Nocturnal saturation and glucose tolerance in children with cystic fibrosis

Dharmeshkumar Suratwala,1 June S H Chan,2 Andrea Kelly,3 Lisa J Meltzer,1 Paul R Gallagher,4 Joel Traylor,1 Ronald C Rubenstein,1 Carole L Marcus1,4

ABSTRACT

Background Glucose intolerance is common in cystic fibrosis (CF), and is associated with worsening pulmonary function and nutritional status, and increased mortality. As sleep-disordered breathing is associated with disorders of glucose metabolism, it was hypothesised that recurrent episodes of hypoxaemia during sleep, and sleep disruption, would be associated with inflammation and glucose intolerance in CF.

Methods 25 children (aged 14±4 (mean±SD) years) with CF underwent polysomnography, actigraphy, measurement of serum inflammatory markers and oral glucose tolerance testing. Blood glucose area under the curve (AUC), as a cumulative measure of glucose response, was determined. Polysomnography data were compared with retrospective data from 25 healthy controls.

Results Forced expiratory volume in 1 s was 92±14% predicted. 24 subjects underwent glucose tolerance testing, of whom 29% had impaired glucose tolerance and 4% had diabetes. The mean nocturnal oxygen saturation correlated negatively with glucose AUC at 120 min (r = −0.49, p = 0.015). Partial correlations and regression models including age, body mass index, nocturnal saturation and pulmonary function indicated that nocturnal saturation accounted for the majority of the predictive power for glucose AUC (R² = 0.24, p = 0.001). There were no meaningful relationships between sleep quality, inflammation and glucose tolerance.

Conclusions Lower oxyhaemoglobin saturation is associated with worse glucose regulation in children with CF. Further studies are needed to determine whether lower saturation negatively impacts glucose regulation or, alternatively, whether abnormalities in glucose metabolism are an early sign of pulmonary dysfunction.

INTRODUCTION

Cystic fibrosis (CF) is a common genetic disease with significant morbidity and mortality. With improved survival as well as improved screening practices, cystic fibrosis-related diabetes mellitus (CFRD) has emerged as a common complication of CF.1 Insulin deficiency is the primary defect in CFRD, although a variable degree of insulin resistance does occur.2,3 CFRD is associated with a more rapid decline in pulmonary status, worse nutritional status and increased mortality.4 However, the underlying pathophysiology linking CFRD and pulmonary function has not been fully elucidated. Sleep-disordered breathing and subclinical inflammation have recently been shown to play an important role in the development of insulin resistance and glucose intolerance in non-CF populations.5 Sleep-disordered breathing may affect glucose metabolism by various mechanisms including sympathetic hyperactivity secondary to sleep fragmentation, sleep loss and hypoxaemia; altered regulation of the hypothalamic–pituitary–adrenal axis; and/or direct effects of hypoxaemia on glucose homeostasis and insulin secretion.6 Patients with CF are prone to impaired sleep quality and sleep-related hypoxaemia due to nocturnal cough, nasal obstruction due to chronic infection or nasal polyps, and hypoxaemia and increased work of breathing related to lower airway obstruction.7,8

Sleep-disordered breathing is also associated with inflammation. Patients with sleep-disordered breathing have been reported to have elevated C-reactive protein (CRP)9 and activation of nuclear factor-κB (NF-κB),10 resulting in increased circulating levels of inflammatory cytokines including interleukin 6 (IL-6),11 IL-8, tumour necrosis factor α (TNFα), soluble E-selectin (sE-selectin), soluble vascular cell adhesion molecule-1 (sVCAM-1)14 and intracellular adhesion molecule-1 (ICAM-1).15 Sleep deprivation also results in elevation of CRP,16 TNFα and IL-6.17 Inflammatory markers, including CRP, IL-6 and sVCAM-1, likewise are increased with glucose intolerance.18 Patients with CF have ongoing infection and neutrophilic inflammation in their airways. They may also have elevated circulating proinflammatory cytokines at baseline, even during exacerbation-free periods,19 although other inflammatory markers such as CRP are more variable. Patients with CF with impaired glucose tolerance and CFRD have significantly higher levels of TNFα compared with patients with CF with normal glucose tolerance, as well as a more rapid rate of pulmonary function (forced expiratory volume in 1 s (FEV1)) decline.20 which may reflect the negative impact of hyperglycaemia on neutrophil function. In addition, patients with CF may be more prone to sleep-disordered breathing due to chronic sinus disease, nasal polyposis and/or increased cough frequency. Thus, it is possible that there is an association, and possibly even a causal relationship, between sleep-disordered breathing and these inflammatory biomarkers, and hence impaired glucose tolerance, in patients with CF.

We hypothesised that recurrent episodes of hypoxaemia during sleep and sleep disruption (poor sleep efficiency and quality) would be associated with worse glucose tolerance in patients with CF, as well as increased biomarkers of systemic inflammation. We therefore evaluated sleep characteristics...
(using both polysomnography and actigraphy), glucose tolerance and inflammatory biomarkers were compared with retrospective data from healthy controls.

METHODS

Additional details of the methods for making these measurements is provided in an online data supplement. Stable subjects with CF aged 8–21 years of age, underwent pulmonary function testing, overnight polysomnography, the Epworth Sleepiness Scale (modified for children),21 glucose tolerance testing and measurement of serum inflammatory markers (CRP, TNF, IL-1β, IL-6, IL-8, IL-10, s-selectin, sVCAM and sICAM) the morning following polysomnography, and 14 days of home actigraphy. Control subjects were obtained retrospectively from a normal control database of healthy individuals recruited from the community for polysomnographic studies.

The Institutional Review Board of the Children’s Hospital of Philadelphia approved the study. Written informed consent was obtained from subjects 18 years of age or older, and from the parent or legal guardian of younger subjects. Assent was obtained from subjects under 18 years of age.

Study group

Subjects with CF ≥8 years of age were recruited from the Cystic Fibrosis Center of the Children’s Hospital of Philadelphia. Subjects were excluded if they had a known history of diabetes mellitus, were pregnant, had acute illness or had used medications (including systemic steroids) known to affect insulin sensitivity within the past 6 weeks, had a history of organ transplantation, a body mass index (BMI) >85th percentile, history of severe liver disease or chronic use of supplemental home oxygen or non-invasive positive pressure ventilation. For polysomnographic data, each subject was gender and age-matched to a normal control subject from our database. To determine whether the study group was representative of the CF Center population at our institution, comparisons were also made between study subjects and all patients in that age range (8–21 years) in our CF Center database.

Polysomnography

All subjects underwent standard paediatric polysomnography.22 Arterial oxygen saturation (SpO2) was measured by pulse oximetry (Nonin Medical, Plymouth, Minnesota, USA), and the oximeter pulse waveform was recorded.

Oral glucose tolerance test (OGTT)

A glucose tolerance test was performed after overnight fasting. Impaired glucose tolerance was defined as a 2 h plasma glucose of 140–199 mg/dl; CFRD without fasting hyperglycaemia as a 2 h plasma glucose ≥200 mg/dl, and indeterminate glucose tolerance as a normal 2 h plasma glucose but a 60 min glucose >200 mg/dl.23 The inter-relationships between demographic, polysomnographic and actigraphic parameters, biomarkers and blood glucose parameters (primarily blood glucose area under the curve (AUC)) were evaluated. Glucose AUC was chosen to characterise glucose status further because the insulin secretory defects which typify CF lead to increases in glucose excursion following a glucose load. The normal glucose tolerance, impaired glucose tolerance and CFRD categories are based only on the 2 h blood glucose, and do not adequately capture the breadth of these glucose abnormalities for study purposes. Like continuous glucose monitoring, OGTT glucose AUC and OGTT blood glucose levels obtained earlier than 120 min frequently identify glucose excursions in the setting of CF that are not captured by the 2 h OGTT blood glucose.25 Total glucose AUC for plasma glucose from 0 to 120 min was therefore calculated. As glucose intolerance worsens with increasing age and is associated with lower BMI in patients with CF, the relationship between blood glucose AUC and mean nocturnal SpO2, controlling for age and BMI z-score, was explored using partial correlation coefficients and linear regression.

Actigraphy

Each subject wore an actigraph (Actiwatch-64, Mini-Mitter, Respironics, Bend, Oregon, USA) on the non-dominant wrist for 14 days following the polysomnogram and glucose tolerance test. Subjects or their caregiver completed a simultaneous sleep diary.

Data analysis

Details of the data analytic methods are provided in the online supplement. Histograms and Kolmogorov–Smirnov tests were used to examine the distributions of continuous outcome variables. Demographic variables, pulmonary function parameters and polysomnographic parameters were compared between subjects with CF and controls using appropriate statistical tests: independent sample t tests were used to compare parametric variables, and Mann–Whitney tests were used to compare non-parametric variables. The Fisher exact test was used to compare the groups on gender. To control for multiple comparisons, a p value <0.017 was considered significant. Within the group with CF, bivariate correlations, partial correlations and linear regression models were used to assess the relationships between demographic, polysomnographic and actigraphic parameters, biomarkers and blood glucose AUC.

RESULTS

Twenty-five subjects with CF were studied (table 1). The study population was comparable with the overall CF Center population aged 8–21 years, which had an FEV1 of 97±19% predicted (p=0.10 compared with study subjects), a mean BMI percentile of 60.5±25.4 (compared with 55.4±26.7 for study subjects, p=0.40) and a rate of impaired glucose tolerance of 17% (p=0.57) and CFRD of 2% (p=0.55) as observed during routine OGTT in otherwise well patients in the outpatient setting.

Spirometry in the study group was consistent with normal lung function or mild obstructive lung disease, and the mean Epworth Sleepiness Scale was normal (table 1).21

Polysomnography results

Polysomnography results are shown in table 1. Subjects with CF had a higher arousal index than controls, but sleep architecture was otherwise similar. The mean SpO2 was significantly lower in subjects with CF compared with controls, although values were still in the clinically normal range.

Actigraphy results

Actigraphic data were obtained for 21 subjects as four subjects failed to return the device. A total of 12±4 nights/subject were fit for analysis. The sleep period was 440±54 min, sleep efficiency 80±7% and waking after sleep onset 85±5 min.

Glucose tolerance

Twenty-four subjects with CF underwent OGTT; one subject refused phlebotomy. Mean fasting plasma glucose was 96±10 mg/dl and mean 2 h glucose was 129±54 mg/dl. One (4%) subject was classified as having CFRD without fasting hyperglycaemia, 7 (29%) subjects with impaired glucose
Cystic fibrosis

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Demographic and polysomnographic data from subjects with cystic fibrosis and controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subjects (n)</td>
<td>Cystic fibrosis</td>
</tr>
<tr>
<td>Age, years (range)</td>
<td>14±4 (8–20)</td>
</tr>
<tr>
<td>Male (%)</td>
<td>15</td>
</tr>
<tr>
<td>BMI z-score</td>
<td>0.1±0.9</td>
</tr>
<tr>
<td>Epworth Sleepiness Scale</td>
<td>5±4</td>
</tr>
<tr>
<td>Pulmonary function parameters</td>
<td>Forced vital capacity (FVC), % predicted</td>
</tr>
<tr>
<td>Forced expiratory volume in 1 s (FEV1), % predicted</td>
<td>92±14</td>
</tr>
<tr>
<td>FEV1/FVC (%)</td>
<td>81±9</td>
</tr>
<tr>
<td>Polysomnographic parameters</td>
<td>Total recording time, min</td>
</tr>
<tr>
<td>Sleep efficiency, % TST</td>
<td>78±13</td>
</tr>
<tr>
<td>Total sleep time, min</td>
<td>333±62</td>
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<tr>
<td>Wake after sleep onset, min</td>
<td>83±65</td>
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<tr>
<td>Sleep latency, min</td>
<td>31±32</td>
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<tr>
<td>Latency to REM, min</td>
<td>128±71</td>
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<tr>
<td>Stage N1, % TST</td>
<td>9±4</td>
</tr>
<tr>
<td>Stage N2, % TST</td>
<td>50±8</td>
</tr>
<tr>
<td>Stage N3, % TST</td>
<td>22±10</td>
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<tr>
<td>REM, % TST</td>
<td>19±5</td>
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<tr>
<td>Arousal index, N/h</td>
<td>16±5</td>
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<td>Obstructive apnea index, N/h</td>
<td>0.0 (0.0, 0.6)</td>
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<tr>
<td>Hypopnoea index, N/h</td>
<td>0.4 (0.0, 6.0)</td>
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<tr>
<td>SpO2 nadir, %</td>
<td>92.5±2.2</td>
</tr>
<tr>
<td>Time with SpO2 &lt;92%, % TST</td>
<td>0.0 (0.0, 6.7)</td>
</tr>
<tr>
<td>TcCO2 mean, mm Hg</td>
<td>47.8±6.8</td>
</tr>
<tr>
<td>Periodic limb movement index, N/h</td>
<td>0.0 (0.0, 22.8)</td>
</tr>
</tbody>
</table>

Data are presented as mean±SD for normally distributed variables and median (range) for skewed variables.

Biomarkers

The values of the circulating inflammatory biomarkers from the 24 subjects, and their comparison with normative data, are presented in table 2. Although a large degree of variability was present, in general the biomarker levels were increased or at the upper level of normal compared with normative data.

Factors predicting glucose intolerance

The inter-relationships between demographic, polysomnographic and actigraphic parameters, biomarkers and blood glucose parameters (primarily blood glucose AUC) were evaluated. There was a significant negative correlation between nocturnal mean SpO2 and glucose AUC (r =−0.49, p=0.015) (figure 1). There were two outliers that were >2 SDs from the mean: one subject with the lowest SpO2 and highest glucose AUC; and another with the lowest glucose AUC. Even after exclusion of these outliers, the correlation remained significant (p=0.011). No significant associations were found between other polysomnographic variables, actigraphic sleep variables or biomarkers and glucose tolerance.

The relationship between blood glucose AUC and mean nocturnal SpO2, controlling for age and BMI z-score, was explored. SpO2 was negatively correlated with glucose AUC after accounting for age and BMI z-score (r=−0.45, p=0.034). Although age was not significantly correlated with blood glucose AUC (r=−0.28, p=0.18), this mild correlation with age was drastically reduced and approached zero after controlling for SpO2. Conversely, controlling for SpO2 increased the mild correlation between BMI z-score and blood glucose AUC (r=−0.56, p=0.092). These findings were supported by a linear regression model of blood glucose AUC in which all three predictors were introduced into the model (table 3).

Multiple linear regressions were further used to find the linear models that best fit the glucose tolerance outcome data. Best subsets regression was used to help determine which predictor variables should be included in a multiple regression model, using adjusted R2 to check for the best model. Consistently appearing among the best models for glucose tolerance outcomes were mean SpO2 and BMI z-score. FEV1 % predicted was found to act as a suppressor covariate (ie, a covariate that was unre-
were more likely. An SpO2 predicted. However, strictly speaking, FEV1 is a measure of characteristic of type 2 diabetes, is present on pathological speci-
detection and aggressive diabetes treatment, survival has outcome with an earlier mortality. 2 Fortunately, with early decreased insulin secretion in CFRD, 2 which arises in part from worse pulmonary and nutritional status 4 and worse clinical CF cannot be overemphasised. CFRD has been associated with glucose disturbances in patients with CF.

Using a potentially more clinically relevant approach, we sought a mean nocturnal SpO2 threshold at which traditionally defined glucose abnormalities (2 h blood glucose ≥140 mg/dl) were more likely. An SpO2 <96.5% was nearly associated with an increased odds (OR 1.9; 95% CI –0.03 to 3.8, p=0.054); this finding requires confirmation with a larger sample size.

DISCUSSION
This study showed that lower nocturnal saturation was associated with worse glucose regulation in children with CF. In contrast to our hypothesis, however, there were no significant associations between parameters of sleep quality (either during polysomnography or during sleep in the home as measured by actigraphy) or markers of inflammation and glucose intolerance. To our knowledge, this is the first study to evaluate sleep and glucose disturbances in patients with CF.

CF-related diabetes
This study confirms that hyperglycaemia is common in children with CF. We studied subjects with no known diagnosis of diabetes, all of whom were at an age where annual diabetes screening by OGTT is often performed. A third of the subjects had either impaired glucose tolerance or CFRD without fasting hyperglycaemia. An additional 20% of subjects had abnormal glucose tolerance based upon a plasma glucose ≥200 mg/dl at 60 min, but were classified as normoglycaemic based upon the 2 h glucose level. 23 The importance of glucose abnormalities in CF cannot be overemphasised. CFRD has been associated with worse pulmonary and nutritional status 8 and worse clinical outcome with an earlier mortality. 7 Fortunately, with early detection and aggressive diabetes treatment, survival has improved. 1 The current study highlights the importance of not only identifying and treating CFRD as per published guidelines, but also considering earlier treatment of glucose abnormalities in CF, and determining the underlying aetiology.

The pathophysiology of CFRD is not completely understood. CFRD is distinct from type 1 and type 2 diabetes mellitus, but shares features of both. 5 Studies have demonstrated primarily decreased insulin secretion in CFRD, 2 which arises in part from pancreatic islet destruction, although islet cell amyloid, a characteristic of type 2 diabetes, is present on pathological specimens. 35 Insulin sensitivity in CF varies, with multiple factors relating to clinical status, and is decreased in the setting of impaired glucose tolerance 3 and CFRD. 2

Saturation and glucose intolerance
In this study, the subjects with CF were in overall good health, with a mean BMI z-score of 0.1 and mean FEV1 of 92% predicted. However, strictly speaking, FEV1 is a measure of forced air flow and not necessarily a measure of the current or ongoing infectious and/or inflammatory burden. Therefore, even though our subjects had a normal or mildly impaired FEV1, these data do not allow direct inference regarding the level of infection, inflammation or ongoing lung tissue damage that may have contributed to our data. The mean nocturnal oxyhaemoglobin saturation was only slightly lower in the subjects with CF than in controls, and was still in the clinically normal range. In the absence of evidence of hypercapnia, the lower saturation was probably secondary to greater ventilation/perfusion mismatch in the subjects with CF as a result of decreased clearance of mucus plugs from the CF airway. Nevertheless, there was a clear association between lower baseline nocturnal saturation and glucose excursion. This is consistent with a recent study in a non-CF population showing that mild desaturations of 2–4% were associated with fasting hyperglycaemia. 27

Clearly, the directionality of the relationship between lower saturation during sleep and hyperglycaemia cannot be deduced from this study. In fact, the finding of increased glucose excursion may only be an early marker of disease severity, a phenomenon that may not be accurately captured by pulmonary function tests. Decreased saturation resulting from increased small airways mucus plugging (that may not be detected by measurement of FEV1) could promote hyperglycaemia, as with other causes of nocturnal desaturation. 27 Conversely, primary hyperglycaemia could impair airway neutrophil effectiveness, which could in turn promote small airways mucus plugging and hypoaxaemia. Nonetheless, these findings offer a potential therapeutic window at a perhaps earlier time than that at which the more rapid decline in FEV1 associated with impaired glucose tolerance in CF is observed. Improving nocturnal saturation may improve glucose excursion or, alternatively, nocturnal oxygen saturation may be improved by improving glucose excursion.

The current understanding of the relationship between nocturnal oxygen saturation and glucose intolerance is based mainly on research on obstructive sleep apnoea and insulin resistance. The nature of this relationship is different in the context of CF, which is not associated with sleep apnoea or obesity. However, artificial induction of hypoaxaemia in non-obese, normal controls has also been shown to impair glucose tolerance. 8, 28 The direct effect of hypoaxaemia on glucose tolerance is not fully understood. Previous studies demonstrated that subjects exposed to hypoxia in the setting of high altitude had worsening glucose tolerance without concomitant rises in circulating levels of epinephrine. 29 Sympathetic hyperactivity caused by hypoaxaemia can affect glucose homeostasis by increasing glycogen breakdown and gluconeogenesis. Hypoxia can also induce a number of reactive mechanisms regulated by hypoaxaemia-inducible factor 1, which induces expression of genes that encode glycolytic enzymes and glucose transporters. 26

Evidence examining the effect of hypoaxaemia on pancreatic β-cell function is sparse. A study of intermittent hypoaxaemia and glucose tolerance in healthy adults showed that intermittent hypoaxaemia was associated with decreased insulin sensitivity but had no effect on insulin secretion. 9 However, animal studies suggest that hypoaxaemia stimulates pancreatic β-cell replication, yet in the presence of hyperglycaemia, hypoaxaemia leads to β-cell apoptosis. 30 There is also evidence to suggest that apoptosis of human pancreatic islets correlates with hypoaxaemia-inducible factor 1 expression when exposed to hypoxia. 31 It is therefore possible that hypoaxaemia may affect both glucose utilisation and β-cell function in patients with CF.
The gold standard for assessment of insulin sensitivity is the hyperinsulinemic euglycaemic clamp, but this is time-consuming and labour-intensive, and is not routinely performed in research studies on children due to ethical concerns.\(^32\)–\(^34\) Furthermore, insulin sensitivity tends to be preserved in CF unless an individual is ill or has CFRD.

**Limitations**

This study was limited by our modest sample size. However, the relationship between nocturnal saturation and glucose was robust; this was verified by vigorous regression analysis accounting for multiple potential confounding factors. It is possible that measurement of oximetry over several nights would have strengthened the outcomes. We did not have actigraphy, OGTT and inflammatory markers for control subjects, which limits our interpretation of these findings with respect to the comparison between subjects with CF and normal, healthy subjects.

**Conclusion**

This study has shown that even mild decreases in nocturnal saturation were associated with impaired glucose regulation in children with CF. Further research is needed to determine the clinical importance of these findings.

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**Competing interests**

None.

**Ethics approval**

This study was conducted with the approval of the Institutional Review Board of the Children’s Hospital of Philadelphia.

**Contributors**

All authors contributed to aspects of study design, data collection, data interpretation and manuscript review.

**Provenance and peer review**

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**REFERENCES**


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