Glucose ingestion during exercise blunts exercise-induced gene expression of skeletal muscle fat oxidative genes

Anthony E. Civitarese,1 Matthijs K. C. Hesselink,2 Aaron P. Russell,3 Eric Ravussin,1 and Patrick Schrauwen4
1Pennington Biomedical Research Center, Baton Rouge, Louisiana; Departments of 2Movement Sciences and 4Human Biology, Nutrition and Toxicology Research Institute, Maastricht University, Maastricht, The Netherlands; and 3Romande Rehabilitation Clinic, Sion, Switzerland

Submitted 3 May 2005; accepted in final form 14 July 2005

Civitarese, Anthony E., Matthijs K. C. Hesselink, Aaron P. Russell, Eric Ravussin, and Patrick Schrauwen. Glucose ingestion during exercise blunts exercise-induced gene expression of skeletal muscle fat oxidative genes. Am J Physiol Endocrinol Metab 289: E1023–E1029, 2005. First published July 19, 2005; doi:10.1152/ajpendo.00193.2005.—Ingestion of carbohydrate during exercise may blunt the stimulation of fat oxidative pathways by raising plasma insulin and glucose concentrations and lowering plasma free fatty acid (FFA) levels, thereby causing a marked shift in substrate oxidation. We investigated the effects of a single 2-h bout of moderate-intensity exercise on the expression of key genes involved in fat and carbohydrate metabolism with or without glucose ingestion in seven healthy untrained men (22.7 ± 0.6 yr; body mass index: 23.8 ± 1.0 kg/m2; maximal O2 consumption: 3.85 ± 0.21 l/min). Plasma FFA concentration increased during exercise (P < 0.01) in the fasted state but remained unchanged after glucose ingestion, whereas fat oxidation (indirect calorimetry) was higher in the fasted state vs. glucose feeding (P < 0.05). Except for a significant decrease in the expression of pyruvate dehydrogenase kinase-4 (P < 0.05), glucose ingestion during exercise produced minimal effects on the expression of genes involved in carbohydrate utilization. However, glucose ingestion resulted in a decrease in the expression of genes involved in fatty acid transport and oxidation (CD36, carnitine palmitoyltransferase-1, uncoupling protein 3, and 5′-AMP-activated protein kinase-α2; P < 0.05). In conclusion, glucose ingestion during exercise decreases the expression of genes involved in lipid metabolism rather than increasing genes involved in carbohydrate metabolism.

Skeletal muscle gene expression; exercise-diet interaction

Despite the capacity of diet and muscle substrate stores to influence gene expression, no published study has described the impact of dietary carbohydrate and lipid ingestion immediately preceding, during, and after repeated exercise sessions. Thus the intensity, type, and duration of the exercise session differentially influence both the species of gene transcripts and the extent to which gene expression is increased.

The specificity of the genes responding to an exercise session indicates that additional influences such as diet may interact to regulate postexercise gene expression. Several studies have addressed the impact of diet on human skeletal muscle gene expression. For example, glucose ingestion during exercise may create an unusual situation in which genes involved in fat metabolism may be stimulated by exercise but inhibited by the preferential usage of CHO. Our laboratory (5) and others (15) have shown that a preexercise CHO load reduces fat availability to the muscle (secondary to insulin-mediated decrease in adipose tissue lipolysis), thus reducing the entry of long-chain FA in the mitochondria. Consistent with these data, after an intense exercise session to lower muscle glycogen concentrations, as little as 48 h of a high-CHO or a high-fat diet to either restore or maintain suppressed muscle glycogen resulted in coordinated alterations in genes encoding key proteins for either CHO or lipid metabolism (15). Only one study has addressed whether the proceeding diet influences gene expression in the recovery period after exercise. In this study, intense exercise and a 24-h dietary manipulation resulted in either low or high muscle glycogen levels. Low muscle glycogen levels were found to increase the transcriptional activation of a range of metabolic genes in the recovery period after exercise (15).

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genes involved in CHO metabolism. This is despite the widespread recommendations for athletes to ingest CHO-rich beverages during and immediately after exercise cessation to treat dehydration and restore glycogen levels. Accordingly, the present study examined the transient regulation of key metabolic genes during endurance exercise with or without glucose ingestion within the first few hours postexercise.

METHODS

Subjects. As previously described, seven healthy [22.7 ± 0.6 yr; body mass index: 23.8 ± 1.0 kg/m²; maximal \( V_O2 \text{max} \); 3.85 ± 0.21 l/min] untrained male volunteers participated in this study (36). None of the subjects participated in endurance sports, but all were moderately active. All subjects gave their written informed consent, and the study was approved by the Medical-ethical Committee of Maastricht University.

Experimental design. All participants were studied on two occasions in a blinded, randomized crossover design with either the water treatment within the first few hours postexercise.

RESULTS

Energy and substrate metabolism. As expected, blood glucose concentration decreased during the fasted state, relative to

Table 1. Gene primer and probe sequences

<table>
<thead>
<tr>
<th>Gene</th>
<th>Sense Primer (5’-3’)</th>
<th>Antisense Primer (5’-3’)</th>
<th>Probe (5’-FAM-BHQ1’3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyclin B</td>
<td>GGC ATG GAG GGC TTT GG</td>
<td>GCA CAT TCA GCA ATT ATC ATC</td>
<td>TCG AGG AAT GGC AAC ACC AAC AAG A</td>
</tr>
<tr>
<td>CPT 1</td>
<td>GAG GCC TCA ATG ACC AGA ATG</td>
<td>CCT GCA TCC CTA GAA GAA</td>
<td>CAT GAC TCC CCT CTC CCC GG</td>
</tr>
<tr>
<td>( \beta )-HAD</td>
<td>TGG CTT CCC GGC TCC TTC TC</td>
<td>TCG AGG CCG TGG ACT ATT TCC</td>
<td>CAT CCA CAT ATG CAT CAA AGC A</td>
</tr>
<tr>
<td>CD36</td>
<td>AGT CAG TCG GAC ATG ATT AAT GGT</td>
<td>CTA GGA CAT CTC CTT TTC A</td>
<td>CAT AGT CCG CTT TCT TGG TT</td>
</tr>
<tr>
<td>AMPK( \alpha_2 )</td>
<td>AAG TCG AGA GAT CCA TTA ACT TTG</td>
<td>GGT CAA ACT GAA GAC AAT AGT CTT</td>
<td>TGG GTC TCT TGA CCG TGG TTT GAC</td>
</tr>
<tr>
<td>AMPK( \gamma )</td>
<td>TGT GGA GCA TGT GT</td>
<td>ACC CGG AGC AGC TGA GC</td>
<td>TGG ACT CTT GCC CTT GCC CAA AAG ATG</td>
</tr>
<tr>
<td>ACC2</td>
<td>ACC ATC TTC GAC TCG ACT TCT ACT</td>
<td>CCG ATC GGC AGA AAG AA</td>
<td>CTC TCG TGG CTA GGG TGG TT</td>
</tr>
<tr>
<td>UCP3</td>
<td>CCG TCG AGA GAC AGA AA</td>
<td>AAT GGC AAC CTA AAC ACT TCG</td>
<td>ACG GCG CTA AGA TGG CCT</td>
</tr>
<tr>
<td>IR</td>
<td>CAA TGG GAT GGC TTA TTA CTA C</td>
<td>GCC AGT AAT AGC CTA CAA G</td>
<td>TCA CTA TGC TTA CAC CTT</td>
</tr>
<tr>
<td>IRS-1</td>
<td>GGC ATG GGC TTT GCC T</td>
<td>TAT AGC TGC TTA GCT TCT CAC C</td>
<td>CTT CCT CAC CAG TCG GCA TCC T</td>
</tr>
<tr>
<td>IRS-2</td>
<td>GRC ACC ATG GCC TGG T</td>
<td>CAC CTC GAT GAA GAA GAA GGA G</td>
<td>TCG GAG CAG CGC TGG GTG AC</td>
</tr>
<tr>
<td>PI 3-kinase (p38)</td>
<td>AGC AAC CTG GCA GAA TTA CAG</td>
<td>AGA GAA TGT AGG TCG AGG AGG AA</td>
<td>AGC TTC TTT ATG TGA ATC CAC CTT CCG TGG</td>
</tr>
<tr>
<td>GLUT4</td>
<td>CCT CTT ATG AAA TGC TCA TCG TTG</td>
<td>CCA COT AGC TGG GCA CCA</td>
<td>CCA TGA TCT CAT GGG GCA TAC T</td>
</tr>
<tr>
<td>PDK-4</td>
<td>GAA GAT ATT TGC CCG CTT TAG</td>
<td>AAA CCA GCC AAA GGA GGA TTT</td>
<td>ACT CCA TGA CAC CAA CCC TGA</td>
</tr>
</tbody>
</table>

CPT 1, carnitine palmitoyltransferase-1 (muscle isoform); \( \beta \)-HAD, \( \beta \)-hydroxacyl-CoA dehydrogenase; CD36, fatty acid transport protein; AMPK\( \alpha_2 \), 5-AMP-activated protein kinase \( \alpha_2 \)-subunit; AMPK\( \gamma \), 5-AMP-activated protein kinase \( \gamma_2 \)-subunit; ACC2, acetyl-CoA carboxylase 2; UCP3, uncoupling protein-3; IR, insulin receptor; IRS-1, insulin receptor substrate-1; IRS-2, insulin receptor substrate-2; PI 3-kinase (p38), p38 subunit of phosphatidylinositol 3-kinase; GLUT4, glucose transporter 4; PDK-4, pyruvate dehydrogenase kinase-4.
the fed state ($P < 0.01$; Fig. 1A), and plasma FFA concentration increased during exercise in the fasted state and remained unchanged after glucose ingestion ($P < 0.01$; Fig. 1B). There was no treatment effect on energy expenditure (Fig. 1C), whereas respiratory quotient (RQ) was lower in the fasted state vs. glucose feeding ($P < 0.01$; Fig. 1D). Accordingly, fat oxidation was 37% higher in the fasted state relative to the glucose trial (data not shown; see Ref. 36).

**mRNA quantification.** The effect of short-term moderate-intensity exercise with or without glucose consumption on the mRNA level of genes involved in CHO metabolism is shown in Fig. 2, whereas the effect on genes involved in fat metabolism is shown in Fig. 3.

**CHO metabolism gene expression.** Exercise with glucose ingestion did not alter the mRNA expression of the insulin receptor (IR; data not shown), insulin receptor substrate-2, (IRS-2; data not shown), IRS-1, and PI 3-kinase over time compared with exercise in the fasted state (Fig. 2). However, exercise did increase PI 3-kinase mRNA expression 4 h after exercise in either treatment group (Fig. 2B).

![Fig. 1. Blood glucose (A), plasma levels of free fatty acid (FFA; B), energy expenditure (C), and respiratory quotient (RQ; D) during and after 2 h of cycling at 50% maximal power output ($W_{max}$), with (●) and without (●; fasted state) glucose ingestion. # $P < 0.05$ compared with fasting trial. CHO, carbohydrate feeding. Data are means ± SE.](image)

![Fig. 2. Skeletal muscle mRNA expression of the insulin receptor substrate-1 (IRS-1; A), phosphatidylinositol 3-kinase (PI3K; B), glucose transporter 4 (GLUT4; C), and pyruvate dehydrogenase kinase-4 (PDK-4; D) during and after 2 h of cycling at 50% $W_{max}$, with (open bars) and without (filled bars; fasted state) glucose ingestion. A repeated-measures ANOVA was performed to discriminate between differences due to the effects of glucose treatment and/or time. Values are means ± SE. *$P < 0.05$ compared with baseline. Significant treatment effect, *$P < 0.05$ and # $P < 0.01$.](image)
GLUT4, glucose feeding did blunt the significant increase in the expression level of GLUT4 that was observed after exercise in the fasted state (*P* < 0.05), indicating a treatment effect. Furthermore, glucose ingestion was associated with a time-by-treatment suppression of pyruvate dehydrogenase-4 (PDK-4) mRNA compared with fasting exercise (*P* < 0.01). Fat metabolism gene expression. Exercise with glucose ingestion caused a time-by-treatment suppression of CD36 (*P* < 0.05), CPT I (*P* < 0.05), UCP3 (*P* < 0.01), and 5′-AMP-activated protein kinase (AMPKα2) mRNA (*P* < 0.05) levels compared with the fasted state (Fig. 3). No exercise-diet interaction was observed for acetyl-CoA carboxylase 2 (ACC2), β-HAD, and AMPKα3 (data not shown).

**DISCUSSION**

During exercise and the subsequent recovery period, the type and quantity of fuel used depends on the interplay between the fuels available from the diet and storage depots, the intensity and duration of the activity, and the training status of the subject. Accordingly, it has long been known that a preexercise glucose load reduces fat oxidation during low- to moderate-intensity exercise (up to ~60% V̇O₂max; see Ref. 40). CHO feeding markedly influences circulating metabolites (increasing glucose concentrations and reducing FFA availability) and presumably changes the pattern of gene transcription. Several studies have shown that sustained training-induced cellular adaptation is the result of the cumulative effects of repeated exercise bouts. However, the initial signaling responses that lead to long-term adaptations can occur in response to each bout of exercise (12, 31). In this context, we examined the regulation of genes involved in CHO and fat metabolism in response to a single 2-h bout of moderate-intensity exercise and in the presence or absence of repeated glucose ingestion. Our first major finding was that glucose consumption lowered the mRNA expression of genes involved in FA transport and oxidation (CD36, UCP3, CPT I, and AMPKα2) and of PDK-4, a gene involved in the regulation of glycolysis. This treatment lowering of gene expression over “time” was associated with reduced FFA concentrations and an increase in CHO oxidation (higher RQ), albeit, at an exercise intensity normally favoring oxidation of lipids (40). These data suggest several important findings. Firstly, acute changes in whole body substrate flux favoring CHO metabolism can modify the expression level of genes involved in transport and oxidation of lipids immediately after exercise. Second, no time-by-treatment effect was observed in our set of CHO metabolism genes (IR, IRS-1/2, PI 3-kinase, and GLUT4), implying that an increased glucose flux during exercise does not upregulate genes involved in insulin signaling and is an effect inherent to the contracting muscle.

The mechanism by which consumption of CHO leads to a decrease in gene expression of fat metabolism during exercise is unclear; however, insulin may play a role. We have previously shown, in a similar experiment, that insulin levels remain elevated during exercise with glucose ingestion compared with exercise in the fasted state (5). Therefore, the elevated circulating insulin produced by the glucose load could have a negative feedback on gene expression. In support of this concept, Rome et al. (33) recently demonstrated that insulin acts on global gene expression by regulating the mRNA levels of genes involved in transcription, energy metabolism, and intracellular signaling. More specifically, insulin has also been
shown to suppress PDK-4 mRNA (21), which is consistent with the current findings.

Conversely, the reduced expression of lipid metabolism genes may have been due in part to suppressed lipolysis and a lowering of circulating FFA. In support of this mechanism, we have recently demonstrated that the administration of acipimox reduced both fat oxidation and UCP3 mRNA levels (13) by blocking lipolysis and reducing FFA plasma concentration. It is well established that FFAs, via their interaction with the peroxisome proliferator activator receptor (PPAR) family of nuclear hormone receptors, can regulate systemic FA metabolism via ligand-dependent transcriptional activation of target genes (20). For example, fasting increases both the lipid supply to oxidative tissue and the expression of both PDK-4 and UCP3 in the skeletal muscle of rats (11, 41) via an FFA-mediated activation of PPARα (46). Interestingly, in humans, the expression of muscle CPT I, the rate-limiting step in fat oxidation (23), and CD36, an important transporter of long-chain FA, is also regulated by PPARα (35). Importantly, in our study, increasing blood glucose concentrations during CHO ingestion was accompanied with a lowering of CD36, CPT I, and UCP3 mRNA over time and reduced lipid flux and oxidation, suggesting that a reduction in ligands for PPAR can reduce the expression of downstream targets.

The main function of PDK-4 is the suppression of glycolysis by phosphorylating and inactivating the pyruvate dehydrogenase complex (11). The activity of PDK-4 is regulated by glucose flux in the cell but may also be enhanced with increased lipid supply and utilization (11, 25). Consistent with these facts, in the present study, we observed an induction in PDK-4 transcription during the entire fasting trial that was associated with high rates of fat oxidation. Conversely, glucose feeding caused a highly significant time-by-treatment suppression of PDK-4 mRNA that was associated with increased CHO oxidation, as evidenced by an elevated RQ. These data are in agreement with previous studies that demonstrate that substrate availability has a profound effect on PDK-4 gene expression (29, 32). Recently, Arkinstall et al. (1) demonstrated that PDK-4 transcription is suppressed by 2 days of CHO feeding to replenish glycogen stores. Conversely, other studies have shown that glucose consumption is not sufficient to inhibit increased PDK-4 transcription during exercise (1, 30). This discrepancy is most likely the result of the timing of the meal ingestion. Several studies have demonstrated that a single preexercise glucose load causing hyperinsulinemia results in a rapid and sustained drop in blood glucose concentrations during submaximal exercise (6, 7). However, in this study, we provided a constant flux of ingested glucose that resulted in elevated plasma glucose concentration and oxidation during the entire glucose trial (Fig. 1A). Glycogen is also a known signaling molecule that can regulate gene transcription, although it is unlikely that it would have contributed to changes in PDK-4 mRNA expression in this current experimental paradigm. It was previously shown that the type of exercise trial used in this study does not alter glycogen oxidation (18). These data suggest that changes in PDK-4 transcription (or the subset of lipid metabolism genes examined in this study) can be repressed during exercise conditions favoring fat oxidation as a result of increased glucose flux and oxidation and are independent of muscle glycogen concentration.

Many of the adaptations taking place during exercise are proposed to involve AMPK, a member of a metabolite-sensing kinase family that functions as a metabolic “fuel gauge” in skeletal muscle (9). However, the independent effect of glucose supplementation on AMPK mRNA expression during exercise is unknown. During exercise, AMPK becomes activated in skeletal muscle in response to changes in cellular energy status (e.g., increased AMP-to-ATP and creatine-to-phosphocreatine ratios; see Ref. 44). In turn, AMPK can phosphorylate ACC2, which leads to the inhibition of ACC2 activity and a consequent reduction in the malonyl-CoA content, thereby derepressing CPT I activity and increasing skeletal muscle FA oxidation (44). Although we and others (24, 26) did not observe an upregulation of AMPKα2 mRNA with exercise in the fasted state, the reduced AMPKα2 mRNA expression observed in this study with glucose feeding and the suppression of fat metabolism genes in this condition is consistent with the fact that AMPK activate pathways involved in FA metabolism when cellular substrate levels decline (2). However, we acknowledge, the extent to which a protein and posttranslational modifications might be modified in response to an exercise-diet interaction cannot be predicted from an increase in mRNA level; however, it has previously been reported that the concentration of mRNA for genes encoding for substrate metabolism is accompanied by a concomitant increase in the cellular content of the transcribed protein (3, 29) and, presumably, function. In addition, without the inclusion of control subjects with rest ± fasting or glucose, it is not possible to attribute the alterations observed after glucose feeding to a modulation of CHO treatment only. Future studies should be aimed at examining this discrepancy.

Results from this study and others (12, 31) demonstrate an increase in GLUT4 mRNA and protein (8) expression after a single bout of moderate-intensity exercise. However, the increase in GLUT4 gene expression in the postexercise period was reduced during the glucose trial. To the best of our knowledge, this is the first study to demonstrate the acute reduction in GLUT4 gene expression in response to dietary manipulation. Recent data suggest that insulin is an important regulator of GLUT4 mRNA after exercise in rats (19). However, muscle contraction during exercise has an insulin-indepen-
dent effect on muscle glucose uptake (34). The two main mediators of this process are thought to involve muscle glyco-
gen content and AMPK activity, as well as several downstream kinases from AMPK, including the p38 mitogen-activated protein kinase (47) and the Ca²⁺-sensitive class of atypical protein kinase C (27). It has repeatedly been shown, both in vivo and in vitro, that glucose uptake increases when muscle glycogen is low (10, 45). In this context, the coordinated decrease in AMPKα2 and GLUT4 mRNA abundance might be expected to decrease protein expression and thereby provide a negative feedback that limits further storage of muscle glyco-
gen when glycogen concentrations and the glucose flux in the myocyte are high. This hypothesis fits well with data from the present study that demonstrate that glucose oxidation was elevated and PDK-4 and GLUT4 gene expression lowered during the postexercise period in the glucose trial.

In summary, we provide evidence that glucose ingestion during moderate-intensity exercise inhibits the expression of genes involved in the transport and oxidation of lipids (CD36, CPT I, UCP3, and AMPKα2) and downregulates PDK-4,
which is involved in glycolysis suppression. The change in mRNA expression was rapid (1–4 h) and occurred at an exercise intensity relying mostly on fat metabolism. Therefore, acute exercise with glucose ingestion does not result in adaptive changes in muscle that favor the capacity for carbohydrate oxidation/metabolism but rather suppresses the exercise-induced adaptive changes that would favor fat oxidative capacity.

ACKNOWLEDGMENTS

We thank Dr. David Cameron-Smith and Stacy Carling for critical comments on manuscript preparation.

REFERENCES


