Exhaled nitric oxide and asthma: complex interactions between atopy, airway responsiveness, and symptoms in a community population of children

P J Franklin, S W Turner, P N Le Souëf, S M Stick

Background: Exhaled nitric oxide (FE NO) is raised in asthmatic children, but there are inconsistencies in the relationship between FE NO and characteristics of asthma, including atopy, increased airway responsiveness (AR), and airway inflammation. The aim of this study was to investigate the relationship between FE NO and asthma, atopy, and increased AR in children.

Methods: One hundred and fifty five children (79 boys) of mean age 11.5 years underwent an assessment that included FE NO measurements, spirometric tests, inhaled histamine challenge, and a skin prick test. Blood was collected for eosinophil count. Current and past asthma like symptoms were determined by questionnaire.

Results: In multiple linear regression analyses FE NO was associated with atopy (p<0.001), level of AR (p = 0.005), blood eosinophil count (p = 0.007), and height (p = 0.002) but not with physician diagnosed asthma (p = 0.1) or reported wheeze in the last 12 months (p = 0.5). Separate regression models were conducted for atopic and non-atopic children and associations between FE NO and AR, blood eosinophils and height were only evident in atopic children. Exhaled NO was raised in children with a combination of atopy and increased AR independent of symptoms.

Conclusion: Raised FE NO seems to be associated with an underlying mechanism linking atopy and AR but not necessarily respiratory symptoms.

here is considerable interest in the measurement of fractional exhaled nitric oxide (FE NO), particularly with regard to its potential role in both the diagnosis and management of asthma. Levels are raised in asthmatic children and adults, increase during asthma exacerbations, and are reduced after corticosteroid treatment. Exhaled NO is thought to reflect airway inflammation in asthma but only limited data are available regarding the relationship between FE NO and any direct evaluation of inflammation such as airway biopsy. On the other hand, numerous studies have investigated the relationships between FE NO and indirect indicators of airway inflammation. For example, FE NO is positively correlated with eosinophils in sputum and lavage fluid. Furthermore, some studies have reported an association between FE NO and airway responsiveness (AR), but the data regarding the associations between FE NO and both eosinophilia and AR are inconsistent.

We have previously described associations between atopy and FE NO in infants and children that are independent of symptoms of asthma. Since our original observations, the importance of taking account of atopy when interpreting FE NO measurements has become apparent. Exhaled NO levels are raised in atopic but not in non-atopic asthmatics, and our observation that FE NO is raised in healthy atopic children has been confirmed in adults. We believe that inconsistencies in the literature with regard to FE NO and indirect markers of inflammation have resulted in part from a failure to fully account for atopy. We therefore hypothesised that atopy modifies the relationships between FE NO and important characteristics of asthma (such as AR, eosinophilia, and symptoms). If this is the case, there are important implications with regard to the use of FE NO as a diagnostic tool in asthma.

To investigate the association between atopy and FE NO in more detail we included FE NO measurements in the 11 year follow up of a well characterised birth cohort. This cohort had longitudinal symptom questionnaire data and measurements of lung function, AR, and atopy that allowed accurate phenotypic descriptions with regard to important asthma related characteristics.

METHODS

Subjects and protocol

Subjects were participants in a prospective birth cohort study of lung function, AR, and atopy that included data from probands and all family members enrolled from an unselected population. The probands had previously been assessed at 4 weeks, 6 months, 12 months, and 6 years of age. Data for the present study were gathered from the 11 year follow up study. Family members were studied in the first year and at the 6 and 11 year follow up surveys. In the present study 191 of the original cohort of 253 infants and 165 siblings were assessed. All children underwent an assessment that included spirometric tests, inhaled histamine challenge, skin prick testing, and blood eosinophil count. Current and past respiratory symptoms were assessed using a modified ATS questionnaire. Assessments took place either at the hospital or the child’s home. Exhaled NO was measured only in those attending hospital (n = 155, 97 of the original cohort; 58 siblings) and the results from these children are presented in this study. None of the children were symptomatic at the time of the study.

The study was approved by the medical ethics committee of Princess Margaret Hospital for Children. Informed consent was obtained from parents.

Exhaled nitric oxide

Exhaled NO was measured using a fast response chemiluminescence analyser (NOA 280, Sievers Instruments Inc, Boulder, CO, USA) as previously described.
were taken before spirometry and histamine challenge. Children maintained an expiratory flow of 35 ml/s and mouth pressure of 15 cm H₂O.

**Pulmonary function and airway responsiveness**

Pulmonary function testing was performed using a hand held spirometer (Pneumocheck Spirometer 6100; Welch-Allyn, Skaneateles Falls, NY, USA) in accordance with published guidelines.³⁹ Airway responsiveness to histamine was determined using the rapid dosimeter technique.³⁹ Responsiveness was expressed as the dose of histamine (μM) that provoked at least a 20% fall in FEV₁ (PD₂₀) and increased AR was defined as PD₂₀ <7.8 μM histamine.³⁹ A dose response slope (DRS) was also calculated using the method of O’Connor *et al.*²²

**Skin prick testing and eosinophil count**

Skin reactivity to cow’s milk, egg white, rye grass, mixed grass, *Dermatophagoides farinae, Dermatophagoides pteronyssinus,* cat dander, dog dander, *Alternaria alternans* (Hollister-Stier, Elkhart, IN, USA) was assessed by skin prick tests as described by Pepys.²³ The positive control *fumigatus* (Hollister-Stier, Elkhart, IN, USA) was assessed by skin prick tests and eosinophil count (p = 0.003), eosinophil count (p = 0.003), and height (p = 0.002) were all significantly associated with FENO (table 1). Neither physician diagnosed asthma (p = 0.1) nor recent wheeze (p = 0.5) were associated with FENO in this model. There was a significant interaction between atopy and AR, and DRS (p = 0.001) and a trend for an interaction between atopy and eosinophil count (p = 0.06). In order to examine these interactions further, separate regression models were constructed for atopic and non-atopic children. In these models, DRS, eosinophils, and height were associated with FENO in atopic (table 2) but not in non-atopic children (table 3). Again, neither physician diagnosed asthma nor recent wheeze were associated with FENO in either of these models.

Five children treated with regular inhaled corticosteroids (ICS) were excluded from analyses because of the known effects of ICS on FENO. Of the remaining 150 children, spirometric tests were performed in all individuals, skin prick testing in 149 (99%), bronchial challenge in 144 (96%), and eosinophil counts in 136 (91%). Eighty three children (56%) were atopic, 54 (38%) had increased AR, 34 (23%) reported wheeze in the past 12 months, and 26 (17%) had physician diagnosed asthma.

In univariate analyses, FENO was higher in children who had reported physician diagnosed asthma (16.4 ppb, 95% CI 11.0 to 24.6) than in non-asthmatic children (11.0 ppb, 95% CI 9.4 to 12.9; p<0.03), in those with reported recent wheeze (16.6 ppb, 95% CI 11.9 to 23.2) than in those without recent wheeze (10.8 ppb, 95% CI 9.2 to 12.7; p = 0.01), and in those with current asthma (24.5 ppb, 95% CI 15.0 to 40.0) than in those without current asthma (11.0 ppb, 95% CI 9.5 to 12.8; p<0.001). Atopic children (17.9 ppb, 95% CI 14.9 to 21.4) had significantly higher FENO levels than non-atopic children (7.2 ppb, 95% CI 6.0 to 8.7; p<0.001) and there was a positive correlation between the number of skin prick reactions and FENO (Pearson’s correlation coefficient r = 0.61, p<0.001). There was a positive association between FENO and DRS (r² = 0.21, p<0.001), eosinophil count (r² = 0.11, p<0.001), and height (r² = 0.05, p<0.008). There were no associations between FENO and measurements of pulmonary function when adjusted for height. The relationship between FENO and DRS in atopic and non-atopic children is shown in fig 1.

In the multiple regression model atopy (p<0.001), DRS (p = 0.003), eosinophil count (p = 0.003), and height (p = 0.002) were all significantly associated with FENO (table 1). Neither physician diagnosed asthma (p = 0.1) nor recent wheeze (p = 0.5) were associated with FENO in this model. There was a significant interaction between atopy and AR, and DRS (p = 0.001) and a trend for an interaction between atopy and eosinophil count (p = 0.06). In order to examine these interactions further, separate regression models were constructed for atopic and non-atopic children. In these models, DRS, eosinophils, and height were associated with FENO in atopic (table 2) but not in non-atopic children (table 3). Again, neither physician diagnosed asthma nor recent wheeze were associated with FENO in either of these models.

![Figure 1](image-url)

**Figure 1** Relationship between FENO and airway responsiveness (DRS) in atopic (○) and non-atopic (●) children. Separate regression lines for atopic and non-atopic children are included. Only in atopic children is there a significant relationship between FENO and DRS (r² = 0.301, p<0.001).

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As there were a number of sibling pairs in this cohort, there may be genetic linkage within the group. The children from the original cohort (n = 97) were therefore analysed separately and the observed associations persisted.

**DISCUSSION**

This study has shown that atopy modifies the associations between FE\(_{\text{NO}}\) and both AR and blood eosinophil counts. An important finding is that FE\(_{\text{NO}}\) is raised in children with a combination of both atopy and increased AR, and this was independent of symptoms. Interestingly, FE\(_{\text{NO}}\) was not raised in subjects with only atopy or increased AR. These data suggest that raised FE\(_{\text{NO}}\) levels are the result of a mechanism(s) linking increased AR and atopy and extend the recently published observations of Steerenberg et al.\(^{24}\)

We have previously reported an association between raised FE\(_{\text{NO}}\) and positive skin prick reactions in healthy children.\(^{14}\) The association between increased FE\(_{\text{NO}}\) and atopy in healthy subjects has been confirmed in other studies,\(^{16,17}\) but it is not a universal finding.\(^{25}\) Similarly, the data regarding the association between FE\(_{\text{NO}}\) and AR have been inconclusive.\(^{11,15}\) The results of this study extend our earlier observations and help to explain some inconsistencies in reported data. Our observations also explain the consistent reports of raised FE\(_{\text{NO}}\) levels in atopic compared with non-atopic asthmatics.\(^{11,15}\)

A major finding from both our study and a recent study by Steerenberg et al.\(^{24}\) is that the relationship between FE\(_{\text{NO}}\) and AR is only evident in atopic children. Ludviksdottir and colleagues\(^{21}\) reported a similar relationship in asthmatic adults. There is a well-established relationship between atopy and increased AR in both children\(^{26,27}\) and adults,\(^{12}\) and our data suggest that increased NO production in the airways may be associated with a mechanism linking these two factors. This may involve inflammatory processes and would support the hypothesis that FE\(_{\text{NO}}\) is a marker of allergic airway inflammation. Peat et al.\(^{29}\) suggested that IgE-mediated inflammatory reactions in the airways of atopic children could lead to increased AR. We found that there was a relationship between FE\(_{\text{NO}}\) and blood eosinophils which was also dependent on the presence of atopy. This relationship has also been reported in an unselected population of children,\(^{29}\) as well as in a group of asthmatic children.\(^{29}\) In our study there was a positive correlation between peripheral eosinophils and DRS in the atopic but not the non-atopic children (data not shown). Blood eosinophils, however, do not necessarily reflect inflammatory processes in the lungs,\(^{28}\) and an alternative explanation is that increased FE\(_{\text{NO}}\) in this phenotype may be due to genetic variations in NO synthase (NOS) genes. In patients with asthma\(^{31}\) and cystic fibrosis,\(^{32}\) variations in FE\(_{\text{NO}}\) are associated with a polymorphism in the NOS1 gene. The NOS1 isoform has been shown to be important in the regulation of AR in animal models.\(^{33}\) Further investigations are required to determine the contribution of the various NOS isoform(s) to NO production in the airways of children with atopy and increased AR.

Interestingly, we found that the association between FE\(_{\text{NO}}\) and atopy and increased AR was independent of symptoms. This was a representative population sample of asthmatic children, although children with more severe asthma (those taking ICS) were excluded because of the known effects of ICS on FE\(_{\text{NO}}\). Our findings are in agreement with those of Leuppi et al.\(^{34}\) who found significantly raised FE\(_{\text{NO}}\) levels in

### Table 1: Fold difference in fractional exhaled nitric oxide (FE\(_{\text{NO}}\)) in children with symptoms compared with children without symptoms, and fold increase per unit change in log(eosinophils), log(DRS), and height in study population (n = 150)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Fold difference/increase</th>
<th>95% CI</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atopy</td>
<td>1.83</td>
<td>1.39 to 2.41</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>PDA</td>
<td>1.36</td>
<td>0.94 to 1.95</td>
<td>0.10</td>
</tr>
<tr>
<td>Recent wheeze</td>
<td>1.10</td>
<td>0.81 to 1.51</td>
<td>0.53</td>
</tr>
<tr>
<td>Eosinophils</td>
<td>1.94</td>
<td>1.26 to 3.00</td>
<td>0.003</td>
</tr>
<tr>
<td>DRS</td>
<td>1.88</td>
<td>1.25 to 2.86</td>
<td>0.003</td>
</tr>
<tr>
<td>Height</td>
<td>1.02</td>
<td>1.01 to 1.03</td>
<td>0.002</td>
</tr>
</tbody>
</table>

*PDA = physician diagnosed asthma; DRS = dose response slope.*

### Table 2: Fold difference in fractional exhaled nitric oxide (FE\(_{\text{NO}}\)) in children with symptoms compared with children without symptoms, and fold increase per unit change in log(eosinophils), log(DRS), and height in atopic children (n = 80)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Fold difference/increase</th>
<th>95% CI</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDA</td>
<td>1.18</td>
<td>0.79 to 1.75</td>
<td>0.40</td>
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<tr>
<td>Recent wheeze</td>
<td>1.09</td>
<td>0.76 to 1.57</td>
<td>0.62</td>
</tr>
<tr>
<td>Eosinophils</td>
<td>2.24</td>
<td>1.22 to 4.06</td>
<td>0.01</td>
</tr>
<tr>
<td>DRS</td>
<td>2.38</td>
<td>1.46 to 3.94</td>
<td>0.001</td>
</tr>
<tr>
<td>Height</td>
<td>1.015</td>
<td>1.003 to 1.03</td>
<td>0.017</td>
</tr>
</tbody>
</table>

*PDA = physician diagnosed asthma; DRS = dose response slope.*
atopic children with increased AR, regardless of symptoms. These authors suggested that FENO may be more closely associated with increased AR than symptoms. In contrast, Henriksen et al.\(^{16}\) found that suspected asthmatic adolescents with both atopy and increased AR had higher FENO levels than healthy subjects with a similar phenotype. Similarly, Steerenberg et al.\(^{14}\) found that FENO was associated with respiratory symptoms in atopic children, but it appears that these authors might not have controlled for AR when investigating the association between FENO and symptoms.

Our observation that FENO is raised in healthy children with both atopy and increased AR raises an intriguing possibility that NO might be protective in these children who are at risk of asthma but who have not developed symptoms. Indeed, there have been suggestions that NO may have a bronchoprotective role through its actions on smooth muscle relaxation and inhibition of smooth muscle proliferation.\(^{15}\) Alternatively, raised FENO may identify children who have latent asthma and are at risk of developing symptoms. Both atopy and increased AR in childhood have been reported as risk factors for the subsequent development of asthma in early adulthood.\(^{26}\) However, atopy and increased AR can coexist in adults in the absence of symptoms.\(^{27}\) The association between raised FENO levels and the development of asthma later in life can only be addressed by longitudinal data. This cohort will be reassessed 5 years after the present study.

Table 3 Fold difference in fractional exhaled nitric oxide (FENO) in children with symptoms compared with children without symptoms, and fold increase per unit change in log(eosinophils), log(DRS), and height in non-atopic children (n = 70)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Fold difference/increase</th>
<th>95% CI</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDA</td>
<td>1.95</td>
<td>0.82 to 4.48</td>
<td>0.13</td>
</tr>
<tr>
<td>Recent wheeze</td>
<td>1.04</td>
<td>0.57 to 1.90</td>
<td>0.14</td>
</tr>
<tr>
<td>Eosinophils (per log unit)</td>
<td>1.52</td>
<td>0.81 to 2.86</td>
<td>0.19</td>
</tr>
<tr>
<td>Eosinophils (per log unit)</td>
<td>0.92</td>
<td>0.41 to 2.07</td>
<td>0.84</td>
</tr>
<tr>
<td>Height (per cm)</td>
<td>1.00</td>
<td>0.99 to 1.03</td>
<td>0.15</td>
</tr>
</tbody>
</table>

In each of these studies the asthmatic patients had increased AR or significant airways reversibility while the non-asthmatics all responded normally. No study has investigated the diagnostic value of FENO in an unselected population. On the basis of our results we propose that low levels of FENO may be useful to exclude increased AR in atopic children with symptoms and, therefore, to help to exclude a diagnosis of asthma. Increased AR is almost ubiquitous in clinically obvious asthma and most asthmatic children are atopic.\(^{21}\) Tests of AR are not feasible in most clinical situations, particularly in children. Our data suggest that atopic children with respiratory symptoms but low FENO levels are unlikely to have increased AR. Indeed, in our study, if FENO levels are less than 18.4 ppb, the likelihood ratio for atopic children to have increased AR is only 0.23. We suggest that the diagnostic value of low FENO levels could be further tested in a prospective study.

We have used an expiratory flow rate of 35 ml/s for measuring FENO. The study was started before publication of recommendations for the measurement of FENO in children.\(^{40}\) However, the marginally lower expiratory flow rate than that suggested in these guidelines used in our study is unlikely to affect our findings since Kissoon et al.\(^{14}\) have reported that flow rates between 30 and 50 ml/s are appropriate for children. Indeed, the use of a low flow rate may have increased our ability to measure differences in FENO between groups. Deykin et al.\(^{38}\) showed in adults using higher flow rates that the discriminatory power of FENO for differentiating between asthmatic and non-asthmatic subjects was not affected by expiratory flow rates ranging from 47 ml/s to 500 ml/s.

In summary, we have shown that atopy is important in the relationship between FENO and AR. In this study, FENO was associated with increased AR only in atopic children. Furthermore, there was an association between FENO and blood eosinophils that was also only evident in atopic children. This supports the concept that FENO reflects allergic airway inflammation and this may be one of the mechanisms explaining the relationship between atopy and AR. Alternatively, raised FENO levels in children with both atopy and increased AR may be due to variations in NOS genes. This needs to be explored further. Raised FENO levels in non-asthmatic atopic children with increased AR may either be predictive for the development of asthma or may indicate a protective role of NO against the development of symptoms. These issues will be addressed in the next follow up study of this population of children. After controlling for both atopy and increased AR, we were unable to show an association between FENO and asthma or asthma like symptoms. This suggests that raised FENO levels in children are associated with a common asthma phenotype but not with asthma per se. These results have implications for the use of FENO as a diagnostic tool for asthma. However, we have proposed a role for FENO in atopic children with symptoms of unknown aetiology to exclude increased AR and, by inference, to help to exclude asthma.
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Authors’ affiliations

P J Franklin, S W Turner, S M Stick, Department of Respiratory Medicine, Princess Margaret Hospital for Children, Perth, Australia

P J Franklin, S W Turner, P N Le Souef, University Department of Paediatrics, Princess Margaret Hospital for Children, Perth, Australia

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