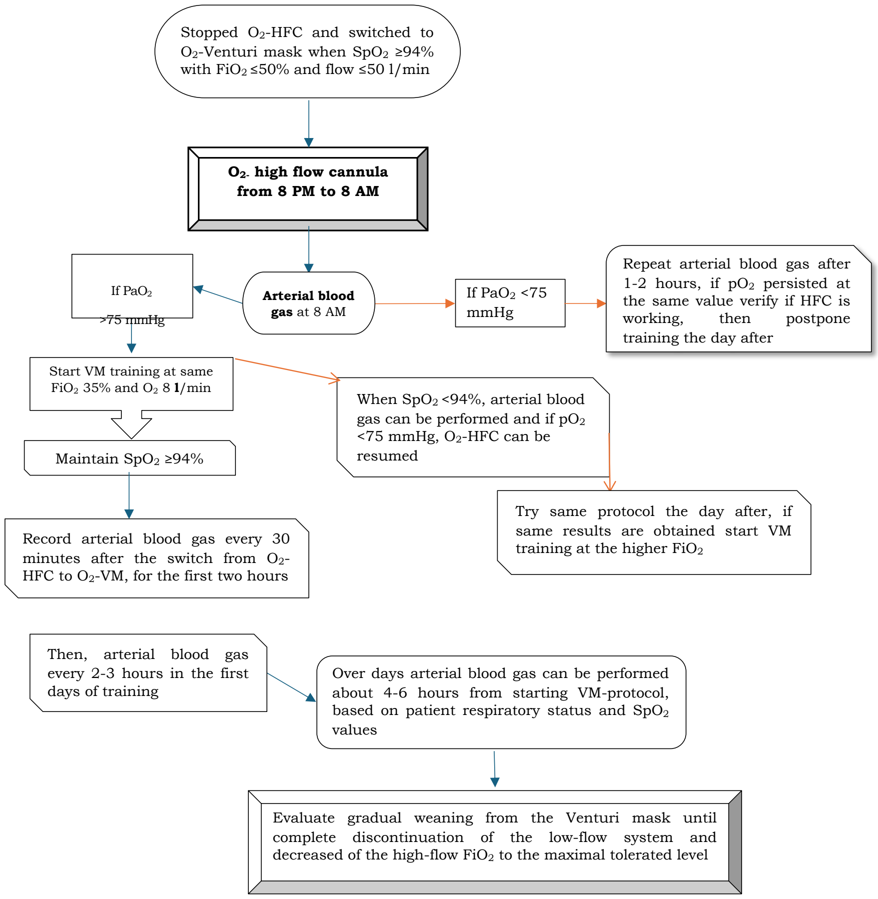

Figure 3. Weaning protocol from O_2 therapy with high flow cannula. At the beginning of the training, until the values of capillary partial oxygen saturation or arterial blood gas are stable, these evaluations are necessary. But, if performing several arterial blood gas analyses would be difficult, we suggest performing an arterial blood gas at 8 AM with O_2-HFC, then after one hour of stopping HFC. Unless a hypercapnia is associated, a capillary partial oxygen monitoring would be sufficient as observation (values ≥ 94%) and arterial blood gas could be implemented as convenient. Then, an arterial blood gas could be performed at 8 PM, before starting O_2-HFC.

in 2014, O_2 therapy with HFC was compared with VM in critically ill patients requiring O_2 therapy after extubating[5]. Moreover, it was shown that O_2 therapy with HFC improved oxygenation and reduced patient discomfort (by reducing episodes of oxygen displacement or desaturation) at the same FIO_2 set after extubating, compared to the VM. The authors concluded that the use of O_2 therapy with HFC in the post-extubating period is associated with less need for non-invasive ventilation (NIV) and endotracheal intubations compared to the VM[5]. On the other hand, Lemiali et al. conducted a multicenter randomized controlled study in which 2-hour O_2 therapy with HFC was compared with VM in immuno-compromised patients with acute respiratory failure admitted to the intensive care unit[6]. No difference was noticed in the need for non-invasive or invasive mechanical ventilation within the first 2 hours between O_2 therapy with HFC and VM, as well as in secondary endpoints such as patient comfort, dyspnea, respiratory rate, or heart rate[6]. The same results were reported in a crossover study by Gatto et al comparing O_2 therapy with HFC and the authors concluded that O_2 therapy with HFC did not improve patient comfort compared to the VM[4]. They found that there was no statistically significant difference in the PaO_2/FiO_2 ratio approximately 20 minutes after switching from O_2 therapy with HFC to VM and vice versa[4]. Several studies have reported on the efficacy of O_2 therapy with high flow nasal cannula (O_2-HFNC). The FLORALI-IM study obtained similar data comparing high-flow nasal oxygen therapy (HFOT) alone versus HFOT with NIV[7].

Recently, Watanabe et al. reported the clinical case of an 87-year-old man with a cervical SCI due to a C5/6 displaced fracture, who complained of dysphagia after surgery[8]. The authors demonstrated that the patient improved his swallowing function after starting HFC oxygen therapy, hypothesizing that O_2 therapy with HFC helped to maintain apnea tolerance time during swallowing by causing a temporary increase in lung volumes due to positive end-expiratory pressure[8]. This enhanced swallowing times by shortening the latency of the swallowing reflex and prolonging the closure time of the laryngeal vestibule during swallowing with increased oxygen flow, reducing the apnea time during swallowing and the risk of aspiration[8].

In our case, we could hypothesize that our patient's respiratory issues were a consequence of the SCI complicated by bed rest syndrome, pulmonary infections, and neurological dysfunction. Therefore, oxygen through the nasal cannula was insufficient to supply PaO_2 which decreases significantly when the patient's inspiratory flow is high, as it often occurs in critically ill patients[2,9]. Our case suggests that the combination training of O_2 therapy with HFC (during the nighttime) and VM (during the daytime) may improve the respiratory pattern of SCI patients. This can be explained by the reduction in anatomical dead space, a low positive end-expiratory pressure level, improved thoraco-abdominal synchrony and a decrease in mucous dryness symptoms[9]. It has been shown that respiratory rehabilitation may enhance cardiopulmonary function, reduce the diaphragm blood consumption, increase the

O_2-HFC (O_2/volumes)					
Date	Venturi Mask pre-treatment		16/02/2024	26/03/2024	29/03/2024
(O_2 /vol)	**10 l/min - 45 l/min**	**6 l/min - 35 l/min**	**7 l/min - 25 l/min**	**6 l/min - 25 l/min**	**3 l/min - 25 l/min**
pH	7.41	7.45	7.45	7.44	7.45
$PaCO_2$ (mmHg)	46.9	48	43	45	44
PaO_2 (mmHg)	107.9	141	148	165	108
HCO_3^-(mEq/L)	28.9	33.4	29.9	30.6	30.6
Venturi Mask					
Date	16/02/2024	21/02/2024	After one month (20/03/2024)	After one week from VM 28% (26/03/2024)	
FiO_2	**35% 8 l/min**	**31% 6 l/min**	**28% 4 l/min**	**24% 4 l/min**	
pH	7.45	7.44	7.43	7.44	
$PaCO_2$ (mmHg)	46	44	42	45	
PaO_2 (mmHg)	111	99	109	80	
HCO_3^-(mEq/L)	32	29.9	27.9	30.6	
Oxygen therapy with filter, only daytime					
Date	29/03/24	29/03/24	>1 week after Venturi mask weaning		After1 month
FiO_2	**5 l/min**	**2 l/min**	**Eupnea**	**Eupnea**	**Eupnea**
pH	7.47	7.46	7.45	7.41	7.43
$PaCO_2$ (mmHg)	44	43	43	41	42
PaO_2 (mmHg)	151	119	71	87	85
HCO_3^-(mEq/L)	32	30.6	29.9	26	27

Table 1. Arterial gas blood during diurnal O_2-HFC and O_2-VM weaning.

blood supply in the limbs, and improve exercise tolerance, reinforcing core strength positively improving postural control, body stability and coordination and limb motor function[10].

CONCLUSION

The O_2-HFC weaning allowed more intensive motor training in the gym, improving the patient tolerance to training. A multidisciplinary team, including a pulmonary specialist, is essential to start the respiratory rehabilitation by identifying the better non-invasive, effective, low-burden oxygen therapy modality. As our findings come from a single case study, further research is needed to confirm whether and to what extent this promising approach works in patients with severe SCI and critically ill patients.

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