Identification of insulin secretory defects and insulin resistance during oral glucose tolerance test in a cohort of cystic fibrosis patients

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Abstract

Background: Cystic fibrosis (CF)-related diabetes is a leading complication of CF and is associated with pulmonary and nutritional deterioration, years before an evident hyperglycemia, possibly because of insulin deficiency and resistance.

Aim: To evaluate glucose tolerance, insulin secretion, and insulin sensitivity by a widely applicable method suitable for accurate and prospective measurements in a CF population.

Methods: A total of 165 CF subjects (80 females) aged 17 ± 5 years and 18 age- and sex-matched healthy controls (CON) received an oral glucose tolerance test with glucose, insulin and C-peptide determinations. Insulin sensitivity was defined on the basis of glucose and insulin concentrations using the oral glucose insulin sensitivity index, whereas β-cell function was determined on the basis of a model relating insulin secretion (C-peptide profile) to glucose concentration.

Results: Fifteen percent of CF patients had glucose intolerance and 6% had diabetes without fasting hyperglycemia and 3% had diabetes with fasting hyperglycemia. β-cell function was reduced in CF patients compared with CON (70.0 ± 4.1 vs 117.9 ± 11.6 pmol/min per m² per mM, P < 0.001) and decreased significantly with age by −2.7 pmol/min per m² per mM per year (confidence interval (CI) −4.5 to −0.82), i.e. almost 4% yearly. The early insulin secretion index was also reduced. Insulin sensitivity was similar to CON. CF patients who attained glucose tolerance comparable to CON had lower β-cell function and higher insulin sensitivity.

Conclusion: The major alteration in insulin secretion and insulin sensitivity of CF patients is slowly declining β-cell function, consisting of delayed and reduced responsiveness to hyperglycemia, that in CF patients with normal glucose tolerance may be compensated by an increased insulin sensitivity.

Introduction

Diabetes is an emerging issue in cystic fibrosis (CF) because its prevalence increases with advancing age, affecting the majority of the patients after the age of 40 (1, 2). In addition, CF-related diabetes (CFRD) has negative implications in terms of pulmonary deterioration, observed years before diabetes diagnosis, and mortality (3–10). CFRD prevalence and health consequences are expected to increase in the future as a result of prolonged survival of CF patients.

Alterations in glucose tolerance are characterized by marked glycemic peaks often followed by rapid normalization (11–13). Fasting glycaemia is generally lower than in other forms of diabetes and fasting hypoglycaemia has been reported (14). Therefore, the categories of ‘diabetes without fasting hyperglycaemia’ (15) and of ‘indeterminate glucose tolerance’ (isolated hyperglycaemia at mid-oral glucose tolerance test (OGTT) or continuous glucose monitoring) were established (16). HbA1c is not sensitive in the diagnosis of CFRD (17, 18).

The classic diabetes diagnostic criteria, based on the detection of chronic hyperglycaemia (19), were historically aimed at identifying the risk for microvascular complications (9). These are not the primary concern in CFRD. Rather, the impaired nutritional status and deterioration in pulmonary function preceding CFRD may be the consequences of insulin deficiency and insulin resistance (2, 20–23). It is currently believed that when the endocrine pancreatic defect progresses beyond a certain threshold, or when insulin resistance arises as a consequence of inflammation or simply because of the endocrine changes of puberty, the absolute or relative insulin deficiency may be responsible for clinical deterioration and eventual CFRD.
The gold standard technique to measure insulin resistance is the euglycemic insulin clamp. Studies performed with these techniques have shown variable results, with both normal insulin sensitivity (24–27) and insulin resistance for glucose (28–30), protein (31, 32), and lipid metabolism (33). These may be related to increased glucose production and gluconeogenesis during fasting (34, 35). Heterogeneous data on insulin sensitivity spanning from increased (36), normal (37, 38), and decreased (11, 39, 40) insulin sensitivity were obtained similarly using surrogate techniques.

Using the hyperglycemic clamp, the reference method for glucose-mediated insulin secretion, defects in first- and second-phase insulin secretion were demonstrated (28, 29, 41). Similar results were obtained with the intravenous glucose tolerance test (IVGTT) technique (23, 39, 42–44). Both methods are unsuitable for large-scale and repeated assessment. The OGTT is the most common diagnostic test for CFRD and can be repeated yearly. Several studies sampled insulin concentrations during OGTT and analyzed insulin secretion using various algorithms and consistently found reduced and delayed insulin responses (8, 37, 45, 46), even in CF patients with normal glucose tolerance (NGT), supporting the concept that insulin secretory defects are inherent to CF.

Information on insulin secretion obtained during OGTT may be biased by increased hepatic first-pass insulin extraction (24, 25), consequent to insulin resistance and modulated by liver disease. Thus, single or integrated measures of insulin concentrations during OGTT may not reflect actual insulin secretion. Furthermore, insulin secretion indexes based on the ratio of insulin to glucose at 30 min after glucose ingestion could be influenced by a delayed but not absolutely defective secretion. A model-derived calculation of insulin secretion based on the C-peptide profile throughout the OGTT can overcome both difficulties (47).

The aim of this study was therefore to simultaneously evaluate glucose tolerance, insulin sensitivity, and insulin secretion in CF patients by means of insulin and C-peptide profiles measured during OGTT.

Methods

Subjects

All CF patients aged >8 years in regular follow-up at our center were offered participation in this study during their annual routine care visits if they had been clinically stable in the previous 3 weeks (neither major clinical events including pulmonary exacerbations nor changes in antibiotic or other drugs). Other exclusion criteria were a CFRD diagnosis or insulin or oral hypoglycemic agents received in the previous 6 months. Overall, 165 patients (80 females) were considered in this analysis. Healthy volunteers of comparable gender and age distribution (8 females and 10 males) were recruited as control group. The most relevant characteristics of the study subjects are reported in Table 1. The study protocol was approved by the Institutional Ethics Committee.

Oral glucose tolerance test

In all subjects, a standard 3-h OGTT (1.75 g/kg, max 75 g) was performed, sampling at baseline and at 30 min intervals plasma glucose, serum insulin, and C-peptide concentrations. Based on fasting and 2-h plasma glucose after OGTT, patients were assigned to one category of glucose tolerance (48): normal, impaired, diabetes without fasting hyperglycemia, or diabetes with fasting hyperglycemia.

Analytical methods

Plasma glucose was measured on fluoride plasma samples (Gluc-o-quant; Roche/Hitachi analyzer; Roche Diagnostics) and the other analytes were measured by commercial assays (ECLIA-Cobas C6000 – Roche Diagnostics).

Analysis and modeling of OGTT

Insulin sensitivity was calculated on the basis of glucose and insulin concentrations using the oral glucose insulin sensitivity (OGIS) index (49). This method is based on a model-derived equation that assesses glucose and insulin concentration at baseline and 90 and 120 min after glucose load.

β-cell function was evaluated according to a previously published model that represents insulin secretion as the sum of two components (50, 51). The first component describes the mean slope of the dose–response relating insulin secretion (calculated from the C-peptide profile) to glucose concentration during OGTT. This dose–response slope is denoted in the current document as β-cell function. This slope changes during the OGTT because it is modulated by a potentiation factor. Because during an acute stimulation, insulin secretion is higher on the ascending phase of hyperglycemia than at the same glucose concentration on the ascending phase. The potentiation factor encompasses several (potentiating) mechanisms (prolonged exposure to hyperglycemia, non-glucose substrates, gastro-intestinal hormones, and neural modulation). It is set to be a positive function of time, and is constrained to average unity during the experiment. In normal subjects, the potentiation factor typically increases from baseline to the end of a 2-h OGTT (47). To quantify this increment, the ratio between the 2-h and the baseline value was calculated. This ratio is denoted as potentiation ratio.

The second component describing insulin secretion represents the dynamic dependence of insulin secretion on the rate of glucose concentration change. This
component is related to early insulin release and is denoted as early insulin secretion index.

The model parameters were estimated from glucose and C-peptide concentrations by regularized least-squares, as previously described (50, 51). Regularization involves the choice of smoothing factors selected to obtain glucose and C-peptide model residuals with S.D. close to the expected measurement error (∼1% for glucose and ∼4% for C-peptide). Insulin secretion rates were calculated from the model every 5 min. The integral of insulin secretion during the 2-h OGTT was denoted as total insulin output.

### Statistical analysis

Statistical analysis was performed by means of PASW statistics 18 software. Comparisons of means were performed by means of Student’s t-test for paired or unpaired data, or by non-parametric tests when appropriate. Data were log-normalized when necessary. The relationship among variables was performed by means of regression analysis. The comparison of proportions was performed by means of χ² test.

### Results

Glucose tolerance distribution in CF and control subjects is shown in Table 1. The mean glucose concentrations during OGGT, providing a continuous measure of glucose tolerance, and the insulin and C-peptide concentrations are reported in Table 2 as median and interquartile ranges.

Glucose concentrations of CF subjects were similar to controls (CON) at basal and increased at 2 h. The mean OGTT glucose concentration was increased in CF subjects (mean ± S.E.M. 128 ± 3 vs 90 ± 4 mg/dl. P < 0.01). In contrast, basal and 2-h insulin and C-peptide concentrations were similar to CON. The 2-h glucose, insulin, and C-peptide concentrations increased in the higher quartiles of mean OGTT glucose concentration.

Insulin secretion was delayed in CF patients, who achieved an insulin peak concentration similar to CON (436 ± 24 vs 314 ± 40 pmol/l. P = NS), but later after glucose ingestion 18, 28, 35, and 18% of CF subjects peaked at 30, 60, 90, and 120 min, respectively, compared with 39, 28, 0, and 33% of CON (χ² P < 0.01).

Pancreatic insufficient CF patients had similar distribution of glucose tolerance categories as pancreatic sufficient patients, despite increased mean OGTT glucose concentration (134 ± 6 vs 104 ± 6 mg/dl) and decreased fasting and 30-min insulin (41 ± 10 vs 72 ± 10 and 198 ± 49 vs 423 ± 49 pmol/l) and C-peptide (0.50 ± 0.07 vs 0.63 ± 0.03 and 1.20 ± 0.17 vs 2.00 ± 0.17 nmol/l) concentrations (P < 0.001 for all parameters).

β-cell parameters are reported in Table 2. β-cell function was reduced in CF compared with CON subjects (mean ± S.E.M. 70.0 ± 4.1 vs 117.9 ± 11.6 pmol/min.
Table 2 Glucose, insulin and C-peptide concentrations and main model-derived parameters of β-cell function and insulin sensitivity during OGTT. Data are expressed as median and interquartile range. Mann–Whitney U test was performed to compare CF against CON and Kruskal–Wallis test to analyze differences in quartiles of mean glucose during OGTT.

<table>
<thead>
<tr>
<th></th>
<th>All subjects</th>
<th>Quartiles of mean glucose during OGTT</th>
<th>Kruskal–Wallis test between quartiles</th>
<th>P value</th>
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<tr>
<td></td>
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<td>1st</td>
<td>2nd</td>
<td>3rd</td>
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<tr>
<td>Basal glucose (mg/dl)</td>
<td>CF 77</td>
<td>68 84 72</td>
<td>63 78 75</td>
<td>69 80 75</td>
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<tr>
<td></td>
<td>CON 76</td>
<td>68 80 76</td>
<td>68 80 77</td>
<td>70 84 –</td>
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<tr>
<td></td>
<td></td>
<td>120 min glucose (mg/dl)</td>
<td>CF 104* 88 135</td>
<td>82 67 93 95</td>
</tr>
<tr>
<td></td>
<td>CON 84</td>
<td>70 94 77</td>
<td>68 88 105 93 110</td>
<td>– – –</td>
</tr>
<tr>
<td>Mean glucose (mg/dl)</td>
<td>CF 118* 101 145</td>
<td>90 84 94 105 102 109</td>
<td>124 119 132</td>
<td>169 153 193</td>
</tr>
<tr>
<td></td>
<td>CON 93</td>
<td>79 101 80 72 95 108 102 111</td>
<td>– – –</td>
<td>– – –</td>
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<tr>
<td>Basal insulin (pmol/l)</td>
<td>CF 40 27 55</td>
<td>42 29 34</td>
<td>22 60 40</td>
<td>25 49 44</td>
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<tr>
<td></td>
<td>CON 42</td>
<td>30 50 40</td>
<td>30 44 50</td>
<td>46 63 –</td>
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<tr>
<td></td>
<td></td>
<td>120 min insulin (pmol/l)</td>
<td>CF 213 117 335</td>
<td>140 98 276</td>
</tr>
<tr>
<td></td>
<td>CON 207</td>
<td>129 272</td>
<td>176 129 247</td>
<td>248 230 310</td>
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<tr>
<td>Basal C-peptide (nmol/l)</td>
<td>CF 0.50</td>
<td>0.33 0.63</td>
<td>0.53 0.40 0.60</td>
<td>0.57 0.33 0.70</td>
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<tr>
<td></td>
<td>CON 0.47</td>
<td>0.43 0.67</td>
<td>0.47 0.43 0.53</td>
<td>0.60 0.43 0.83</td>
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<tr>
<td>120 min C-peptide (nmol/l)</td>
<td>CF 1.83</td>
<td>1.40 2.40</td>
<td>1.57 1.17 1.96</td>
<td>1.63 1.20 2.33</td>
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<tr>
<td></td>
<td>CON 1.73</td>
<td>1.47 2.33</td>
<td>1.50 1.43 2.23</td>
<td>1.96 1.96 2.36</td>
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<tr>
<td>β-cell function (pmol/min per m² per mM)</td>
<td>CF 57* 32.4 89.4</td>
<td>86.2 55.9 140.5</td>
<td>80.5 51.4 98.6</td>
<td>45.7 28.9 72.5</td>
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<tr>
<td></td>
<td>CON 107.0</td>
<td>74.6 151.9</td>
<td>131.7 100.5 151.9</td>
<td>74.6 73.0 98.9</td>
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<tr>
<td>Potentiation factor at 120 min dimensionless</td>
<td>CF 1.32 1.04 1.85</td>
<td>1.12 0.80 1.31</td>
<td>1.26 0.89 1.53</td>
<td>1.53 1.11 2.16</td>
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<tr>
<td>Early insulin secretion</td>
<td>CF 28†</td>
<td>0 406 281</td>
<td>0 1609 94 0 446</td>
<td>1 0 250</td>
</tr>
<tr>
<td>index (pmol/m² per mM)</td>
<td>CON 536</td>
<td>0 1651 507</td>
<td>0 1962 944 493 1136</td>
<td>– – –</td>
</tr>
<tr>
<td>Insulin secretion at time 0 (pmol/min per m²)</td>
<td>CF 74.4 53.9 97.1</td>
<td>76.5 61.0 92.9</td>
<td>80.1 54.5 100.7</td>
<td>66.0 52.4 82.3</td>
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<tr>
<td>Total insulin output (nmol/m²)</td>
<td>CF 45.0 25.9 61.2</td>
<td>40.2 35.1 51.5</td>
<td>42.9 33.9 56.6</td>
<td>44.7 36.0 56.7</td>
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<tr>
<td>OGIS (ml/min per m³)</td>
<td>CF 540</td>
<td>467 594 573</td>
<td>552 633 566 489 628</td>
<td>548 507 590</td>
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<tr>
<td></td>
<td>CON 540</td>
<td>506 573 558</td>
<td>530 599 506 501 529</td>
<td>– – –</td>
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</table>

*P<0.001; †P<0.05. OGIS, oral glucose insulin sensitivity index.
per m² per mM, P <0.001). This tended to decrease with increasing quartiles of mean OGTT glucose concentrations. The frequency distribution of β-cell function (log-normalized data) is shown in Fig. 1 (panel A).

β-cell function declined significantly with age in CF but not in CON subjects. To avoid a selection bias due to diabetes-free long survivors, the regression analysis of β-cell function dependence on age was performed in patients younger than 25 years, as reported in Fig. 2 for both genders. The slope of β-cell function decline was −2.7 pmol/min per m² per mM (CI −4.5 to −0.82) each year, i.e. almost 4% per year. The potentiation factor for insulin secretion at 120 min, known to modulate β-cell function, was not different in CF and CON subjects. It increased with increasing quartiles of mean OGTT glucose concentrations, but did not show any dependence on age.

The early insulin secretion index was lower in CF, tended to decrease with increasing quartiles of mean OGTT glucose concentrations, and did not show any dependence on age.

Baseline fasting insulin secretion was similar in CF and CON subjects and between quartiles of mean OGTT glucose concentration. Total insulin output was also similar between CF and CON subjects although it increased with increasing quartiles of mean OGTT glucose concentration.

Pancreatic insufficient CF patients had reduced β-cell function (62.2±9.8 vs 104.8±10.9, P <0.001), potentiation factor at 120 min (1.29±0.08 vs 1.75±0.07, P=0.012), and early insulin secretion index (268±511 vs 1357±508, P <0.001), but a similar total insulin output compared with those with pancreatic sufficiency.

Insulin sensitivity measured by OGIS was similar in CF and CON subjects (552±10 vs 543±17 ml/min per m², P=0.781), but it decreased with increasing quartiles of mean OGTT glucose concentrations and it was unaffected by gender, age, and pancreatic status. The frequency distribution of insulin sensitivity in CF and CON subjects is shown in Fig. 1 (panel B).

The relationship of β-cell function and insulin sensitivity in determining glucose tolerance according to the quartiles of mean OGTT glucose concentration is shown in Fig. 3. CF patients who attained glucose tolerance comparable to CON (the lower 2 quartiles of mean OGTT glucose concentration) had lower β-cell function but similar or higher insulin sensitivity than CON.

**Discussion**

In a large population of CF patients, we applied an OGTT model to measure insulin secretion and insulin sensitivity. We also quantified the two defective components of insulin secretion in CF subjects, i.e. the delay and the reduction in β-cell responses to glucose, providing parameters suitable for comparison among research groups and evaluation for predictiveness of future diabetes development.

Our main findings are: i) β-cell function is impaired even in CF patients with NGT, specifically with regard to
Insulin sensitivity measures in CF patients, although skewed towards lower values, were distributed over a wider range compared with CON and were not significantly related to age. Even though recent pulmonary exacerbations, IV antibiotics, steroid treatment, and insulin therapy were exclusion criteria, other factors such as insulinopenia, hypoxia secondary to lung disease (29), chronic inflammation (56), and puberty (57) could have affected insulin sensitivity.

In an earlier preliminary study, we suggested that the individual changes in glucose tolerance in repeated OGTT tests were due to changes in insulin sensitivity rather than changes in β-cell function, which appeared to be more stable over time (58). However, it is generally assumed that increasing CFRD prevalence with age is related to progressive deterioration of pancreatic function, but the formal demonstration is currently lacking. In the current, larger study, we were able to demonstrate that the decrement in β-cell function is age-related, fully supporting the above concept, and providing the rough estimate of a 3–4% yearly rate of decrement. Further validation will be needed from prospective assessments of β-cell function in studies with adequate sample size and duration, involving also older CF populations.

In conclusion, we quantified several defects in β-cell function, in both total and early insulin secretion in CF patients. Increased insulin sensitivity may compensate for the β-cell function defects, producing NGT. Hyperglycemia during OGTT may eventually stimulate a delayed insulin secretion to absolute rates comparable to CON. However, the secretory defects progress

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with age. Accurate, large scale, and prospective measurements of β-cell function and insulin resistance can be obtained by modeling C-peptide and insulin concentrations during OGTt tests.

**Declaration of interest**

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

**Funding**

The study is supported by a grant from Italian Cystic Fibrosis Research Foundation – ONLUS (Prog. FFC #16/2005).

**Author contribution statement**

Study concept and design: A Battezzati and C Colombo. Analysis and interpretation of data: G Alicandro, A Battezzati, F M Battezzati, C Colombo. Acquisition of data: G Alicandro, A Battezzati, L Claut, C Colombo, L Zazzeron. Modelling: A Mari. Drafting of the manuscript: A Battezzati and C Colombo. Critical revision of the manuscript for important intellectual content: A Battezzati and Colombo C.

**References**

1 Cystic Fibrosis Foundation Patient Registry. 2008 Annual Data Report Bethesda, MD. 2009 Cystic Fibrosis Foundation.
28 Austin A, Kalhan SC, Orenstein D, Nixon P & Arslanian S. Roles of insulin resistance and beta-cell dysfunction in the pathogenesis


42 Hinds A, Sheehan AG & Parsons HG. Tolbutamide causes a modest increase in insulin secretion in cystic fibrosis patients with impaired glucose tolerance. Metabolism 1995 44 13–18. (doi:10.1016/0026-0495(95)90283-3)
