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Muscle Oxygen Supply Impairment during Exercise in Poorly Controlled Type 1 Diabetes

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ABSTRACT

TAGOUGUI, S., E. LECLAIR, P. FONTAINE, R. MATRAN, G. MARAIS, J. AUCOUTURIER, A. DESCATOIRE, A. VAMBERGUE, K. OUSSAIDENE, G. BAQUET, and E. HEYMAN. Muscle Oxygen Supply Impairment during Exercise in Poorly Controlled Type 1 Diabetes. Med. Sci. Sports Exerc., Vol. 47, No. 2, pp. 231–239, 2015. Purpose: Aerobic fitness, as reflected by maximal oxygen (O2) uptake (V˙O2max), is impaired in poorly controlled patients with type 1 diabetes. The mechanisms underlying this impairment remain to be explored. This study sought to investigate whether type 1 diabetes and high levels of glycated hemoglobin (HbA1c) influence O2 supply including O2 delivery and release to active muscles during maximal exercise. Methods: Two groups of patients with uncomplicated type 1 diabetes (T1D-A, n = 11, with adequate glycemic control, HbA1c < 7.0%; T1D-I, n = 12 with inadequate glycemic control, HbA1c > 8%) were compared with healthy controls (CON-A, n = 11; CON-I, n = 12, respectively) matched for physical activity and body composition. Subjects performed exhaustive incremental exercise to determine V˙O2max. Throughout the exercise, near-infrared spectroscopy allowed investigation of changes in oxyhemoglobin, deoxyhemoglobin, and total hemoglobin in the vastus lateralis. Venous and arterialized capillary blood was sampled during exercise to assess arterial O2 transport and factors able to shift the oxyhemoglobin dissociation curve. Results: Arterial O2 content was comparable between groups. However, changes in total hemoglobin (i.e., muscle blood volume) was significantly lower in T1D-I compared with that in CON-I. T1D-I also had impaired changes in deoxyhemoglobin levels and increase during high-intensity exercise despite normal erythrocyte 2,3-diphosphoglycerate levels. Finally, V˙O2max was lower in T1D-I compared with that in CON-I. No differences were observed between T1D-A and CON-A. Conclusions: Poorly controlled patients displayed lower V˙O2max and blunted muscle deoxyhemoglobin increase. The latter supports the hypotheses of increase in O2 affinity induced by hemoglobin glycation and/or of a disturbed balance between nutritive and nonnutritive muscle blood flow. Furthermore, reduced exercise muscle blood volume in poorly controlled patients may warn clinicians of microvascular dysfunction occurring even before overt microangiopathy. Key Words: AEROBIC FITNESS, GLYCATED HEMOGLOBIN, OXYGEN DELIVERY, OXYGEN RELEASE, SKELETAL MUSCLE

The beneficial effects of physical activity and the advantages of good physical fitness are well established both in healthy individuals and in those with chronic disease (20,21). Aerobic fitness, as measured by maximal oxygen (O2) uptake (V˙O2max), is a strong predictor of cardiovascular risk (2). In patients with type 1 diabetes, poor fitness represents an important barrier to regular physical activity (9). Consequently, better understanding of the underlying factors involved in the possible impairment of V˙O2max in patients with type 1 diabetes is warranted.

Low aerobic fitness levels have been reported in several (28,32), albeit not all (21,39), studies in adults with type 1 diabetes and seem to be associated with poor glycemic control, as reflected by high glycated hemoglobin (HbA1c) levels (5,24,30). A high HbA1c level is indeed an important factor in the initiation and progression of micro- and macrovascular complications. In turn, these complications may alter the functioning of tissues that are important for exercise adaptations, such as blood vessels, lungs, and heart (11,41) and, consequently, reduce V˙O2max.
However, there may be other factors involved in the impairment of aerobic fitness observed in individuals with poor glycemic control. In this respect, the HbA1c–VO2max relation has been found even in the absence of diabetic complications in young patients with type 1 diabetes (24,35). O2 supply, including arterial O2 delivery and O2 release (i.e., oxyhemoglobin dissociation) to active muscles, is a well-established factor influencing VO2max in healthy subjects or subjects with a chronic disease (17,29). In adolescents with type 1 diabetes, one study reported reduction in forearm blood flow after local exercise (rhythmic handgrip) despite the absence of any otherwise clinically detectable vascular disorders (33). To our knowledge, arterial O2 delivery (i.e., a leftward shift of the O2Hb dissociation curve) has been found to be, contradictorily, either reduced (15,16) or elevated in patients with type 1 diabetes (8), especially in cases of chronically impaired glycemic control (1).

Therefore, we aimed to determine whether O2 delivery and/or release to an active muscle during maximal exercise is altered in patients with uncomplicated type 1 diabetes and high levels of HbA1c and whether any subsequent relation to impairment in VO2max exists.

**MATERIAL AND METHODS**

A written informed consent was obtained from all participants before their inclusion in this study, which was approved by the North Western IV regional ethics committee (N° EudraCT, 2009-A00746-51). Twenty-three patients, age 18–40 yr, who had type 1 diabetes for at least 1 yr and were free from vascular complications, volunteered to participate in this study (Table 1). The absence of microvascular (retinopathy, nephropathy, and neuropathy) and macrovascular (high blood pressure, coronary disease, peripheral arteriopathy) complications was carefully checked by a clinician during the initial examination. The patients were then divided into two groups according to their HbA1c levels measured at inclusion, as follows: adequate glycemic control, T1D-A (n = 11; HbA1c <7% (53 mmol·mol⁻¹)); and inadequate glycemic control, T1D-I (n = 12; HbA1c >8% (64 mmol·mol⁻¹)). Two control groups, CON-A and CON-I, composed of healthy subjects age 18–40 yr, were recruited (as described in the following section) to strictly match the T1D-A and T1D-I groups, respectively.

**TABLE 1. Participants’ characteristics.**

| Anthropometric and demographic data | CON-A | T1D-A | CON-I | T1D-I |
|------------------------------------|-------|-------|-------|-------|
| Total (male/female), n             | 11 (110) | 11 (110) | 12 (75) | 12 (75) |
| Age (yr)                           | 25.9 ± 5.6 | 27.1 ± 6.1 | 26.2 ± 5.0 | 25.5 ± 7.3 |
| Smoking status (smokers/non smokers) | 1/0 | 1/0 | 2/0 | 2/0 |
| BMI (kg·m⁻²)                       | 23.5 ± 2.5 | 23.4 ± 3.0 | 22.9 ± 1.8 | 23.1 ± 1.8 |
| Fat mass (%)                       | 15.5 ± 3.8 | 16.7 ± 5.5 | 19.6 ± 5.8 | 20.0 ± 7.5 |
| Right leg fat mass (%)             | 20.5 ± 7.8 | 20.9 ± 7.7 | 23.8 ± 9.0 | 23.6 ± 9.7 |
| Right leg lean mass (kg)           | 9.78 ± 1.86 | 9.74 ± 1.37 | 9.98 ± 1.62 | 9.14 ± 2.48 |
| Adipose thickness at the right vastus lateralis (mm) | 10.67 ± 2.32 | 9.86 ± 3.19 | 11.57 ± 2.52 | 10.27 ± 2.76 |
| HbA1c (%)                          | 5.5 ± 0.2 | 6.6 ± 0.7* | 5.3 ± 0.2 | 9.1 ± 0.7** |
| HbA1c (mmol·mol⁻¹)                 | 37.0 ± 2.2 | 49.0 ± 7.7* | 34.8 ± 2.2 | 76.1 ± 7.7** |
| Diabetes duration (yr)             | 4.5 ± 3.6 | 9/2 | 10.9 ± 3.4 |
| Insulin delivery (MDI/CSII)        | 2.52 ± 10.27 | 2.48 ± 9.7 | 2.76 ± 23.4 | 70.2 ± 207.1 |
| Accelerometry (min⁻¹)              | 233.4 ± 70.2 | 233.4 ± 70.2 | 233.4 ± 70.2 | 233.4 ± 70.2 |
| Light + moderate + vigorous intensities | 182.5 ± 49.9 | 184.9 ± 76.2 | 233.4 ± 70.2 | 207.1 ± 76.5 |
| Usual daily macronutrient intake    | 134.3 ± 34.1 | 134.5 ± 32.2 | 123.6 ± 30.6 | 120.4 ± 26.3 |
| TC (kg·kg⁻¹·d⁻¹)                   | 16.1 ± 3.3 | 16.3 ± 2.3 | 15.5 ± 3.6 | 14.9 ± 2.6 |
| Fat (% of TC)                      | 34.5 ± 4.7 | 33.8 ± 4.2 | 34.7 ± 4.0 | 32.9 ± 8.4 |
| Polysaturated/saturated fatty acids ratio | 0.4 ± 0.2 | 0.3 ± 0.1 | 0.4 ± 0.1 | 0.4 ± 0.2 |
| Cholesterol (mg·dl⁻¹)               | 303.7 ± 135.4 | 363.6 ± 142.5 | 286.6 ± 148.8 | 287.5 ± 122.6 |
| CHO (mg·dl⁻¹)                      | 45.8 ± 7.2 | 47.0 ± 3.6 | 46.6 ± 5.6 | 48.6 ± 7.6 |
| High glycemic index CHO (% of TC)  | 19.8 ± 4.2 | 15.1 ± 5.5 | 17.3 ± 4.9 | 16.7 ± 5.1 |
| Fiber intake (g·d⁻¹)               | 18.9 ± 4.9 | 21.3 ± 4.9 | 17.7 ± 4.9 | 19.2 ± 4.8 |

Values are means ± SD. Fat mass was measured by dual energy x-ray absorptiometry. HbA1c was recorded just before exercise.
*Significantly different from their respective CON group (Wilcoxon test), P < 0.01.
**Significantly different from their respective CON group (Wilcoxon test), P < 0.001.
BMI: body mass index; CSII: continuous subcutaneous insulin infusion; MDI, multiple daily injections; TC, total caloric intake.
Selection process of the healthy control subjects. Healthy participants were selected from a list (n = 250) drawn from patients’ friends and contacts. Each healthy control was chosen after a case patient with type 1 diabetes according to the following preestablished ranges or values: gender, same as the case patient; age, ±7 yr; body mass index, ±4 kg·m⁻²; moderate-to-vigorous physical activity levels, ±1 h when the patients’ physical activity category was 0 h·wk⁻¹, ±2 h for category 2–6 h·wk⁻¹, ±4 h for category >6 h·wk⁻¹, pairs of patient/control being in the same category, and tobacco status, grouped according to no smoking, <10 cigarettes a day, and >10 cigarettes a day. The healthy controls chosen were then recruited after an oral glucose tolerance test (75 g). Individuals were excluded if they had a fasting blood glucose level of >6.05 mM or an abnormal glucose tolerance test result using World Health Organization criteria (14). The similarity of body composition and physical activity levels between groups was then accurately checked using dual energy x-ray absorptiometry (Hologic, Inc., Waltham, MA) and accelerometry (ActiGraph, model GT1M) over seven consecutive days, respectively (Table 1).

Besides physical activity levels, we added an assessment of lifestyle diet. Dietary data were based on a 3-d diary (based on two weekdays and one weekend day). Written instructions were given to provide detailed information about the quantity and quality of all items consumed. The patients were then interviewed by a research-trained dietician, who gathered information to supplement the diaries.

Laboratory testing. Subjects were requested to refrain from vigorous physical activity for 48 h before the test and from using tobacco in the morning of the test. Patients with type 1 diabetes received their usual morning insulin bolus, defined as 0–233 mg·d⁻¹, pairs of patient/control being in the same category, and tobacco status, grouped according to no smoking, <10 cigarettes a day, and >10 cigarettes a day. The healthy controls chosen were then recruited after an oral glucose tolerance test (75 g). Individuals were excluded if they had a fasting blood glucose level of >6.05 mM or an abnormal glucose tolerance test result using World Health Organization criteria (14). The similarity of body composition and physical activity levels between groups was then accurately checked using dual energy x-ray absorptiometry (Hologic, Inc., Waltham, MA) and accelerometry (ActiGraph, model GT1M) over seven consecutive days, respectively (Table 1).

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Blood analyses. Venous blood samples were collected from a forearm catheter at rest and during exercise. HbaA1c was measured at rest from EDTA blood (HPLC assay, VARIANT2 Turbo; Bio-Rad) (Table 1). At rest and maximal exercise, fluorinated and heparinized samples were used to analyze blood glucose (hexokinase enzymatic assay, Modular automat) and erythrocyte 2,3-DPG (spectrophotometry; Sigma-Aldrich, St. Louis, MO), respectively.

At rest and immediately at exhaustion, a microcapillary arterialized earlobe blood sample (vasodilator pomade
TABLE 2. Cardiopulmonary and metabolic data from participants during incremental maximal exercise.

| CON-A | T1D-A | Main Effect by ANOVA | CON-I | T1D-I | Main Effect by ANOVA |
|-------|-------|----------------------|-------|-------|----------------------|
| Aerobic fitness | | | | | |
| VO\(_{2}\) max (mL·min\(^{-1}\)·kg\(^{-1}\)) | 43.0 ± 7.8 | 40.9 ± 9.3 | | 41.2 ± 7.2 | 34.6 ± 7.2\(^*$\) |
| HR\(_{max}\) (bpm) | 190.6 ± 8.8 | 191.6 ± 12.3 | | 188.4 ± 11.5 | 185.9 ± 12.2 |
| RE\(_{max}\) | 1.1 ± 0.1 | 1.1 ± 0.1 | | 1.1 ± 0.1 | 1.2 ± 0.1\(^*$\) |
| Blood lactate max (mM) | 13.6 ± 4.7 | 12.7 ± 2.5 | | 11.9 ± 4.2 | 13.6 ± 2.2 |
| RPE max | 19.1 ± 0.8 | 18.8 ± 0.9 | | 18.8 ± 0.6 | 19.1 ± 0.9 |
| \(\text{O}_2\) pulse (mL·beat\(^{-1}\)) | 4.9 ± 1.7 | 4.5 ± 1.6 | | Exercise, \(P < 0.001\) | 4.7 ± 1.7 | 4.8 ± 2.1 | Exercise, \(P < 0.001\) |
| Rest | 16.6 ± 3.1 | 16.0 ± 3.4 | | Group, NS | 15.1 ± 3.7 | 13.6 ± 3.7 | Group, NS |
| Arterial \(\text{O}_2\) transport | | | | | |
| Pa\(\text{O}_2\) (mm Hg) | 97.6 ± 8.2 | 97.9 ± 13.5 | | Exercise, \(P < 0.01\) | 98.7 ± 9.7 | 90.9 ± 7.6 | Exercise, \(P < 0.01\) |
| Max | 107.0 ± 13.2\(^††\) | 102.4 ± 12.9 | | Group, NS | Interaction, NS | 105.8 ± 6.9\(^††\) | 103.4 ± 14.2\(^†††\) | Group, NS |
| Rest | 97.9 ± 0.6 | 98.2 ± 1.0 | | Exercise, \(P < 0.05\) | 98.5 ± 0.5 | 97.9 ± 1.3 | Exercise, \(P < 0.01\) |
| Max | 97.2 ± 1.8 | 97.0 ± 1.1\(^††\) | | Group, NS | Interaction, NS | 97.3 ± 0.6\(^††\) | 97.4 ± 0.7 | Interaction, NS |
| Ca\(\text{O}_2\) (mL per 100 mL) | 15.0 ± 0.7 | 15.8 ± 1.1 | | Exercise, \(P < 0.0001\) | 14.0 ± 1.7 | 14.6 ± 1.4 | Exercise, \(P < 0.01\) |
| Rest | 16.0 ± 0.8 | 17.3 ± 1.9 | | Group, NS | Interaction, NS | 15.0 ± 1.9 | 15.8 ± 1.3\(^†\) | Group, NS |
| Max | 21.8 ± 1.2 | 23.4 ± 2.6\(^††\) | | Group, NS | Interaction, NS | 20.3 ± 2.4 | 21.4 ± 1.7\(^††\) | Group, NS |
| Factors influencing \(\text{O}_2\)Hb dissociation curve | | | | | |
| pH | 7.41 ± 0.02 | 7.40 ± 0.04 | | Exercise, \(P < 0.0001\) | 7.42 ± 0.02 | 7.42 ± 0.01 | Exercise, \(P < 0.0001\) |
| Max | 7.27 ± 0.09\(^†††\) | 7.25 ± 0.03\(^†††\) | | Group, NS | Interaction, NS | 7.26 ± 0.06\(^†††\) | 7.26 ± 0.03\(^†††\) | Group, NS |
| Pa\(\text{CO}_2\) (mm Hg) | 39.3 ± 2.3 | 39.2 ± 2.0 | | Exercise, \(P < 0.0001\) | 39.0 ± 2.0 | 39.0 ± 2.7 | Exercise, \(P < 0.0001\) |
| Max | 31.1 ± 0.51\(^†††\) | 29.9 ± 2.4\(^†††\) | | Group, NS | Interaction, NS | 29.6 ± 3.0\(^†††\) | 31.7 ± 3.8\(^†††\) | Group, NS |
| Erythrocyte 2,3-DPG (mmol·L\(^{-1}\)·red blood cells) | 3.32 ± 0.9 | 3.97 ± 0.5 | | Exercise, \(P < 0.001\) | 3.50 ± 0.7 | 3.69 ± 0.9 | Exercise, NS |
| Max | 3.56 ± 1.0 | 3.97 ± 0.6 | | Group, NS | Interaction, NS | 3.64 ± 0.7 | 4.00 ± 0.9 | Group, NS |
| Metabolic data | | | | | |
| Plasma glucose (mM) | 5.2 ± 0.5 | 6.87 ± 1.9 | | Exercise, \(P < 0.01\) | 5.3 ± 0.9 | 7.2 ± 3.2 | Exercise, \(P < 0.0001\) |
| Rest | 6.8 ± 1.3\(^†\) | 7.52 ± 1.6 | | Group, NS | Interaction, NS | 6.2 ± 0.8 | 8.8 ± 2.4\(^†††\) | Group, NS |
| Max | | | | | |

Values are means ± SD. “Rest” indicates values at rest just before the exercise, and “max” indicates values at exhaustion from the incremental exercise; NS, non significant. The main effects from ANOVA are as follows: exercise, exercise effect, group, group effect, interaction, and exercise-group interaction. Wilcoxon (variables only indicated at max):

- Significantly different from their respective CON group, \(P < 0.05\).
- Mixed model post hoc ANOVA: Significantly different from their respective CON group, \(P < 0.05\).
- Significantly different from rest, \(P < 0.05\).
- Significantly different from rest, \(P < 0.01\).
- Significantly different from rest, \(P < 0.001\).

applied 5 min before sampling) was collected to analyze lactate (amperometry, on ABL800 radiometer), factors able to modify the \(\text{O}_2\)Hb dissociation curve (pH, partial pressure of carbon dioxide (Pa\(\text{CO}_2\)), by potentiometry, on ABL800 radiometer), and components of arterial \(\text{O}_2\) content (Ca\(\text{O}_2\)) (27) (arterial \(\text{O}_2\) saturation (Sa\(\text{O}_2\)) by spectrophotometry, partial pressure of \(\text{O}_2\) (Pa\(\text{O}_2\)) by amperometry, hemoglobin concentration by spectrophotometry, on ABL800 Radiometer). Ca\(\text{O}_2\) was calculated as the sum of bound (1.39 (hemoglobin) \times \text{SaO}_2) and dissolved \(\text{O}_2\) (0.003 Pa\(\text{O}_2\)).

**Statistical analyses.** Statistics were computed using SAS 9.3 (SAS Institute, Inc., Cary, NC). Results are reported as means ± SD unless otherwise indicated. Normality was tested using the Shapiro–Wilk test. Demographic, anthropometric, and aerobic fitness data were compared between patients with type 1 diabetes and their respective group of healthy controls using the Wilcoxon matched-pairs test. NIRS data, arterialized \(\text{O}_2\) transport, and blood factors able to influence the \(\text{O}_2\)Hb dissociation curve were compared between patients with type 1 diabetes and their respective control group using a linear mixed model
for repeated measurements. In this model, the fixed effects were the group effect (i.e., T1D-A vs CON-A and T1D-I vs CON-I), the exercise effect (repeated measurements corresponding to relative intensity levels—10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100% of VO\textsubscript{2max})—and the group–exercise interaction. The mixed model is an extension of the classical ANOVA allowing handling of correlations between repeated measurements. The choice of the covariance pattern model was based on the Akaike information criterion. The influence of each individual on the results was investigated using the Cook distance. If significant main effects or an interaction was observed with ANOVA, Bonferroni post hoc pairwise comparisons were applied. Pearson correlation coefficients were used to detect correlations between two continuous parametric variables. \( P < 0.05 \) was considered statistically significant.

**RESULTS**

**Subjects' characteristics.** Demographic and physical activity data from patients with type 1 diabetes and their matched healthy controls are summarized in Table 1. On the day of the exercise test, HbA\textsubscript{1c} levels ranged between 8% and 10.3% in T1D-I and between 5.5% and 7.5% in T1D-A. The latter is explained by the fact that, for four of the 11 patients in the T1D-A group, HbA\textsubscript{1c} changed from levels <7.0% the day of inclusion to levels between 7.0% and 7.5% on the day of exercise test. Plasma glucose concentrations...
increased during exercise in all groups (Table 2). None of the patients with type 1 diabetes became hypoglycemic during exercise.

\( \text{VO}_{2\text{max}} \) - T1D-I had lower \( \text{VO}_{2\text{max}} \) than CON-I despite comparable levels of habitual physical activity (Table 1) as well as comparable HR achieved at exhaustion (Table 2). No significant difference in \( \text{VO}_{2\text{max}} \) was observed between T1D-A and CON-A (Table 2).

**Aerobic fitness.** Despite being relatively physically active (average of 41.3 ± 23.4 min of moderate to vigorous activities per day), the poorly controlled patients included in our study displayed a level of aerobic fitness (\( \text{VO}_{2\text{max}} = 34.6 ± 7.2 \text{ mLkg}^{-1}\text{min}^{-1} \)) corresponding to levels usually observed in sedentary subjects (3), suggesting increased risk for cardiovascular diseases (2). In our study, the lower aerobic fitness in poorly controlled patients with type 1 diabetes compared with healthy controls was consistent with several studies in the literature (5,30), in which some patients undoubtedly suffered from micro- and macrovascular complications (30). Thus, besides the indirect effect of HbA\(_{1c}\) on aerobic fitness through the presence of chronic hyperglycemia-induced complications, our results raise the possibility of a direct effect of HbA\(_{1c}\) levels on \( \text{VO}_{2\text{max}} \). The mechanisms underlying

### DISCUSSION

We found that patients with inadequate glycemic control but without any clinically detectable vascular complications displayed impaired aerobic capacity as well as reduction in blood volume and dramatic impairment in HHb increase in active skeletal muscles during intense exercise. However, regardless of their HbA\(_{1c}\) levels, patients with type 1 diabetes had adequate CaO\(_2\). These results seem all the more relevant, given that this is the first *in vivo* study to assess all steps from O\(_2\) delivery to release in the skeletal muscle during maximal exercise in patients with type 1 diabetes. In addition, the patients were divided into two groups having distinct levels of HbA\(_{1c}\) and all were free from clinical micro- and macroangiopathy. Another noteworthy feature of this study lies in the care taken to closely match each patient with a healthy control, taking into account the usual demographic data as well as the exact levels of physical activity (7-d accelerometry) (34). Regular physical activity is one of the major determinants of \( \text{VO}_{2\text{max}} \) (21,22) and thus could explain some discrepancies regarding aerobic fitness and type 1 diabetes reported in previous literature.

**Aerobic fitness.** Despite being relatively physically active (average of 41.3 ± 23.4 min of moderate to vigorous activities per day), the poorly controlled patients included in our study displayed a level of aerobic fitness (\( \text{VO}_{2\text{max}} = 34.6 ± 7.2 \text{ mLkg}^{-1}\text{min}^{-1} \)) corresponding to levels usually observed in sedentary subjects (3), suggesting increased risk for cardiovascular diseases (2). In our study, the lower aerobic fitness in poorly controlled patients with type 1 diabetes compared with healthy controls was consistent with several studies in the literature (5,30), in which some patients undoubtedly suffered from micro- and macrovascular complications (30). Thus, besides the indirect effect of HbA\(_{1c}\) on aerobic fitness through the presence of chronic hyperglycemia-induced complications, our results raise the possibility of a direct effect of HbA\(_{1c}\) levels on \( \text{VO}_{2\text{max}} \). The mechanisms underlying
this direct relation may involve muscle O₂ delivery (including arterial O₂ transport and muscle blood perfusion) and/or O₂ release to muscles, which are two main determinants of VO₂max (6,37).

**Arterial O₂ transport.** Arterial O₂ transport is dependent on two key factors. The first is the ability of the lungs to oxygenate the blood as it passes through the pulmonary capillary network. In the current study, this was reflected by the O₂ content of arterialized blood (27). O₂ transport also depends on cardiac output, which is determined by the product of stroke volume (as reflected by O₂ pulse) and HR. We observed that arterial O₂ transport capacity was comparable in poorly controlled patients with type 1 diabetes and their healthy controls. This finding suggests that, in patients with type 1 diabetes but free from clinically detectable microangiopathy, the increase in pulmonary capillary blood flow and alveolar–capillary diffusion induced by high-intensity exercise does not highlight any limitation in lung function. In agreement with our results, Wanke et al. (38) showed that patients with type 1 diabetes, in the absence of overt pulmonary disease, have a normal alveolar–arterial O₂ gradient at comparable power outputs.

**Blood volume in active skeletal muscles.** Changes in THb are thought to reflect changes in tissue blood volume (19). Therefore, the significant increase in ΔTHb in both groups of healthy controls and of patients with adequate glycemic control in the present study is consistent with the increase in muscle blood volume usually observed with increasing exercise intensity (7). However, in cases of inadequate glycemic control, patients with type 1 diabetes had significantly lower ΔTHb than their healthy controls. Our results supplement those of Pichler et al. (33). In children and adolescents with type 1 diabetes, among whom some were poorly controlled (mean HbA₁c, 9.2% ± 1.8%), the authors found lower ΔTHb at the forearm muscle in response to a short submaximal local exercise (1-min rhythmic handgrip) performed in addition to provoked nonphysiological increase in forearm arterial inflow. The latter was artificially set up using brachial venous occlusion (three occlusions of 20 s interspaced by a rest period of 40 s). The current study suggests that, even without a preconditioning stress such as venous occlusion, the physiological condition of maximal exercise was sufficient to induce alteration in muscle perfusion. This alteration is possibly favored by endothelial dysfunction and/or functional alterations of the microcirculation occurring even before overt microvascular complications in cases of chronic hyperglycemia (i.e., high HbA₁c levels) and/or in cases of long-term diabetes. The poorly controlled patients, indeed, had longer duration of disease than the well-controlled patients in our study.

**The exercise-induced HHb increase in active muscles.** There were no differences in ΔHHb levels and its increase between patients with adequate glycemic control and their healthy controls. These results coincide with those of Peltonen et al. (32), who reported a comparable level of ΔHHb at maximal exercise in patients with type 1 diabetes with an HbA₁c of 7.7% ± 0.7% and healthy subjects. We did, however, find that patients with inadequate glycemic control displayed dramatic impairment in exercise-induced ΔHHb increase and reduced ΔHHb levels, especially with intense exercise (>60% VO₂max).

During a bout of exercise, several factors may explain the reduction in ΔHHb increase. First, a lower ΔHHb may be observed in the case of better matching between muscle O₂ delivery (particularly depending on CaO₂ and muscle blood perfusion) and muscle O₂ use. For example, this scenario is seen at the onset of heavy-intensity exercise in young healthy adults compared with older healthy adults because the former displays better increase in muscle blood volume (as reflected by ΔTHb) for a comparable need for O₂ for muscle contraction (13). However, this mechanism does not explain the ΔHHb impairment in our poorly controlled patients with type 1 diabetes, as they otherwise displayed lower ΔTHb rates during the exercise test.

Secondly, the lower ΔHHb may be explained by lower muscle O₂ extraction (19). This could occur in two situations, as follows: 1) reduced capacity of O₂-Hb dissociation, which can occur in pathological circumstances (e.g., CO intoxication) or in sport (e.g., hyperventilation-induced alkalosis in mountaineering), and 2) reduced tissue capacity of O₂ use (e.g., mitochondrial dysfunction). The hypothesis of the former situation (i.e., a disturbed O₂-Hb dissociation rate) is probably involved in the lower exercise level of ΔHHb found *in vivo* in our poorly controlled (HbA₁c >8%) patients. Indeed, it has been shown *in vitro* that glycation of hemoglobin, at percentages that might be found in patients with diabetes (i.e., 8% HbA₁c), reduced the kinetics of hemoglobin O₂ release by 10% in comparison with a 4% HbA₁c level (25). In our study, the possibility of higher O₂ affinity of HbA₁c seems all the more likely, with the consideration that other stimuli, able to shift the O₂-Hb dissociation curve to the right during intense exercise (Bohr effect) (26), were either comparable (blood pH, erythrocyte 2,3-DPG) or higher (PaCO₂) in the poorly controlled patients compared with those in healthy controls.

Thirdly, we cannot exclude the possibility that the exercise-induced switch of muscle blood flow from the “nonnutritive” route (i.e., the flow “reserve” irrigating muscle connective tissues and their associated adipocytes) to the “nutritive” route (i.e., capillaries in intimate contact with the skeletal muscle fibers) (12) was impaired in our poorly controlled patients with long-standing diabetes, hence reducing overall O₂ extraction proportion. This phenomenon has never been investigated *in vivo* during exercise in humans with type 1 diabetes but can be suggested through previous work on animal models of diabetes (31).

Notwithstanding, the lower HHb increase in the vastus lateralis muscle found in the patients with inadequate glycemic control may contribute to their impaired aerobic fitness because we detected significant positive correlation between VO₂max and ΔHHb at maximal exercise in all the patients with type 1 diabetes (*r* = 0.54, *P* < 0.01).
Further studies are needed to determine whether the blunted HHb increase in muscles observed in patients with poor glycemic control may also be related to impaired muscle mitochondrial function.

**CONCLUSIONS**

In summary, the ΔHHb increase in the vastus lateralis during maximal exercise is blunted in patients with type 1 diabetes and with high levels of HbA1c. This result, obtained in vivo during a physiological condition, supports the hypothesis of an increase in O2 affinity induced by hemoglobin glycation and/or of a disturbed balance between nutritive and nonnutritive muscle blood flow routes, as previously put forward by in vitro and animal studies, respectively. This finding is of particular clinical relevance, considering the negative correlation between ΔHHb increase and VO2max found in patients with type 1 diabetes in the current study.

Ultimately, from a practical perspective, maximal exercise coupled with NIRS measurement represents a promising noninvasive method of physiologically assessing disorders of muscle perfusion in patients without otherwise clinically detectable microangiopathy. Determining whether these disorders of muscle blood expansion can be reversed with HbA1c improvement will be a challenge for future prospective clinical trials.

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S. T. performed the experiments, analyzed the data, and wrote the manuscript. E. L. performed the experiments, contributed to the discussion, and reviewed the manuscript. P. F. contributed to the conception of the experiments, recruited the patients, and reviewed the manuscript. R. M. contributed to the conception of the experiments and reviewed the manuscript. G. M. performed the experiments. J. A. performed the experiments and reviewed the manuscript. A. D. recruited the patients and reviewed the manuscript. A. V. recruited the patients. K. O. performed the experiments. G. B. researched data and reviewed the manuscript. E. H. is the guarantor of this work and, as such, had full access to all data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis. She conceived and designed the experiments, performed the experiments, analyzed data, and wrote the manuscript.

This study is registered as a clinical trial, NCT02051504, at ClinicalTrial.gov.

The authors have nothing to disclose.

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