Effects of a Single Bout of Interval Hypoxia on Cardiorespiratory Control and Blood Glucose in Patients With Type 2 Diabetes

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OBJECTIVE—Hypoxia may cause functional autonomic imbalance in diabetes. Intermittent hypoxia (IH), a technique improving the adaptation to hypoxia, might improve cardiorespiratory reflexes and, ultimately, blood glucose concentrations in patients with type 2 diabetes. We tested whether a single bout of IH could initiate a long-lasting response potentially leading to better adaptation to hypoxia.

RESEARCH DESIGN AND METHODS—In 14 patients with type 2 diabetes without autonomic complications, we measured blood pressure, heart rate, oxygen saturation, chemoreflex (hypoxic and hypercapnic ventilatory responses, ventilatory recruitment threshold), and baroreflex sensitivity before, immediately after, and 3 and 6 h after a 1-h single bout of IH (6-min breathing of 13% oxygen mixture 5 times each separated by 6-min recovery). The measurements were repeated on a placebo day (at least 1 week apart, in random sequence) when subjects were only breathing room air (single-blind protocol).

RESULTS—IH significantly increased hypercapnic ventilatory responses and reduced ventilatory recruitment threshold, and increased oxygen saturation and blood pressures, whereas increases in heart rate variability and baroreflex sensitivity were not significant. Blood glucose significantly decreased after IH. No such changes were observed during the placebo day, except an increase in oxygen saturation. Some of the effects lasted 3 h after IH, and some even persisted until 6 h after IH.

CONCLUSIONS—A single bout of IH induced an initial adaptation to hypoxia, with improvement in cardiorespiratory reflexes and reduction in blood glucose. Patients with type 2 diabetes could potentially benefit from the application of a full (>2 weeks) IH intervention.

Diabetes Care 36:2183–2189, 2013

In diabetes, abnormalities of the autonomic nervous system (ANS) represent one important complication of the disease (1) because it can predispose to severe cardiovascular events (2,3). ANS dysfunction is not exclusively induced by anatomic lesions but has an important functional component (4). Low oxygen content (hypoxia), described in most organs and tissues of diabetic patients (5–9), recently has been suggested as one cause of ANS abnormalities (10,11). As a consequence, improvement of existing hypoxia might improve autonomic abnormalities that, in turn, also might have consequences on glucose metabolism.

One possible strategy to improve hypoxia could be the application of intermittent hypoxia (IH). IH improves exercise capacity in athletes, improves the acclimatization to high altitude in climbers (12,13), and improves ANS in various patients (14,15). The technique consists of intermittent exposures to hypoxic stimuli (3–5 times per day, lasting at least 5–6 min, and spaced at least by 5–6 min) repeated over 2–3 weeks. The principle of the method is like any other type of training: a given stress (here, hypoxia), if appropriately administered and spaced in time, creates a counter-regulatory response that lasts longer and, when repeated a sufficient number of times, leads to a sustained “training” effect (16). IH could increase resting oxygen saturation by increasing the ventilation and the chemoreflexes and, consequently, could reduce the sympathetic activation associated with hypoxia, as previously shown in patients with chronic bronchitis (17).

However, until now the effects of IH in patients with type 2 diabetes are unknown, even though respiratory and cardiovascular reflexes (18–24) and molecular responses to hypoxia (25) have been found to be generally impaired. Therefore, performing a short course of IH might initiate a chain of events that may eventually lead to an “acclimatization” process (when prolonging IH to >1 day). The consequence of relieving hypoxia should be restoration and correction of the cardiorespiratory reflexes.

If positive results could be found from this initial study performed in type 2 diabetic subjects without complications, then performing a full training period of IH could be justified in diabetes to test whether this intervention is able to prevent the development of diabetes complications.

RESEARCH DESIGN AND METHODS

Participants

In this single-blind, placebo-controlled study, we tested 14 type 2 diabetic subjects
(3 female, 11 male) without clinical evidence of respiratory dysfunction or autonomic complications. Patients were recruited through general practitioners in and around Innsbruck, Austria. Exclusion criteria were the presence of exercise-limiting pulmonary or musculoskeletal diseases, unstable diabetes, previous or acute myocardial infarction, proliferative retinopathy, cardiovascular complications, ventricular arrhythmias and atrial fibrillation, severe hypertension ($\geq 180/110$ mmHg), unstable or stable angina, smoking, insulin treatment, and treatment with B-blockers. Participants were advised to maintain their habits concerning medications, nutrition, and extent of physical activity. The conditions mentioned in the exclusion criteria were assessed using a medical interview. In addition, the participants underwent clinical examination, including blood pressure measurements, determination of red and white blood cell counts, and lung function testing. A stress test (i.e., spiroergometry including electrocardiogram monitoring) was performed to determine exercise capacity ($VO_2\text{peak}$) and to reveal ischemic heart disease.

The study was accomplished in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of the Medical University of Innsbruck. Written informed consent was obtained before the study from each subject. Characteristics of the study groups are shown in Table 1.

### Protocol

To test this hypothesis, we exposed patients with type 2 diabetes to 1 h of IH and followed the response over the course of 6 h thereafter in a single-blind, placebo-controlled protocol. All subjects were examined on 2 different days with a minimum time interval of 3–5 days to avoid possible carryover effects. Baseline measurements on each day were performed during the morning at least 2 h after breakfast and subjects were advised to abstain from caffeinated beverages for 12 h and from alcohol for 36 h before the examinations. The intermittent hypoxic protocol was applied on one day (IH day), whereas on the other day the same participants underwent an identical protocol of solely breathing room air (placebo day). Thus, subjects served as their own controls (cross-over design). The sequence of hypoxia day or placebo day was randomized to avoid possible confounding factors attributable to the “learning” effect. After the baseline measurements, the hypoxic or placebo sessions were performed during 1 h in the morning under standardized conditions (Supplementary Fig. 1). Each hypoxia session had five hypoxic periods (13% O$_2$ inspired fraction of oxygen) each lasting 6 min, interspersed with five normoxic exposures of the same duration. The procedure for the normoxia day was the same, but the participants inhaled normoxic air. Patients were breathing hypoxic or normoxic air in a supine position using a facial mask. Breathing periods were regulated and controlled by a technician under the supervision of a medical doctor, and without being noticed by the patient. After the hypoxic or placebo exposure, three further structured measurement sessions were performed immediately after, after 3 h, and after 6 h. During the exposure, blood pressure (Portapres; FMS Medical Systems, Amsterdam, the Netherlands), heart rate, and arterial oxygen saturation (COSMOpulse; Novametrix) were continuously monitored. The appearance of symptoms or a decline of oxygen saturation <80% was set as criteria for interrupting the administration of hypoxia until saturation levels recovered to $\geq 80\%$. After measurements immediately after IH, a meal was given to the patients, based on their specific diet requirement. The same meal was administered to each patient on both the hypoxia and the placebo days.

### Cardiovascular and respiratory testing

To examine the control of the respiratory systems, measurements of hypoxic ventilatory response (HVR) and hypercapnic ventilatory response (HCVR) were performed four times per day (before,

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### Table 1—Baseline characteristics of type 2 diabetic patients

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender (female/male)</td>
<td>3/11</td>
</tr>
<tr>
<td>Age (years)</td>
<td>$59.3 \pm 1.5$</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>$174.9 \pm 1.5$</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>$90.3 \pm 3.9$</td>
</tr>
<tr>
<td>BMI (kg/m$^2$)</td>
<td>$29.4 \pm 1.0$</td>
</tr>
<tr>
<td>Systolic blood pressure (mmHg)</td>
<td>$130.7 \pm 2.2$</td>
</tr>
<tr>
<td>Diastolic blood pressure (mmHg)</td>
<td>$78.9 \pm 1.3$</td>
</tr>
<tr>
<td>Hypertensive subjects (n)</td>
<td>6</td>
</tr>
<tr>
<td>Resting heart rate (beat/min)</td>
<td>$80.3 \pm 3.6$</td>
</tr>
<tr>
<td>Waist/hip ratio</td>
<td>$1.05 \pm 0.3$</td>
</tr>
<tr>
<td>Serum creatinine (µmol/L)</td>
<td>$82.4 \pm 4.2$</td>
</tr>
<tr>
<td>Fasting plasma glucose (mmol/L)</td>
<td>$7.7 \pm 0.6$</td>
</tr>
<tr>
<td>HbA$_1c$ (%)</td>
<td>$7.2 \pm 0.3$</td>
</tr>
<tr>
<td>Total cholesterol (mmol/L)</td>
<td>$4.6 \pm 0.2$</td>
</tr>
<tr>
<td>HOMA-IR</td>
<td>$7.6 \pm 1.7$</td>
</tr>
<tr>
<td>$VO_2\text{peak}$ (mL/kg/min)</td>
<td>$28.2 \pm 1.3$</td>
</tr>
<tr>
<td>Physical activity (h/week)</td>
<td>$4.39 \pm 0.9$</td>
</tr>
<tr>
<td>HDL cholesterol (mmol/L)</td>
<td>$1.2 \pm 0.08$</td>
</tr>
<tr>
<td>Triglycerides (mmol/L)</td>
<td>$1.7 \pm 0.2$</td>
</tr>
<tr>
<td>Microalbuminuria (n; %)</td>
<td>$1.7 \pm 1$</td>
</tr>
<tr>
<td>Macroalbuminuria (n)</td>
<td>0</td>
</tr>
<tr>
<td>GFR (mL/min)</td>
<td>$113.3 \pm 10.0$</td>
</tr>
<tr>
<td>Baseline O$_2$ saturation (%)</td>
<td>$94.8 \pm 0.4$</td>
</tr>
<tr>
<td>Deep breathing (E:I ratio)</td>
<td>$1.16 \pm 0.02$</td>
</tr>
<tr>
<td>Smokers (n)</td>
<td>0</td>
</tr>
<tr>
<td>Duration of diabetes (years)</td>
<td>$9.8 \pm 1.8$</td>
</tr>
<tr>
<td>FEV$_1$ (L)</td>
<td>$3.62 \pm 0.2$</td>
</tr>
<tr>
<td>FEV$_{C50}$ (L)</td>
<td>$4.02 \pm 0.2$</td>
</tr>
<tr>
<td>FEV$<em>1$/FEV$</em>{C50}$ (%)</td>
<td>$90.4 \pm 3.1$</td>
</tr>
<tr>
<td>Medications</td>
<td></td>
</tr>
<tr>
<td>Metformin (n)</td>
<td>7</td>
</tr>
<tr>
<td>Sulphonylureas (n)</td>
<td>4</td>
</tr>
<tr>
<td>Dipeptidyl peptidase-4 inhibitors (n)</td>
<td>5</td>
</tr>
<tr>
<td>Antihypertensive medications (n)</td>
<td>4</td>
</tr>
</tbody>
</table>

Data are presented as means ± SEM. E:I ratio, expiration/inspiration ratio; FEV$_1$, forced expiratory volume in 1 s; FEVC, forced expiratory vital capacity; GFR, glomerular filtration rate; HOMA-IR, homeostasis model assessment of insulin resistance.
immediately after, and 3 and 6 h after a 1-h single bout of IH) during IH and placebo day. All participants were evaluated in a lying position in a silent and well-tempered room. At first, 4-min recordings at rest were obtained during spontaneous breathing for the measurement of baroreflex sensitivity (BRS). Then, using a mouthpiece and an antibacterial filter, they were connected to a rebreathing circuit, as previously described and validated (17,26–28). During the testing, we continuously measured end-tidal CO2 (CO2-et) applying a capnograph connected to the mouthpiece (COSMOplus) and oxygen saturation (SaO2). Continuous airflow measurements were arranged through a heated Fleish pneumotachograph (Metabo, Epalinges, Switzerland) that was connected to a differential pressure transducer (RS part N395–257; Corby) connected in series to the expiratory component of the rebreathing system. The electrocardiogram was recorded via chest leads, whereas the continuous blood pressure was recorded using a digital plethysmograph (Portapres).

Ventilation is stimulated when inhaled oxygen is progressively reduced or carbon dioxide concentration increases. To test the response to hypoxia, a variable part of the exhausted air was passed into a scrubbing circuit filled with soda lime, subsequently returning it into the rebreathing bag. This enabled a permanent increase in CO2-et allowing the maintenance of oxygen saturation (SaO2). Continuous airflow measurements were arranged through a heated Fleish pneumotachograph (Metabo, Epalinges, Switzerland) that was connected to a differential pressure transducer (RS part N395–257; Corby) connected in series to the expiratory component of the rebreathing system. The electrocardiogram was recorded via chest leads, whereas the continuous blood pressure was recorded using a digital plethysmograph (Portapres).

Data acquisition and analysis
All signals were continuously acquired on a personal computer (Apple Macintosh, Cupertino, CA) at 600 samples per channel. An automatic and interactive program, written in BASIC by one of our group members (L.B.), was implemented to identify each single breath and to obtain breath-by-breath minute ventilation, tidal volume by integration of the flow signal, and, in addition to breathing rate, CO2-et and SaO2 percentage.

Measurement of chemoreflex sensitivity
The slope of the linear regression line of minute ventilation versus SaO2 or CO2-et indicates the chemoreflex sensitivity to hypoxia or hypercapnia, respectively. The change in ventilation attributable to hypercapnia is interpreted as a main indicator for the central chemoreflex sensitivity, whereas the change in ventilation attributable to hypoxia is interpreted as a main indicator for peripheral chemoreflex sensitivity. The point at which the ventilation started to increase during the progressive HCVR (called ventilatory recruitment threshold [VRT-CO2]; Supplementary Fig. 2) was identified by interpolating the ventilation/CO2-et plot using a fourth-order polynomial function.

Assessment of baroreflex sensitivity
The BRS was measured during recordings of spontaneous breathing at each measurement session. Previous studies have shown a poor correlation between different indices of BRS without better performance of one over the others (29). Accordingly, BRS was calculated as the average of the following seven different methods (30): positive and negative sequence methods (31); the α coefficient in the low- and high-frequency bands and its average (32); the transfer function technique (33); and the ratio of SDs of R-R interval of the respiratory re...
showed no significant changes after IH (Fig. 1). After both placebo and IH, CO₂-et increased with respect to baseline. Slight increases in tidal volume and minute ventilation were observed 6 h after IH, whereas respiration rate did not change.

Oxygen saturation increased significantly after both IH and placebo; however, the extent of the increase was not significantly higher after IH than after placebo.

**Effects of IH on cardiovascular data.** The R-R interval significantly increased immediately after the exposure during both testing days. Thereafter, R-R interval decreased more on the placebo day than after IH. Heart rate variability (SDNN) decreased more on the placebo day than both testing days. Thereafter, R-R interval significantly increased subsequent to the hypoxia exposure, but decreased again at 3 h and 6 h from baseline. Changes in baroreflex sensitivity were not significantly different between the IH day and the placebo day.

**Changes in blood glucose** Baseline blood glucose concentrations before the chemoreflex testing did not differ between the intervention day and the placebo day (P = 0.12). A significant decrease in plasma glucose (P < 0.01) occurred after the hypoxic exposure, whereas
no significant change was apparent on the placebo day (Fig. 2A). During the second evaluation after the intervention, the glucose concentrations increased during both days because of the effect of the meal; however, when evaluated in terms of differences from the baseline values a clear trend emerged, showing a progressive decrease in blood glucose after the IH as compared with the corresponding times of the placebo day (Fig. 2B).

To our knowledge, this is the first study specifically evaluating the cardiovascular and respiratory effects of IH in patients with type 2 diabetes without autonomic complications. The main findings of the present investigation, limited to a single bout of IH, are of potential practical interest. Exposure to IH rebalanced the main cardiorespiratory reflexes, accompanied by a sustained reduction in blood glucose after IH.

**Effects of IH on respiratory control in type 2 diabetes**

A decreased ventilatory response to hypercapnia (20–22) or hypoxia (18–20) previously has been described in diabetes, and this impaired ventilatory response may increase the risk of diabetes complications. Likewise, in our study, baseline respiratory reflexes appeared slightly decreased as compared with our reference values (17). In line with these findings, VRT-CO$_2$ was shifted to the right at baseline, indicating that these patients need to reach a higher level of CO$_2$ before starting ventilation. After IH, we observed a significant increase in HCVR and a shift to the left in VRT-CO$_2$. No change was observed in HVR. IH caused a slight increase in tidal volume and in minute ventilation.

The evident increase in the HCVR and the lack of change in the HVR seems, at first sight, paradoxical. However, the first effect of an increase in ventilation is a reduction in the CO$_2$-et. This limits or even stops the hyperventilation, because the carbon dioxide is a potent stimulus of ventilation. Accordingly, the only possibility to allow a persistent hyperventilation is through resetting of the VRT-CO$_2$ at lower levels. The changes in HCVR and VRT-CO$_2$ thus are compatible with the
Intermittent hypoxia and type 2 diabetes

Initial chain of events leading to a training effect on the cardiorespiratory reflexes. The oxygen saturation increased significantly after the IH, but also during the placebo day. Because these changes did not seem to result from an increase in ventilation, alternative explanations could be an improvement in gas exchange (8) or a favorable change in the oxygen transport of hemoglobin (34). The increase in oxygen saturation during placebo might suggest that the exposure to hypoxia during the measurement of the HVR could have modified some variables also during the placebo day.

Effects of IH on cardiovascular control
Abnormalities of the cardiovascular control, evidenced by decreased BRS and heart rate variability, have been observed in patients with type 2 diabetes (23, 24). Impairment of cardiovascular control can lead to severe multiorgan dysfunction and, finally, to adverse cardiovascular events in people with diabetes (2, 3). Immediately after IH, a significant increase in the R-R interval was found, together with a nonsignificant increase in BRS and SDNN, suggesting an increase in parasympathetic activity. Increases in systolic and diastolic blood pressures also were evident after IH, and they could be explained by the increased oxygenation of the hypoxic patients. In a previous article (10), we showed that patients with type 1 diabetes had increased blood pressure in response to hypoxia. This might have stimulated the increase in parasympathetic activity that prolonged the R-R interval (i.e., induced a relative bradycardia) and increased the SDNN and the BRS (similar to what found in the current study). However, Haider et al. (17) showed that the long-term effect of IH (1 h per day for 3 weeks) in chronic obstructive pulmonary disease patients was even a slight decrease in systolic blood pressure. Thus, one may suggest that the increase in systolic blood pressure observed in our study may be an initial response that is followed by adaptation.

Changes in blood glucose
Surprisingly, a significant decrease in blood glucose appeared. The link between hypoxia, cardiorespiratory reflexes, and blood glucose might be highly complex and will certainly require further studies. As speculation, this first observation that IH improves both cardiorespiratory reflexes and glucose concentrations could be the consequence of improving hypoxia through improved tissue oxygenation and reduced sympathetic activity. This may lead to better glucose utilization.

Preexisting hypoxia in type 2 diabetic patients
Hypoxia is a new, yet common, finding in diabetes and may result from various factors. Diabetic patients show decreased skin oxygenation (reduced transcutaneous partial pressure of oxygen) and increased venous oxygen partial pressure (5). Glycosylation of hemoglobin decreases oxygen transport (6), whereas in the lungs the glycosylation of basal membranes leads to impaired diffusing capacity for carbon monoxide (7). Obstructive sleep apnea is another cause of hypoxia, particularly in patients with type 2 diabetes (9). In addition, low SaO2 at rest has been observed in diabetic subjects (11). In contrast to healthy subjects, responses to experimental (in isolated cell and tissues) and clinical hypoxia in diabetes are impaired (25, 35), possibly leading to diabetes complications.

Limitations
In this investigation, the control day included a minor exposure to IH because each HVR test (which was repeated four times on IH days and placebo days) exposes the subject to a transitory hypoxia. In addition, some of the effects observed in this study might be mediated by hypoxemia (a small amount of oxygen had to be administered to perform the HCVR test). For safety reasons, because of the novelty of this approach, the subjects in this first study were a selected group of patients without evidence of autonomic complications. Therefore, the present findings may not be generalized or transferred to patients with diabetes with evidence of ANS abnormality.

CONCLUSIONS
Exposure to a single bout of IH improved hypoxia, rebalanced cardiorespiratory reflexes, and reduced glucose levels in patients with type 2 diabetes without autonomic complications. These preliminary findings support future studies applying IH for a longer period of time to test whether a full IH protocol may potentiate or prolong these initial positive effects, which potentially can have an important clinical impact.

Acknowledgments—P.H.G. has received lecture fees from Eli Lilly, Boehringer Ingelheim, Novartis, Genzyme, MSD, and Novo Nordisk, and he is an advisory board member of Boehringer Ingelheim, Novartis, and Cebix. No other potential conflicts of interest relevant to this article were reported.

T.D. performed the experiments, researched data, and had the primary responsibility of drafting the manuscript. H.G. contributed to data collection and interpretation. P.-H.G. critically revised the manuscript for important intellectual content. M.B. supervised the
References


