Use of nitric oxide inhalation in chronic obstructive pulmonary disease

Kumar Ashutosh, Kishor Phadke, Jody Fragale Jackson, David Steele

Abstract

***Background*—Inhalation of nitric oxide with oxygen could be a promising treatment in patients with chronic obstructive pulmonary disease (COPD) and pulmonary hypertension. However, the current methods of delivery of NO are cumbersome and unsuitable for long term use. The present study was undertaken to investigate the safety and efficacy of a mixture of nitric oxide (NO) and oxygen administered via a nasal cannula for 24 hours in patients with oxygen dependent COPD.**

***Methods*—Twenty five parts per million (ppm) of NO was administered by inhalation combined with supplemental oxygen at a flow rate of 2 l/min via a nasal cannula for 24 hours to 11 ambulatory men with stable, oxygen dependent COPD. Room air with supplemental oxygen at 2 l/min was administered in an identical manner for another 24 hours as control therapy in a randomised, double blind, crossover fashion to all patients. Pulmonary function tests, exercise tolerance, dyspnoea grade, and lung volumes were measured at baseline, 24, and 48 hours. Pulmonary artery pressure (PAP), cardiac output (CO), pulmonary vascular resistance (PVR), arterial blood gas tensions, and minute ventilation were measured at baseline, after 30 minutes and 24 hours of breathing NO and oxygen. Venous admixture ratio (Qs/Qt) and dead space ratio (Vd/Vt) were also calculated. Concentrations of nitrogen dioxide (NO_2) and NO in the inhaled and ambient air were monitored continuously. Differences in pulmonary function, arterial blood gas tensions, pulmonary haemodynamics, exercise tolerance, and dyspnoea between oxygen and NO breathing periods were analysed for significance using paired *t* tests.**

***Results*—A significant ($p<0.05$) fall was observed in PVR (183.1 (116.05) and 137.2 (108.4) dynes.s.cm^{-3} before and after breathing NO for 24 hours, respectively) with NO administration without significant changes in symptoms, pulmonary function, arterial oxygen tension, or exercise tolerance.**

***Conclusions*—NO at a concentration of 25 ppm blended with oxygen can be safely administered by nasal cannula for 24 hours without significant adverse effects and lowers PVR in stable patients with COPD receiving long term oxygen therapy.**

Department of Medicine, Pulmonary Disease and Cardiology Section, Veterans Affairs Medical Center and SUNY Upstate Health Science Center, Syracuse, New York 13210, USA
K Ashutosh
K Phadke
J F Jackson
D Steele

Correspondence to:
Dr K Ashutosh

Received 1 February 1999
Returned to authors
19 April 1999
Revised manuscript received
26 October 1999
Accepted for publication
27 October 1999

(*Thorax* 2000;**55**:109–113)

Keywords: nitric oxide; chronic obstructive pulmonary disease

Nitric oxide (NO) is an important pulmonary vasodilator with few side effects and may have a role in the treatment of chronic obstructive pulmonary disease (COPD), especially in the presence of pulmonary hypertension.[1 2] Onset of persistent pulmonary hypertension in patients with COPD presents a therapeutic challenge as it is associated with a significantly worse prognosis[3–6] and may persist in spite of the currently available treatments.[5 6] Oxygen therapy alone fails to reduce the increased pulmonary artery pressure (PAP) or prolong survival in a significant proportion of cases.[7] The usefulness of vasodilator agents is limited due to their side effects and poor tolerance.[8 9] The potential therapeutic effects of NO in COPD are therefore of great interest and a number of studies have reported promising results.[10–14] However, its use remains limited by the practical difficulties involved in its administration to ambulatory patients. Most methods of administering NO use closed systems involving sealed masks, ventilator circuits, suctioning devices, and soda lime absorbers or transtracheal catheters.[2 10–16] Furthermore, most studies of the use of NO in patients with COPD have been confined to short periods with conflicting results.[2 10–14]

We aimed to investigate the feasibility, safety, and therapeutic effects of NO administered by a nasal cannula for a period of 24 hours in patients with oxygen dependent COPD.

Methods

Eleven patients with documented severe COPD according to the American Thoracic Society criteria who were receiving long term home oxygen therapy under the Veterans Affairs Medical Center (VAMC) home oxygen programme were recruited to the study. All had fulfilled the criteria for provision of long term oxygen therapy and were considered to be at risk for pulmonary arterial hypertension. None had acute exacerbations of COPD, active infection, left ventricular failure, or malignancy and all had been clinically stable for at least three months before the study. Informed consent approved by the VAMC institutional review board was obtained from all patients. The patients were then admitted to hospital and continued to receive their usual medications and oxygen by nasal cannula at their usual flow rate.

MEASUREMENTS

Complete pulmonary function tests including flow-volume loops and lung volume determination by body plethysmography were obtained. Patients then performed a symptom limited stepwise incremental work load exercise on a treadmill with work load beginning at 0 watts and increasing by 10 watts every minute.[17] Heart rate, oxygen saturation by percutaneous pulse oximetry (Spo_2), and respiratory rate were continuously monitored and recorded at one minute intervals and at the breaking point of exercise. The total exercise time and sensation of dyspnoea on a modified Borg's dyspnoea scale[18] were recorded every day before and after exercise.

After a rest period of three hours the patients were transported to the cardiac catheterisation laboratory and lay supine on the table in a relaxed position. A pulmonary artery balloon flotation catheter (Argon Maxum, Athens, Texas, USA) was then introduced into the pulmonary artery via the antecubital vein and secured in place. PAP was measured using a pressure transducer-oscilloscope system connected to the PA catheter. Expired air was collected for five minutes and carbon dioxide output ($\dot{V}CO_2$) and dead space/tidal volume ratio ($\dot{V}d/\dot{V}t$) were measured. After three minutes of collecting expired air arterial blood was obtained by arterial punctures using a 22 gauge needle and simultaneously mixed venous blood was obtained from the pulmonary arterial line. Cardiac output (CO) was determined by the carbon dioxide Fick equation using $\dot{V}CO_2$ from analysis of mixed expired air and calculations of arterial and mixed venous carbon dioxide contents from directly measured mixed venous and arterial oxygen and carbon dioxide tensions (PO_2 and PCO_2) based on McHardy's equations[19] as discussed by Jones.[20] These measurements were validated using the thermodilution technique in 24 samples obtained simultaneously from four patients; a good correlation was obtained ($r = 0.6$; $p<0.01$) and the individual values agreed within one litre of each other. Furthermore, values of PVR obtained by the two methods had excellent correlation ($r = 0.96$).

INTERVENTIONS

The patients then breathed either the control gas or NO in the following manner. NO in concentrations of 200 ppm in nitrogen was stored in tanks (MG Industries, Liverpool, NY, USA) fitted with regulators (high purity regulator, model 98202-2, MG Industries) allowing precise delivery of NO. Patients breathed oxygen by a nasal cannula from tanks containing 100% oxygen at a rate of 2 l/min to which NO was added via a Y connector at a flow rate sufficient to yield 25 ppm of NO in the inspired air; its actual concentration at the nares was measured and displayed by an electrochemical NO/NO_2 analyser (Pulmonox II, Research & Development Corp, Tofield, Alberta, Canada). The patients were kept in a single room with no special exhaust or air exchange devices. The concentrations of nitrogen dioxide (NO_2) in the inspired and room air were also monitored continuously and recorded by the same device. A similar looking set up was used for delivering oxygen in which the NO tank was shut off and the patient received only supplemental oxygen with air. The flow rate of supplemental oxygen was kept at the patient's usual rate which was 2 l/min in most cases. A designated respiratory therapist checked on the NO and NO_2 readings every 1–2 hours and recorded them in a log book under the supervision of one of the co-investigators (DS) who administered the gas mixtures and made the switches between the control gas (oxygen/air) and NO (NO/oxygen/air) and ensured the specified delivery of appropriate gas mixtures to the patients. The NO/NO_2 display and the log book were not revealed to the patients. No other investigator was privy to the NO/NO_2 readings or was informed of the identity of the gas mixtures breathed by the patients. The investigator (DS) in charge of the administration and monitoring of the gas mixtures did not participate in the evaluation of patients in any fashion. Thus, neither the patients nor the investigators responsible for making the measurements were aware of the identity of the gas mixture. Control gas and NO were each delivered for 24 hours in a randomised, double blind, crossover fashion. Each subject therefore received 25 ppm NO for 24 hours and oxygen/air for another 24 hours in a randomised order and each served as his or her own control.

All measurements were repeated at 30 minutes after the switch in the inhaled gases and at 24 and 48 hours of the study in the same order as previously described for day 1. The concentration of methaemoglobin in the venous blood was also measured at 24 and 48 hours of the study.

STATISTICAL ANALYSIS

The measurements made upon breathing NO for 30 minutes and 24 hours were compared with the baseline values. As all patients received long term oxygen therapy for their COPD, the baseline values were taken to be the measurements breathing oxygen immediately before the switch to NO. These were obtained while breathing the control gas mixture (oxygen/air) for 24 hours for the patients randomised to receive control gas in the first part of the crossover study and the initial measurements, also breathing oxygen/air at the same flow rate

Table 1 Selected mean (SD) clinical data on the study patients

No. of patients	11
Age (years)	63 (10.6)
FEV_1 (l)	0.89 (0.37)
FEV_1 (% predicted)	25.8 (9.4)
FVC (l)	2.10 (0.75)
FEV_1/FVC (%)	43 (8.5)
Haemoglobin (%)	14.8 (1.1)
TGV (% predicted)	231 (90.2)
Dyspnoea (grade)	4.78 (2.17)
Peak work rate (watts)	23.5 (22.9)
Exercise time (s)	165 (95)
Duration of COPD (years)	12 (4)
Smoking history (pack years)	21 (8)

FEV_1 = forced expiratory volume in one second; FVC = forced vital capacity; TGV = thoracic gas volume at functional residual capacity.

Table 2 Selected measurements on breathing oxygen and NO/oxygen

	Baseline Mean (SE)	NO Mean (SE)	Difference Mean (95% CI)	p value
Pa_{O_2} (kPa)	11.3 (0.6)	11.5 (0.6)	0.2 (−1.2 to +1.5)	>0.5
Pa_{CO_2} (kPa)	6.2 (0.5)	6.2 (0.4)	0.2 (−0.93 to +0.97)	>0.5
PAP (torr)	26.1 (2.5)	25.1 (2.8)	1.0 (−3.1 to +5.1)	>0.5
Systolic PAP (torr)	35.5 (3.5)	36.0 (4.3)	0.5 (−5.3 to +6.3)	>0.5
P wedge (torr)	13.8 (1.7)	14.3 (1.4)	0.5 (−3.4 to +4.3)	>0.5
CO (l/min)	5.9 (0.4)	8.2 (1.1)	2.3 (+0.3 to +4.3)	0.026*
PVR (dyne.s.cm^{-3})	183.1 (36.7)	137.2 (34.2)	−45.9 (−2.5 to −89.3)	0.04*
Vd/Vt (%)	50.1 (2.5)	52.6 (1.9)	2.1 (−2.5 to +6.7)	0.35
Qs/Qt (%)	7.5 (1.7)	10.9 (0.9)	3.4 (−0.3 to +7.1)	0.07

*Statistically significant difference.
Baseline = measurements breathing supplemental oxygen with air alone prior to administration of NO; NO = values obtained after 24 hours of breathing NO; difference = values on NO minus baseline values; Pa_{O_2}, Pa_{CO_2} = arterial oxygen and carbon dioxide tensions; PAP = pulmonary artery pressure; P wedge = pulmonary wedge pressure; CO = cardiac output; PVR = pulmonary vascular resistance; Vd/Vt = dead space/tidal volume ratio; Qs/Qt = venous admixture ratio.

as the control gas mixture, for others. Measurements made on breathing oxygen at 24 hours after the completion of NO treatment periods were not considered comparable to the baseline due to the possible confounding effects of the prior use of NO. Similarly, measurements made breathing oxygen at 30 minutes after the completion of NO administration were not deemed comparable to those breathing oxygen for 30 minutes prior to NO for the same reasons. Changes in the selected measurements between control and each treatment periods were analysed for significance using paired *t* tests. ANOVA was used to test for differences between all test periods in selected variables. Correlation between selected variables was analysed by linear regression.

Results

The patients were all male veterans with severe COPD who met the criteria for prescription of long term home oxygen and had been clinically stable for at least three months before the study. Selected demographic and clinical characteristics of the patients are given in table 1. NO_2 concentrations in the ambient air and inspired gas remained usually below 0.1 ppm and never exceeded 0.5 ppm. There was no significant difference in any of the measured variables between the baseline measurements and on breathing NO for 30 minutes. Measurements obtained on breathing oxygen/air for 30 minutes, oxygen/air for 24 hours, NO for 30 minutes, and oxygen/air after completion of breathing NO did not differ significantly from the baseline values. Values of selected variables obtained at baseline and after 24 hours of NO breathing are shown in table 2. The PVR fell in every patient and the difference from the baseline was statistically significant when analysed by paired *t* test at 24 hours of NO breathing. There was a slight but insignificant fall in PAP and a significant rise in CO after breathing NO for 24 hours.

Table 3 Selected measurements on breathing oxygen and NO/oxygen and after the discontinuation of NO

	Baseline	NO	After NO
PAP (torr)	26.1 (2.5)	25.1 (2.8)	27.6 (4.0)
PVR (dyne.s.cm^{-3})	183.1 (36.7)	137.2 (34.3)	162 (56.6)
CO (l/min)	5.9 (0.4)	8.2 (1.1)	6.5 (1.2)
PaO_2 (kPa)	11.3 (0.6)	11.5 (0.6)	11.51 (0.7)

Values are mean (SE).
Baseline = breathing supplemental oxygen/air before NO administration; NO = after breathing NO for 24 hours; after NO = breathing oxygen/air for 24 hours after stopping NO; PAP = pulmonary artery pressure; PVR = pulmonary vascular resistance; CO = cardiac output; Pa_{O_2} = arterial oxygen tension.

Table 3 shows the values of selected variables at baseline, after breathing NO for 24 hours, and 24 hours after discontinuation of NO. CO, PVR, and PAP tended to approach the baseline values and were not significantly different from baseline at 24 hours after stopping administration of NO. All patients completed the study without any severe adverse effects. Although breathing NO caused no change in exercise time, peak work load, pulmonary function, or dyspnoea index from baseline values when all patients were considered together, six patients (54%) reported an improvement in dyspnoea. The dyspnoea index fell by >1 in four of these six patients. Two patients (18%) had a worsening of dyspnoea but only one of them developed wheezing and was unable to do exercise after NO. Exercise time increased by >10% in four patients. Four patients, including the two with increased dyspnoea, reported increased cough and a sensation of substernal rawness after 24 hours of breathing NO. Forced expiratory volume in one second (FEV_1), forced vital capacity (FVC), FEV_1/FVC ratio, and thoracic gas volume at functional residual capacity (FRC) did not change significantly on breathing NO for 24 hours. There was no rise in the serum concentration of methaemoglobin which stayed below 1% throughout the study.

Discussion

The major findings of this study are that the administration of 25 ppm NO with supplemental oxygen at a rate of 2 l/min for 24 hours via a nasal cannula is safe, generally well tolerated, and does not result in a rise in blood concentrations of methaemoglobin or an accumulation of NO_2 in the inhaled gas or ambient air. Furthermore, NO administered in this manner significantly lowers PVR without significant changes in Pa_{O_2} or pulmonary function.

Current methods of administration of NO require cumbersome apparatus, closed systems, continuous suction, and absorbers in various combinations.[21] NO has been administered via endotracheal tubes in intubated, mechanically ventilated, frequently paralysed and sedated patients.[22] A workshop on the use of NO recommended continuous scavenging of all exhaust gases in the breathing circuit.[23] Even short term administration of NO for a few minutes during an exercise test has required a closed non-rebreathing circuit in some studies.[24]

The use of NO inhalation in patients with COPD has been previously reported by a number of investigators.[2 10–14] However, all of these studies were conducted for short periods lasting from a few minutes to hours only. Furthermore, the methods of NO delivery in these studies included tight fitting face masks, demand valves with wall suction, soda lime absorbers, and non-rebreathing circuits with reservoirs. To the best of our knowledge, ours is

the first study of the use of NO for 24 hours using a simple and inexpensive method of delivery in ambulatory patients with COPD performed in a randomised, double blind fashion.

We noted a significant lowering of PVR after 24 hours of NO breathing in all patients, suggesting vasodilation and relaxation of the pulmonary arterial bed. Although the mean and systolic PAP fell slightly, the changes were not significant. Other workers have shown a fall in PAP[2 10 16 25] with administration of NO but their patients had a higher mean PAP than those in our study. We suggest two possible explanations for the absence of a significant fall in PAP in our patients. Firstly, all had received long term oxygen therapy for a long time, were in a stable condition, and had only mildly elevated PAP. None had overt congestive heart failure. We surmise that the PAP could not be lowered any further with NO if these patients had already achieved the maximal reduction in PAP commensurate with their underlying disease with long term oxygen therapy. Alternatively, a rise in CO noted in nine (82%) of our patients could have prevented a fall in PAP. The rise in CO remains unexplained. However, other workers have also noted a dose dependent rise in CO with the use of NO in patients with ARDS,[26] those undergoing cardiac transplantation,[27] and those with acute right heart syndrome in COPD.[28] Although none of our patients had overt heart failure, they all had severe COPD with an increased likelihood of underlying right ventricular strain or insufficiency. Use of NO could improve CO by reducing the right ventricular afterload in these patients.

Abolition of the hypoxic vasoconstrictor reflex could worsen the venous admixture ratio (Qs/Qt) after NO inhalation.[12 29] However, we noted no significant change in Pa_{O_2} or Qs/Qt. The small fall in Pa_{O_2} could result from a dilution of oxygen by the inhaled gas mixture during the NO breathing periods. The risks of accumulation of NO_2 in air and significant methaemoglobinaemia to the patients seem insignificant with our method of administration. There was no rise in blood concentrations of methaemoglobin or accumulation of NO_2 in the environment or inspired air after administration of NO for 24 hours. This is in agreement with Adatia and colleagues[22] who also showed no rise in NO_2 or blood methaemoglobin concentrations after administration of NO in a concentration of 80 ppm for up to 98 hours. No significant adverse effects were noted in our study although four of the 11 subjects complained of cough and a sensation of rawness in the tracheal and substernal areas. In none of them were the symptoms severe enough to withdraw from the study. One of these subjects had underlying reversible airway obstruction suggestive of chronic asthma and possible increased susceptibility to the side effects of NO. It is known that NO has a significant inflammatory effect on the airways and may worsen asthmatic inflammation.[30]

A formal dose response study of NO was not attempted as it was beyond the scope of the present investigation. We chose to administer 25 ppm of NO based upon the following consideration. A fall in PVR and improvement in oxygenation have been reported with NO concentrations as low as 2 ppm by previous workers.[2 10 31] It has also been shown that the maximum haemodynamic response is achieved at concentrations of NO below 1 ppm in patients with ARDS[32] and concentrations of NO higher than 10 ppm are no more effective in improving Pa_{O_2} and venous admixture ratios.[25 31] In another study Katayama *et al*[33] have shown that a small volume of NO administered at the beginning of each breath was as effective a vasodilator as a 40 fold higher dose of NO delivered conventionally. On the other hand, inhalation of NO at a concentration of 40 ppm, even for a period as short as 30 minutes, could result in a significant worsening of Pa_{O_2} and Va/Q distribution.[12] Therefore, 25 ppm of NO administered by a nasal cannula seemed to be adequate for investigating its therapeutic effects while also being safe.

We conclude that NO in a concentration of 25 ppm can be safely administered to patients with oxygen dependent COPD via nasal cannulae concomitantly with supplemental oxygen for 24 hours without accumulation of NO_2 or a rise in serum levels of methaemoglobin. This method does not require complex apparatus, is well accepted by patients, and results in a fall in PVR even in stable patients receiving long term supplemental oxygen. Its potential use as a therapeutic agent to lower PVR and improve right ventricular function in patients with COPD and cor pulmonale receiving optimal long term oxygen therapy merits further investigation. The long term effects, optimal dosage, and the criteria for selection of appropriate patients for administration of NO also need to be determined.

The authors gratefully acknowledge Ms Lillian Legler and Ms Mary Ross for their invaluable technical assistance in the Cardiac Catheterization Laboratory, Ms Norma Jones in providing valuable suggestions in addition to technical assistance, the nursing service on 4 East for caring for the patients, and Ms Mary Guszcza for her patient and painstaking preparation of the manuscript.

1 Perke-Zaba J, Higenbottom TW, Tuan Dinh-Xuan A, *et al*. Inhaled nitric oxide as a cause of selective pulmonary vasodilatation in pulmonary hypertension. *Lancet* 1991;**338**:1173–4.
2 Germann P, Ziescher R, Leitner C, *et al*. Addition of nitric oxide to oxygen improves cardiopulmonary function in patients with severe COPD. *Chest* 1998;**114**:29–35.
3 Weitzenlum E, Donohue A, Mirlow R, *et al*. Prognostic value of pulmonary artery pressure in COPD. *Thorax* 1981;**36**:752–8.
4 Kanner RE, Meuzetti AD, Stanish WM, *et al*. Predictors of survival in subjects with chronic airflow limitation. *Am J Med* 1983;**74**:249–55.
5 Timms RM, Kheja FU, Williams GW, and NOTT Group. Hemodynamic response to oxygen therapy in chronic obstructive pulmonary disease. *Ann Intern Med* 1985;**102**: 29–36.
6 Medical Research Working Party. Long-term domiciliary oxygen therapy in chronic hypoxic cor pulmonale complicating chronic bronchitis and emphysema. *Lancet* 1981;i: 681–6.
7 Ashutosh K, Mead G, Dunsky M. Early effect of oxygen administration and perfusion in chronic obstructive pulmonary disease and cor pulmonale. *Am Rev Respir Dis* 1983;**127**:399–404.
8 Whyte KF, Fleuley DC. Can pulmonary vasodilators improve survival in cor pulmonale due to hypoxic chronic bronchitis and emphysema? *Thorax* 1988;**43**:1–8.
9 Mookherjee S, Ashutosh K, Vardan S, *et al*. Arterial oxygenation and pulmonary function with saralasin in chronic lung disease. *Chest* 1983;**83**:842–7.

10 Yoshida M, Taguchi O, Gabazza EC, *et al*. Combined inhalation of nitric oxide and oxygen in chronic obstructive pulmonary disease. *Am J Respir Crit Care Med* 1997;**155**: 526–9.
11 Katayama Y, Higgenbottom TW, Diaz de Atauri MJ, *et al*. Inhaled nitric oxide and arterial oxygen tension in patients with chronic obstructive pulmonary disease and severe pulmonary hypertension. *Thorax* 1997;**52**:120–4.
12 Barbera J, Roger N, Roca J, *et al*. Worsening of gas exchange with nitric oxide inhalation in chronic obstructive pulmonary disease. *Lancet* 1996;**347**:436–40.
13 Roger N, Barbera JA, Roca J, *et al*. Nitric oxide inhalation during exercise in chronic obstructive pulmonary disease. *Am J Respir Crit Care Med* 1997;**156**:800–6.
14 Moinard J, Manier G, Pillet O, *et al*. Effect of inhaled nitric oxide on hemodynamics and V/Q inequalities in patients with chronic obstructive pulmonary disease. *Am J Respir Crit Care Med* 1994;**149**:1482–7.
15 Haroldsson A, Kieler-Jensen N, Northorst-Westfelt U, *et al*. Comparison of inhaled nitric oxide and inhaled aerosolized prostacyclin in the evaluation of heart transplant candidates with elevated pulmonary vascular resistance. *Chest* 1998;**114**:780–6.
16 Wessel DL, Adatia L, Thompson JE, *et al*. Delivery and monitoring of inhaled nitric oxide in patients with pulmonary hypertension. *Crit Care Med* 1994;**22**:930–8.
17 Whipp BJ, Davis JA, Torres F, *et al*. A test to determine parameters of aerobic function during exercise. *J Appl Physiol* 1981;**50**:217–21.
18 Borg GA. Psychophysical basis of perceived exertion. *Med Sci Sports Exerc* 1982;**14**:377–81.
19 McHardy GJR. Relationship between difference in pressure and CO_2 content in arterial and venous blood. *Clin Sci* 1967;**32**:299–309.
20 Jones NL, Campbell EJM, Edwards RHT, *et al*. Appendix 2. In: *Clinical exercise testing*. 2nd ed. Philadelphia: WB Saunders, 1975: 190–1.
21 Bruer J, Waidelich F, von Brenndorff CI, *et al*. Technical considerations for inhaled nitric oxide therapy: time response to nitric oxide dosing changes and formation of nitrogen dioxide. *Eur J Pediatr* 1997;**156**:460–2.
22 Adatia I, Lillehei C, Arnold JH, *et al*. Inhaled nitric oxide in the treatment of post-operative graft dysfunction after lung transplantation. *Ann Thorac Surg* 1994;**57**:1311–8.
23 Zapol W, Rimar S, Gillis N, *et al*. Nitric oxide and the lung. NHLBI workshop summary. *Am J Respir Crit Care Med* 1994;**149**:1375–80.
24 Bocchi EA, Auler JO Jr, Guimaraes GV, *et al*. Nitric oxide inhalation reduces pulmonary tidal volume during exercise in severe chronic heart failure. *Am Heart J* 1997;**134**:737–44.
25 Channick R, Hoch RC, Newhart JW, *et al*. Improvement in pulmonary hypertension and hypoxemia during nitric oxide inhalation in a patient with end stage pulmonary fibrosis. *Am J Respir Crit Care Med* 1994;**149**:811.
26 Benzing A, Mois G, Beyer U, *et al*. Large increases in cardiac output in a patient with ARDS and acute right failure during inhalation of nitric oxide. *Acta Anesth Scand* 1997;**41**: 643–6.
27 George SJ, Boscoe MJ. Inhaled nitric oxide for right ventricular dysfunction following cardiac transplantation. *Br J Clin Pract* 1997;**51**:53–5.
28 Bhorade S, Christenson J, O'Connor M, *et al*. Response to inhaled nitric oxide in patients with acute right heart syndrome. *Am J Respir Crit Care Med* 1999;**159**:571–9.
29 Benzing A, Loop T, Mols G, *et al*. Effect of inhaled nitric oxide on venous admixture depends upon cardiac output in patients with acute lung injury in acute respiratory distress syndrome. *Acta Anesth Scand* 1996;**40**:466–74.
30 Barnes PJ. NO or no NO in asthma. *Thorax* 1996;**51**:218–20.
31 Maruyama K, Kobayasi H, Tagucli O, *et al*. Higher doses of inhaled nitric oxide might be less effective in improving oxygenation in a patient with interstitial pulmonary fibrosis. *Anesth Analg* 1995;**81**:210–1.
32 Scherrer U, Vollenweider L, Delabays A, *et al*. Inhaled nitric oxide for high altitude pulmonary edema. *N Engl J Med* 1996;**334**:624–9.
33 Katayama Y, Higenbottom TW, Cremona G, *et al*. Minimizing the inhaled dose of NO with breath by breath delivery of spikes of concentrated gas. *Circulation* 1998;**98**:2429–32.