EFFECT OF HUMIDIFICATION ON FRACTION OF INSPIRED OXYGEN WITH NASAL OXYGEN THERAPY

Chuhsien Wang¹, Chin-Hsing Li²

Abstract

We incorporated the Michigan Dual Adult Training & Test Lung (TTL), Laerdal Airway Management Trainer, and two mechanical ventilators in a model to imitate spontaneous breathing. Then we monitored and compared the FIO₂ in the TTL bellows as oxygen therapy with or without a bubble-type humidifier through a nasal cannula with different flow rates on the Laerdal Airway Trainer, with an open or closed mouth states. We use the paired t-test, two-tailed, α = 0.05, to compare FIO₂ data between using and not using a humidifier. The research data shows, in open or closed mouth breathing states, using the humidifier always resulted in lower FIO₂ than not using the humidifier, with statistical significance. As with humidifier use or non-use, open mouth breathing always resulted in higher FIO₂ than closed mouth breathing, with statistical significance. In conclusion, bubble-type humidification with nasal cannula oxygen therapy resulted in a lower FIO₂ than dry nasal oxygen therapy. Nasal oxygen therapy in open mouth breathing produces a higher FIO₂ than in closed mouth breathing. Bubble-type humidifier should be used with caution clinically. The inappropriate use of the oxygen therapy device may cause inadvertent hypoxia. Besides, open mouth breathing can elevate FIO₂ during nasal cannula oxygen therapy.

Key Words: Oxygen therapy, Humidification, Bubble-type humidifier, Nasal cannula, Training & test lung

Abbreviation List

COPD: chronic obstructive pulmonary disease
FIO₂: fraction of inspired oxygen in a gas mixture
I/E: inspiration time/expiration time ratio
MV: mechanical ventilator
NC: nasal cannula
PEEP: positive end-expiratory pressure
RR: respiration rate
SPO₂: oxygen saturation by pulse oximetry
TTL: Training & Test Lung
V₁: tidal volume

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Introduction

Oxygen therapy has a history of more than 100 years. The nasal cannula (NC) has been the most widely used device to administer low-flow oxygen therapy in hospitals and at home during the past 100 years. The original gas from the oxygen source is dry without humidification. The nose is an efficient active humidifier, adding heat and humidification to the inspired gas. The guidelines of oxygen therapy via NC with regard to humidification suggest a humidifier is used only when the oxygen flow exceeds 4 L/min.1,2 Oxygen need not be humidified with flow rates less than 4 L/min because the nose is assumed to supply adequate humidification for inspired gas.3,4 However, in clinical settings, some patients really feel discomfort in the nose and throat with oxygen therapy via NC at flow rates of 1-2 L/min.5,6 Bubble-type humidifiers are usually used for humidification of oxygen therapy via NC, although the bubble-type humidifiers do not efficiently humidify the delivered oxygen, and the water-vapor content of the outlet gas falls as flows are is increased.7 Some nurses, doctors and respiratory therapists routinely provide active humidification in oxygen therapy via NC, even if flow rates are less than 4 L/min. They think this will make patients more comfortable, even with the greater cost of the humidifiers. However, a patient of ours with chronic obstructive pulmonary disease (COPD) in acute exacerbation, and receiving oxygen therapy with an NC flow of 1 L/min with a bubble-type humidifier, presented lip cyanosis and oxygen desaturation (SpO2 86%) by pulse oximetry. When we removed the humidifier without changing the oxygen flow rate, the oxygenation status improved greatly, with SpO2 up to 92%. Humidification by bubble-type humidifier for nasal oxygen therapy seems to have a negative effect on oxygen therapy. We searched through MEDLINE PubMed and found that the phenomenon we observed was not addressed in the literature. Therefore, we designed an in vitro spontaneous breathing lung model to assess the effects of humidification on nasal oxygen therapy.

Methods and Materials

We designed a spontaneous breathing lung model with the Training & Test Lung (TTL) (Dual Adult Lung Simulator 5600i, Michigan Instruments Inc; Grand Rapids, MI), Laerdal Airway Management Trainer 250000 (Laerdal Medical Inc; Wappingers Falls, NY), and two mechanical ventilators (MV) to imitate spontaneous breathing. (see Fig. 1)

The TTL was set up for spontaneous breathing simulation. The lung coupling clip (lifting bar) was utilized when one lung (one bellows, called the “driving bellows”) of the TTL was connected to a MV (Nellcor Puritan Bennett 7200AE Critical Care Ventilator, Covidien-Nellcor and Puritan Bennett Inc; Boulder, CO) to drive the other lung (the other bellows, called the “ventilation bellows”) of the TTL for spontaneous breathing simulation. The ventilator settings were as follows: volume-control mode, tidal volume (Vt) 450 ml, inspiratory: expiratory ratio (I : E ratio) 1/2, ventilation rate 12/min, sine wave flow pattern, FiO2 0.21 and positive end expiratory pressure (PEEP) 0 cm H2O.

For simulation of spontaneous breathing through a human-like anatomy (nose, mouth, nasopharynx, larynx and upper trachea) with oxygen therapy via NC, we utilized an airway management trainer with lifelike upper torso and head anatomy (Laerdal Airway Management Trainer 25 00 00). The esophagus was clipped for closure, and both lung parts were removed from the airway trainer. The open end of the right main bronchus was connected to the “ventilation bellows” of the TTL. Between them, we incorporated two one-way valves and one T adapter. (see Fig. 1) For simulation of inspiration, the air was inhaled only from the nose and mouth into the “ventilation bellows” of the TTL through the in-line one-way valve (directed to the ventilation bellows). To simulate expiration, the air was exhaled from the “ventilation bellows” of the TTL to the outside through the other one-way valve (directed to the outside), perpendicular to the in-line one-way valve, instead of through the nose and mouth. In
addition, the open end of the left main bronchus of the airway trainer was connected to the other ventilator (Nellcor Puritan Bennett 760, Covidien-Nellcor and Puritan Bennett Inc; Boulder, CO). The ventilator settings were as follows: continuous positive airway pressure (CPAP) mode, $F_{O_2}$ 0.21, VT 400ml, flow rate 30 l/min, and PEEP 0 cm H$_2$O. For simulation of expiration, we pressed the
manual inspiration button of the PB760 ventilator to flush out the previous inspiratory gas in the upper airway of the airway management trainer to imitate the anatomic dead space effect.

We connected an oxygen analyzer (MiniOXR I Oxygen Analyzer, MSA Medical Products Inc; Pittsburgh, PA) to the oxygen analyzer port of the “ventilation bellows” of the TTL to monitor the fraction of oxygen (FiO2) within the “ventilation bellows” of the TTL. We then measured the FiO2 in the “ventilation bellows” of the TTL as 1, 2, 3, 4, 5 and 6 L/min of oxygen therapy sequentially with or without a bubble-type humidifier (Hudson Reusable Bubble Humidifier, Cat. No. 3100, Hudson RCI Inc; Durham, NC) through a NC applied on the nose of the Laerdal Airway Trainer with open mouth or closed mouth. The natural position of the Laerdal Airway Trainer’s mouth is open. To simulate spontaneous breathing with a closed mouth, we closed the mouth with adhesive tape. Also, some twigs from an artificial Christmas tree were inserted into the nasal cavity to increase resistance in the nasal cavity for simulation of a genuine nose condition. We recorded the stabilized FiO2 data (fluctuation range within 0.1% during the last 30 seconds) in each condition.

**Data Analysis**

We used the paired t-test, two-tailed, to compare FiO2 data between the use and non-use of humidification in both open-mouth and closed-mouth breathing patterns. A p-value ≤ 0.05 was considered statistically significant.

**Results**

Table 1 and Fig. 2 show the data of FiO2 in various nasal oxygen therapies with different breathing conditions from our spontaneous breathing lung model. Humidified nasal oxygen therapy resulted in statistically significantly lower FiO2 than dry nasal oxygen therapy in both closed mouth and open mouth conditions. The open mouth breathing pattern resulted in statistically significantly higher FiO2 than the closed mouth breathing pattern in nasal oxygen therapy, irrespective of humidification. With regard to FiO2 in nasal oxygen therapy, humidification seemed to have a greater effect than the open or closed mouth breathing pattern.

**Discussion**

The nasal cannula is the most widely used oxygen delivery device in oxygen therapy. Oxygen delivery devices can be categorized into low-flow systems and high-flow systems, by design. The gas flow rate from the high-flow system device can exceed the peak inspiratory flow rate of patients. All the gas inhaled by patients is from the high-flow system device. The fraction of oxygen in the gas from high-flow system devices is equal to the FiO2 of patients, if applied properly. On the other hand, the gas flow rate from low-flow system devices is less than the peak inspiratory flow rate of patients. The oxygen from low-flow oxygen delivery systems is always diluted with air in varying ratios.

### Table 1. FiO2 determined with nasal oxygen therapy in various settings

<table>
<thead>
<tr>
<th>FiO2</th>
<th>Open Mouth</th>
<th></th>
<th>Closed Mouth</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Humidification</td>
<td>With</td>
<td>Without</td>
<td>With</td>
<td>Without</td>
</tr>
<tr>
<td>NC 1L/min</td>
<td>25.3</td>
<td>28.4</td>
<td>24.1</td>
<td>27.5</td>
</tr>
<tr>
<td>NC 2L/min</td>
<td>32.1</td>
<td>38.7</td>
<td>27</td>
<td>33.5</td>
</tr>
<tr>
<td>NC 3L/min</td>
<td>35.1</td>
<td>49.7</td>
<td>30.4</td>
<td>38.8</td>
</tr>
<tr>
<td>NC 4L/min</td>
<td>40.5</td>
<td>60.1</td>
<td>32.6</td>
<td>45</td>
</tr>
<tr>
<td>NC 5L/min</td>
<td>46.6</td>
<td>64.8</td>
<td>36.9</td>
<td>50</td>
</tr>
<tr>
<td>NC 6L/min</td>
<td>50.1</td>
<td>68.7</td>
<td>40.2</td>
<td>54.8</td>
</tr>
</tbody>
</table>

Data are presented as No. (%)
The FiO\textsubscript{2} is variable and cannot be assured. Since the NC is a low-flow oxygen delivery system, it is hard to evaluate clinically the FiO\textsubscript{2} of patients on nasal oxygen therapy. The rule of thumb is that the FiO\textsubscript{2} has an estimated 4% increase from 21% with each liter of oxygen therapy via NC, and the FiO\textsubscript{2} level peaks at about 6L/min.\textsuperscript{1} The actual FiO\textsubscript{2} via NC is greatly influenced by ventilation patterns (tidal volume, inspiratory time, inspiratory flow pattern, inspiratory flow rate, NC flow rate) and anatomic features (nasal cavity patency and volume, etc.)

The clinical practice guidelines for oxygen therapy for adults in the acute care facility recommend that oxygen supplied via NC at flow rates less than 4 L/min need not be humidified.\textsuperscript{5,6} Since the nasal oxygen therapy does not bypass the nose, the nose and other upper airway compartments are assumed to adequately humidify the inhaled gas with NC oxygen flow rates < 4 L/min. From the standpoint of clinical necessity and cost considerations, dry nasal oxygen therapy is justified with NC oxygen flow rates less than 4 L/min. However, some patients have indeed experienced nasal itching and drying even with NC at a flow rate of 1-2 L/min.\textsuperscript{5,6} Some healthcare practitioners often add bubble-type humidification to NC oxygen therapy, irrespective of oxygen flow rates, just for the comfort of the patients.

In our study, the bubble-type humidifier negatively affected NC oxygen therapy and induced lower FiO\textsubscript{2} in the lung model. These results were
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compatible with what we have observed clinically. The patient we mentioned previously had COPD in acute exacerbation, and presented oxygen desaturation ($\text{SpO}_2$ 86%) and cyanosis with oxygen therapy via NC 1 L/min with bubble-type humidification when he was taken to the emergency unit. His saturation rose to 92% within two minutes after I removed the humidifier and maintained NC at 1 L/min.

Our results showed that not only did bubble-type humidification have a negative effect on nasal oxygen therapy, but the open mouth breathing pattern had a positive effect on nasal oxygen therapy. This interesting finding is contrary to the popular belief that breathing with a closed mouth is recommended for better humidification and the avoidance of mouth drying, leaving less anatomic dead space, providing a better appearance, etc. We tried to determine the mechanisms that account for the phenomena we observed.

The negative effect of nasal oxygen therapy by bubble-type humidifier may be attributed to a turbulent (or vibrant) oxygen flow from the bubble-type humidifiers and increased airway resistance in the nasal cavity. Since the oxygen in the nasal cavity is in a turbulent (or vibrant) state and there is increased resistance in the oxygen portion, ambient calm air is favored for inhalation, and lower $\text{FiO}_2$ ensues.

The positive effect of nasal oxygen therapy with open mouth breathing may be attributed to the larger oxygen reservoir volume, including the nasal cavity, nasopharynx and mouth cavity, resulting in higher $\text{FiO}_2$. This finding obviously runs against our traditional thinking. Closed mouth breathing is generally regarded as a normal and healthier breathing pattern, because open mouth breathing may increase anatomic dead space and partially bypass the humidification function of the nasal cavity. The traditional thinking holds true only when room air breathing is considered, and not when nasal oxygen therapy is incorporated. As far as nasal oxygen therapy is concerned, not only does open mouth breathing increase anatomic dead space and bypass the humidification function of the nasal cavity, but more oxygen reservoir volume is created in the nasopharynx and mouth cavity, and the previously exhaled gas in the anatomic dead space (nasopharynx and mouth cavity) is flushed out even more by the oxygen flow from the nasal cavity.

According to our research data, the effects of open mouth breathing and the absence of humidification on $\text{FiO}_2$ via NC are synergistic. It seems that the impact on $\text{FiO}_2$ by the humidification state exceeds the impact on $\text{FiO}_2$ associated with open or closed mouth breathing.

There are some limitations to the utilization of our study results in clinical practice. First, we used a TTL and an artificial airway model, and the nasal cavity is spacious in the artificial airway model. Although some plastic twigs were inserted into the nasal cavity to imitate nasal conchae and airway resistance in the genuine nasal cavity, we did not measure nasal cavity resistance and do not know how different it was from the genuine condition. In our study, the nasal cavity was always patent with open or closed mouth breathing. When a patient receives nasal oxygen therapy clinically in an open mouth state, we should assess what factors cause the patient to use an open mouth for breathing. If the nasal cavity is not patent, the effect of nasal oxygen therapy will be poor. Caution should be exercised before extrapolating our research results to clinical practice.

Another limitation of this study is that we only monitored $\text{FiO}_2$. We could not assess the ventilation effect, $\text{PaCO}_2$ and the patients’ subjective feeling in our current lung model. More studies are needed to address these problems clinically.

From our study results, dry oxygen therapy in open mouth breathing will attain the highest $\text{FiO}_2$, if the nasal cavity is patent, among the four nasal oxygen therapy breathing conditions. However, open mouth breathing may apparently sacrifice the patients’ comfort, due to mouth drying, nasal drying, itching and bleeding. The current guidelines for humidification in nasal oxygen therapy (humidification is indicated when NC $\text{O}_2$ is more than 4 L/min) are acceptable and reasonable. This is a compromise between the efficiency of oxygen therapy and the patients’ comfort dur-
In our opinion, the guidelines can be modified to state that in nasal oxygen therapy, a bubble-type humidifier should not be used when the oxygen flow rate is less than 4 L/min, unless indicated clinically.

We conclude that, from our spontaneous breathing lung model, bubble-type humidification in nasal oxygen therapy resulted into a lower Fio₂ than dry nasal oxygen therapy. Nasal oxygen therapy with open mouth breathing produces a higher Fio₂ than with close mouth breathing. The inappropriate use of the oxygen therapy device may cause inadvertent hypoxia. Monitoring of oxygenation status, by pulse oximetry and clinical evaluation, is very important to avoid inadvertent hypoxia in oxygen therapy.

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Author contributions: Both authors were involved with the preparation of the lung model, execution of the study and the acquisition of data. Dr. Wang was involved with the designing of lung model, the drafting of the manuscript and statistical analysis.

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摘要

前言：經鼻導管給與氧氣是氧氣治療最廣泛使用的形式，因鼻子有對氣體加溫加濕的功用，治療準則都建議氧氣流量在 4 L/min 以下，不需要加潮濕裝置。但實際臨床情形，即使流量在 4 L/min 以下，醫護人員為了病患舒適常會加潮濕瓶。但臨床上我們觀察到，加潮濕瓶會降低氧氣治療效果。如未加氧氣飽和度監測有可能病患發生缺氧的情形。於是我們設計人體外研究探討潮濕裝置對經鼻導管氧氣治療的影響。

方法：這研究利用機械人工肺、模擬假人氣道模組與兩台呼吸器模擬自發呼吸。以此模型，分別以加或不加潮濕裝置，閉口或張口呼吸，共有四種不同組合，給予不同流量 (1-6 L/min) 的氧氣，並用氧氣濃度分析儀監測人工肺腔內氧氣濃度 (FiO2)，評估氧氣治療效果。以呼吸最後 30 秒 FiO2 變動在 0.001 內為最終數據。以成對雙尾 t 值檢定 (a= 0.05) 比較四種組合不同流量的氧氣測得的人工肺腔內氧氣濃度 (FiO2)。

結果：不論閉口或張口呼吸，加潮濕裝置會導致較低的 FiO2 (p < 0.001；p = 0.005)。不論加與不加潮濕裝置，張口呼吸會導致較高的 FiO2 (p < 0.01；p < 0.01)

結論：根據此自發呼吸鼻導管氧氣治療模型，加氣泡型潮濕器會顯著降低氧氣治療效果。我們也意外發現正常呼吸形式的閉口呼吸反不利氧氣治療。

關鍵詞：氧氣治療，溫氣，氣泡型潮濕器，鼻導管，人工肺