Inhaled nitric oxide and arterial oxygen tension in patients with chronic obstructive pulmonary disease and severe pulmonary hypertension

Yoshikiko Katayama, Timothy W Higenbottam, Maria J Díaz de Atauri, George Cremona, Shinji Akamine, Joan Albert Barbera, Robert Rodriguez-Roisin

Abstract

Background – Inhaled nitric oxide (NO) is a selective pulmonary vasodilator which can improve gas exchange in acute lung injury. However, it is uncertain that this effect on arterial oxygenation can be generalised to all lung diseases.

Methods – The effects of inhaled NO on gas exchange were studied in nine patients with chronic obstructive pulmonary disease (COPD), 11 patients with severe pulmonary hypertension, and 14 healthy volunteers. A randomised sequence of 40 ppm of NO or air was inflated for 20 minutes through an orofacial mask.

Results – Inhaled NO reduced mean (SE) transcutaneous arterial oxygen tension (TcPO₂) from 9.6 (0.3) to 8.9 (0.4) kPa in healthy volunteers and from 7.4 (0.6) to 7.0 (0.5) kPa in patients with COPD. There was no change in TcPO₂ in patients with severe pulmonary hypertension. During inhalation of NO and air no change occurred in transcutaneous arterial carbon dioxide tension (TcPCO₂), arterial oxygen saturation (SaO₂) measured by pulse oximeter, or cardiac output determined by the transthoracic impedance method.

Conclusions – Inhaled NO does not improve TcPO₂ nor increase cardiac output in normal subjects and patients with COPD, suggesting that inhaled NO worsens gas exchange. This could represent inhaled NO overriding hypoxic pulmonary vasoconstriction in COPD. The finding that TcPO₂ also fell when normal subjects inhaled NO suggests that a similar mechanism normally contributes to optimal gas exchange. Whilst inhaled NO can improve oxygenation, this effect should not be considered to be a general response but is dependent on the type of lung disease.

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Keywords: nitric oxide, chronic obstructive pulmonary disease, pulmonary hypertension.

Methods

Nine patients with COPD, 11 with severe pulmonary hypertension, and 14 healthy volunteers were studied. All gave their informed consent and the study was approved by the local hospital ethics committee. The diagnosis of COPD was established from a history of clinical and physiological evidence of irreversible airway obstruction. All patients with COPD ceased bronchodilators 12 hours before the study. The diagnosis of severe pulmonary hypertension was established by previous right heart catheterisation. All patients with severe pulmonary hypertension were receiving vasodilator therapy.

Measurements were made after breathing normal air or after breathing air with 40 ppm NO, both for 20 minutes. The order of giving the treatments was randomised and delivered in a single blind fashion.

The NO (British Oxygen Company Ltd, London, UK) was supplied in cylinders in a concentration of 10 000 ppm NO in nitrogen. The inspired gas mixture of NO in air (40 ppm) was prepared using an NO delivery system (PneuPAC Ltd, Luton, UK) which was delivered to the patients using a close fitting nasal mask (Nasal CPAP mask, Puritan-Bennett Corporation, Indianapolis, Indiana, USA) fitted with two one-way valves (fig 1). Continuous monitoring of the NO and nitrogen dioxide (NO₂) concentration in the inspirate was made by fuel cell monitors (Models EC90 and EC40,
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Massachusetts, USA). Total lung capacity (TLC) was measured by whole body plethysmography, and dynamic lung volumes (forced expiratory volume in one second (FEV1) and forced vital capacity (FVC)) were measured with a dry wedge spirometer. Transcutaneous arterial oxygen and carbon dioxide tensions (TcP\textsubscript{O\textsubscript{2}}, TcP\textsubscript{CO\textsubscript{2}}) were measured, respectively, by Servo-med Oxymonitor and Servomed Kapnomonitor (Hellige GmbH, Freiburg im Breisgau, Germany). Arterial oxygen saturation (Sa\textsubscript{O\textsubscript{2}}) was measured by pulse oximeter (Pulsox-DP7, Minolta, Tokyo, Japan) and cardiac output by the transthoracic impedance method (NCCOM 3 cardiovascular monitor, BioMed Medica Manufacturing Inc, Irvine, California, USA).11

Flow meters

Gas cylinders

One way valves

Figure 1 Nitric oxide delivery system.

Table 1 Mean (SE) data for patients and volunteers

<table>
<thead>
<tr>
<th>Number</th>
<th>Age (years)</th>
<th>M:F</th>
<th>FEV\textsubscript{1} (% pred)</th>
<th>VC (% pred)</th>
<th>FEV\textsubscript{1}/FVC (%)</th>
<th>Mean arterial pressure (mm Hg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volunteers</td>
<td>14</td>
<td>32.2 (2.1)</td>
<td>10:4</td>
<td>101 (5)</td>
<td>98 (4)</td>
<td>94 (4)</td>
</tr>
<tr>
<td>COPD</td>
<td>9</td>
<td>69.0 (2.0)</td>
<td>5:4</td>
<td>26 (9)</td>
<td>50 (10)</td>
<td>38 (7)</td>
</tr>
<tr>
<td>Pulmonary hypertension</td>
<td>11</td>
<td>32.4 (2.0)</td>
<td>4:7</td>
<td>73 (7)</td>
<td>77 (7)</td>
<td>86 (5)</td>
</tr>
</tbody>
</table>

FEV\textsubscript{1} = forced expiratory volume in one second; VC = vital capacity; FVC = forced vital capacity; COPD = chronic obstructive pulmonary disease.

Results

The FEV\textsubscript{1} was 26 (9)% predicted and the FEV\textsubscript{1}/FVC ratio was 38 (7)% in patients with COPD (table 1). Most patients with severe pulmonary hypertension took calcium antagonists or angiotensin converting enzyme inhibitors. No patient was receiving treatment with continuous intravenous infusion of prostanycin (table 2). The patients with severe pulmonary hypertension had high values of pulmonary vascular resistance (PVR). Inhaled NO reduced mean TcP\textsubscript{O\textsubscript{2}} from 9.6 (0.3) kPa to 8.9 (0.4) kPa (p <0.05) in healthy volunteers and from 7.4 (0.6) kPa to 7.0 (0.5) kPa (p

Table 2 Haemodynamic data of the patients with pulmonary hypertension

<table>
<thead>
<tr>
<th>Age</th>
<th>Diagnosis</th>
<th>P\textsubscript{ap} (mm Hg)</th>
<th>PVR (dynes.s.cm\textsuperscript{-5})</th>
<th>SVR (dynes.s.cm\textsuperscript{-5})</th>
<th>CI (l.m\textsuperscript{-2}.min\textsuperscript{-1})</th>
<th>P\textsubscript{aO\textsubscript{2}} (kPa)</th>
<th>P\textsubscript{aCO\textsubscript{2}} (mm Hg)</th>
<th>Sa\textsubscript{O\textsubscript{2}} (%)</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>34</td>
<td>PPH</td>
<td>54</td>
<td>18.8</td>
<td>31.3</td>
<td>1.3</td>
<td>8.5</td>
<td>--</td>
<td>--</td>
<td>W, Heparin</td>
</tr>
<tr>
<td>22</td>
<td>PPH</td>
<td>53</td>
<td>21.7</td>
<td>31.5</td>
<td>--</td>
<td>7.7</td>
<td>88</td>
<td>94</td>
<td>W, Diltiazem</td>
</tr>
<tr>
<td>61</td>
<td>PPH, thrombo</td>
<td>47</td>
<td>16.6</td>
<td>37.9</td>
<td>1.3</td>
<td>8.0</td>
<td>95.2</td>
<td>94</td>
<td>W, Diltiazem, Frusemide</td>
</tr>
<tr>
<td>32</td>
<td>PPH</td>
<td>54</td>
<td>23.7</td>
<td>31.5</td>
<td>--</td>
<td>7.7</td>
<td>87</td>
<td>94</td>
<td>W, Diltiazem, Frumil, Digtokin</td>
</tr>
<tr>
<td>51</td>
<td>PPH</td>
<td>40</td>
<td>8.3</td>
<td>30.5</td>
<td>2</td>
<td>8.8</td>
<td>94</td>
<td>94</td>
<td>W, Dill, Frumil, Digtokin</td>
</tr>
<tr>
<td>34</td>
<td>PPH</td>
<td>54</td>
<td>18.8</td>
<td>31.3</td>
<td>1.3</td>
<td>8.5</td>
<td>--</td>
<td>--</td>
<td>W, Heparin</td>
</tr>
<tr>
<td>22</td>
<td>PPH</td>
<td>53</td>
<td>21.7</td>
<td>31.5</td>
<td>--</td>
<td>7.7</td>
<td>88</td>
<td>94</td>
<td>W, Diltiazem</td>
</tr>
<tr>
<td>24</td>
<td>PPH</td>
<td>75</td>
<td>17.6</td>
<td>22.4</td>
<td>2.2</td>
<td>9.6</td>
<td>94</td>
<td>94</td>
<td>W, Diltiazem</td>
</tr>
<tr>
<td>26</td>
<td>PPH</td>
<td>80</td>
<td>16.2</td>
<td>21.4</td>
<td>1.8</td>
<td>9.7</td>
<td>96</td>
<td>94</td>
<td>W, Diltiazem</td>
</tr>
<tr>
<td>29</td>
<td>PPH</td>
<td>83</td>
<td>17.9</td>
<td>23.5</td>
<td>2.55</td>
<td>9.5</td>
<td>88</td>
<td>94</td>
<td>W, Diltiazem</td>
</tr>
<tr>
<td>36</td>
<td>SPH, sarcoïdosis</td>
<td>53</td>
<td>17.8</td>
<td>21.3</td>
<td>1.9</td>
<td>9.6</td>
<td>92</td>
<td>94</td>
<td>W, Diltiazem, Frumil, Prednisolone</td>
</tr>
<tr>
<td>42</td>
<td>SPH, CPA</td>
<td>9</td>
<td>9</td>
<td>17.8</td>
<td>2.1</td>
<td>8.8</td>
<td>88</td>
<td>94</td>
<td>Nasal oxygen</td>
</tr>
<tr>
<td>37.7 (4.1)</td>
<td>39</td>
<td>15.6 (1.5)</td>
<td>17.0 (1.9)</td>
<td>1.9 (0.2)</td>
<td>8.8 (0.2)</td>
<td>92.2 (1.1)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

P\textsubscript{ap} = pulmonary arterial pressure; PVR = pulmonary vascular resistance; SVR = systemic vascular resistance; CI = cardiac index; P\textsubscript{aO\textsubscript{2}} = arterial oxygen tension; P\textsubscript{aCO\textsubscript{2}} = arterial oxygen saturation; PPH = primary pulmonary hypertension; SPH = secondary pulmonary hypertension; thrombo = secondary to pulmonary thromboembolism; CFA = cryptogenic fibrosing alveolitis; W = warfarin; Dil = diltiazem.
Discussion

In patients with COPD and in normal subjects the TcP₂ fell during the 20 minute period of breathing 40 ppm of NO in air; no change in TcP₂ occurred in patients with severe pulmonary hypertension. These observations support the idea that inhaled NO appears to worsen gas exchange in those patients where the change in pulmonary haemodynamics is small. A concentration of 40 ppm inhaled NO was chosen on the basis of an isolated lung experiment in which pretreatment with the NO synthase inhibitor N⁵-nitro-L-arginine caused a fall in PVR which was normalised by 40 ppm and 80 ppm inhaled NO but not by 10 ppm. To ensure that the correct concentration of NO was administered a nasal CPAP mask was used which is more airtight than a face mask. Moreover, the use of two one-way valves ensured that patients were unable to re-breathe expired air. The SaO₂ and NO and NO₂ concentrations were monitored to avoid the development of hypoxia and NO and NO₂ toxicity. NO reacts with oxygen and forms NO₂ which can cause airway injury so NO was first mixed with nitrogen and then oxygen (fig 1).

The study was dependent on the accuracy of the non-invasive measurements which were chosen to involve minimal disturbance to the haemodynamics of the study participants. The measurement of TcP₂ was first reported in 1969 by Huch et al. The sensor allows measurement of TcP₂, which reflects the arterial oxygen pressure (PaO₂) in many clinical conditions. We allowed 20 minutes exposure to each gas mixture which is sufficient for the fall in PaO₂ to be detected by the TcP₂. The low cardiac output and poor tissue perfusion in the patients with severe pulmonary hypertension could have decreased the accuracy of the TcP₂ measurement. However, inhaled NO does not necessarily increase the PaO₂ in patients with severe pulmonary hypertension. This is partly explained by the fact that, although the pulmonary artery pressure falls, cardiac output does not increase with inhaled NO. As previously reported, cardiac output did not change in any of our patient groups (table 3). The transthoracic impedance method of measuring cardiac output is valid in many patient groups and in normal subjects and reliably follows the changes in cardiac output seen with exercise. An additional explanation for the failure to improve TcP₂ in patients with severe pulmonary hypertension could be the existing vasodilator treatment which will lessen the vasodilator effects of inhaled NO.

Inhaled NO is a selective pulmonary vasodilator causing relaxation of smooth muscle cells of the pulmonary precapillary resistance arteries. These vessels are found within the pulmonary acini and the distance of diffusion of inhaled NO into the smooth muscle of these vessels is no greater than into the alveolar capillaries. Most of the inhaled NO is taken up in alveolar capillaries where it combines rapidly with oxyhaemoglobin within red blood cells and then oxygen (®g 1). The formation of methaemoglobin effectively inactivates NO which has no subsequent action on the systemic circulation. Our failure to demonstrate a change in venous MetHb% agrees with earlier work on short term exposure to NO and reflects the efficiency of the red blood cell methaemoglobin reductase in restoring iron II haemoglobin.

Table 3 Mean (SE) haemodynamic and gas exchange data on air and after 20 minutes of 40 ppm nitric oxide (NO) inhalation

<table>
<thead>
<tr>
<th></th>
<th>Volunteers</th>
<th>COPD</th>
<th>Pulmonary hypertension</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Air</td>
<td>NO</td>
<td>Air</td>
</tr>
<tr>
<td>Cardiac output (1/min)</td>
<td>5.2 (0.4)</td>
<td>5.1 (0.4)</td>
<td>4.3 (0.6)</td>
</tr>
<tr>
<td>TcP₂ (kPa)</td>
<td>6.6 (0.3)</td>
<td>6.5 (0.4)</td>
<td>8.1 (0.4)</td>
</tr>
<tr>
<td>TcP₂ (kPa)</td>
<td>9.6 (0.3)</td>
<td>8.9 (0.6)*</td>
<td>7.4 (0.6)</td>
</tr>
<tr>
<td>SaO₂ (%)</td>
<td>97.6 (0.2)</td>
<td>97.4 (0.3)</td>
<td>87.2 (2.1)</td>
</tr>
<tr>
<td>Methaemoglobin (mg/dl)</td>
<td>0.8 (0.1)</td>
<td>0.8 (0.1)</td>
<td>1.0 (0.2)</td>
</tr>
</tbody>
</table>

*p<0.05 versus air inhalation.
Inhaled nitric oxide improves PaO₂ in certain lung diseases. In ARDS inhaled NO is distributed to ventilated regions of the lung where it increases perfusion. Probably by a "steal" phenomenon, the inhaled NO lessens blood flow in regions of intrapulmonary shunt by diverting it from the unventilated regions to ventilated regions. On the other hand, the effect of aerosolised prostacyclin in ARDS has been reported to be the same as inhaled NO. However, there was a still larger decrease in systemic vascular resistance during aerosolised prostacyclin than during inhaled NO. In persistent pulmonary hypertension of the newborn the PaO₂ is also increased by inhaled NO. This is simply by reducing the pulmonary artery pressure which reverses the amount of right to left shunt through the patient's ductus arteriosus.

Patients with COPD do not have high values of pulmonary vascular resistance and have normal or even raised cardiac output. Inhaled NO will be expected to have only a minimal haemodynamic effect in these patients. One of the major abnormalities in patients with COPD is the disturbance of the distribution of ventilation. The homogeneity of the distribution of ventilation is reflected by the wide range of time constants. Conventional NO inhaled at a fixed concentration can be expected to reach regions with both slow and fast ventilation. Furthermore, in diseases such as emphysema collateral ventilation occurs. We do not know the minimum alveolar concentration of inhaled NO needed to cause pulmonary vasodilatation in humans, although concentrations as low as 1 ppm in the inhaled gas mixture can cause vasodilatation. Alveolar concentrations are likely to be well below this level and yet are effective, so even slow ventilated regions of the lungs in patients with COPD are likely to receive sufficient NO to overcome hypoxic vasoconstriction. This, in turn, will lead to poorer matching of V/Q and worsening gas exchange. The pulmonary endothelial production of NO is dependent on alveolar partial pressure of oxygen. Hypoxia inhibits endothelial NO production, which suggests that it might play a parallel role to the direct action of hypoxia on pulmonary artery tone in regulating pulmonary blood flow. In diseases such as COPD alveolar hypoxia enhances the matching between the distribution of ventilation and perfusion by reducing perfusion of unventilated regions. Overriding of this effect by inhaled NO may account for the fall in TcPO₂ seen in the patients with COPD and is supported by the observed widening of the distribution of the V/Q relation in patients when NO is inhaled.

It is interesting that a similar fall in TcPO₂ with inhaled NO was also seen in normal volunteers. As the cardiac output was unchanged it can be concluded that, under resting conditions, matching of ventilation and perfusion is an active process even in healthy subjects. It is possible that pulmonary artery vasoconstriction occurs even in normal subjects and that this is a cause of close matching of Va/Q. This is supported by the fact that, in normal volunteers, inhalation of hyperoxic gas mixtures can cause an increased inequality in Va/Q. In other words, there is evidence that hypoxic vasoconstriction contributes to the matching of Va/Q even in normal subjects.

It can be questioned whether pulmonary endothelial NO subserves a similar function. Whilst inhaled NO does not necessarily improve PaO₂ in patients with COPD, it is still effective in other chronic lung diseases. In patients with pulmonary fibrosis inhaled NO improves arterial oxygenation. These patients, however, behaved like the patients with severe pulmonary hypertension, with marked improvement of pulmonary haemodynamics as well as a rise in PaO₂. This serves to emphasise the fact that important differences in the response of patients to inhaled NO depend upon the underlying pathophysiology of the lung disease.

In conclusion, inhaled NO is a selective pulmonary vasodilator with considerable therapeutic potential. In many diseases it can also improve gas exchange, lowering hypoxaemia. In patients with COPD the gas exchange is not necessarily improved. Existing delivery systems for inhaled NO do not selectively distribute NO to fast ventilated regions alone and so the benefits of hypoxic vasoconstriction are overridden. The same effect of inhaled NO in our volunteers suggests that an element of mismatching between Va/Q driven by hypoxic vasoconstriction occurs even in the normal lung.

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