Effect of chronic bradykinin administration on insulin action in an animal model of insulin resistance

ERIK J. HENRIKSEN,1 STEPHAN JACOB,2 DONOVAN L. FOGT,2 AND GUENTHER J. DIETZE2

1Muscle Metabolism Laboratory, Department of Physiology, University of Arizona College of Medicine, Tucson, Arizona 85721-0093; and 2Hypertension and Diabetes Research Unit, Max-Grundig-Klinik, 77815 Bühl, Germany

Henriksen, Erik J., Stephan Jacob, Donovan L. Fogt, and Guenther J. Dietze. Effect of chronic bradykinin administration on insulin action in an animal model of insulin resistance. Am. J. Physiol. 275 (Regulatory Integrative Comp. Physiol. 44): R40–R45, 1998.—The nonapeptide bradykinin (BK) has been implicated as the mediator of the beneficial effect of angiotensin-converting enzyme inhibitors on insulin-stimulated glucose transport in insulin-resistant skeletal muscle. In the present study, the effects of chronic in vivo BK treatment of obese Zucker (fa/fa) rats, a model of glucose intolerance and severe insulin resistance, on whole body glucose tolerance and skeletal muscle glucose transport activity stimulated by insulin or contractions were investigated. BK was administered subcutaneously (twice daily at 40 µg/kg body wt) for 14 consecutive days. Compared with a saline-treated obese group, the BK-treated obese animals had significantly (P < 0.05) lower fasting plasma levels of insulin (20%) and free fatty acids (26%), whereas plasma glucose was not different. During a 1-g/kg body wt oral glucose tolerance test, the glucose and insulin responses [incremental areas under the curve (AUC)] were 21 and 29% lower, respectively, in the BK-treated obese group. The glucose-insulin index, the product of the glucose and insulin AUCs and an indirect index of in vivo insulin action, was 52% lower in the BK-treated obese group compared with the obese control group. Moreover, 2-deoxyglucose uptake in the isolated epitrochlearis muscle stimulated by a maximally effective dose of insulin (2 mU/ml) was 52% greater in the BK-treated obese group. Contraction-stimulated (10 tetani) 2-deoxyglucose uptake was also enhanced by 35% as a result of the BK treatment. In conclusion, these findings indicate that in the severely insulin-resistant obese Zucker rat, chronic in vivo treatment with BK can significantly improve whole body glucose tolerance, possibly as a result of the enhanced insulin-stimulated skeletal muscle glucose transport activity observed in these animals.

The “insulin resistance syndrome” (8) or “syndrome X” (26) is a pathophysiological condition characterized by the clustering of several atherogenic risk factors, including hypertension, skeletal muscle insulin resistance, hyperinsulinemia, dyslipidemia, and central adiposity. Skeletal muscle insulin resistance and the resulting elevation in plasma insulin may be important factors in the etiology of this condition (8, 25, 26) and can themselves be considered cardiovascular disease risk factors (1, 20). A logical course of action in the treatment of this condition, therefore, would be one that enhances insulin action and lowers circulating insulin.

Chronic treatment with angiotensin-converting enzyme (ACE) inhibitors results not only in a lowering of blood pressure, but also improves insulin action on whole body and muscle glucose disposal in both animal model (17, 19, 22, 31) and clinical (13, 24, 25, 28, 30, 31, 34) investigations. In addition to inhibiting the conversion of angiotensin I to angiotensin II, treatment with ACE inhibitors, via inhibition of the kininase II reaction (10), increases the circulating level of the nonapeptide bradykinin (7, 31). An increasing body of evidence indicates that bradykinin may be involved in enhancing insulin action on skeletal muscle. For example, the direct arterial infusion of bradykinin into the human forearm causes an increase in skeletal muscle glucose uptake in the presence of insulin (9), and the acute administration of bradykinin to insulin-resistant, hyperglycemic rodents lowers blood glucose (23, 35). In addition, the in vitro administration of bradykinin within a specific concentration range increases glucose transport and metabolism in rat soleus muscle (22, 23) and myocardium (27). However, the effect of chronic in vivo bradykinin treatment on insulin action in an animal model of the insulin resistance syndrome has not yet been reported.

In this context, the present study was designed to characterize the effects of chronic (14 days) in vivo treatment with bradykinin on oral glucose tolerance, glycemia, insulinemia, lipidemia, and insulin-dependent and contraction-dependent skeletal muscle glucose transport activities in lean and obese Zucker rats, the latter being a well-established model of insulin resistance, hyperinsulinemia, and dyslipidemia.

METHODS

Animals and treatments. Female obese Zucker rats (Hsd/Ola:ZUCKER-fa; Harlan, Indianapolis, IN) and lean littermates (Fa−/−) were received at 6–7 wk of age and were housed two per cage in a temperature-controlled room (20–22°C) at the Central Animal Facility of the University of Arizona. A 12:12-h light-dark cycle was maintained, and animals had free access to water and chow (Purina, St. Louis, MO). All procedures described below were approved by the University of Arizona Animal Use and Care Committee. Starting at 8 wk of age, lean and obese animals received subcutaneous injection of either 0.9% saline (vehicle-treated controls) or bradykinin (B3259; Sigma Chemical, St. Louis, MO) twice daily at 40 µg/kg body wt for 14 consecutive days. This is an effective acute glucose-lowering bradykinin dose in...
Bradykinin and Muscle Glucose Transport

Lilly, Indianapolis, IN). The flasks were shaken in a Dubnoff mally effective concentration of pork insulin (2 mU/ml; Eli treatment on insulin action, one muscle from each animal glucose, 32 mM mannitol, and 0.1% BSA (radioimmunoassay vitro incubation. Epitrochlearis muscles were surgically removed and prepared for in pentobarbital sodium (Nembutal, 50 mg/kg ip). Both epitrochlearis muscles were initially incu- the previous 15 h, animals were deeply anesthetized with went an oral glucose tolerance test (OGTT) using a 1 g/kg (unpublished observations), it is unlikely that the effects on insulin action seen 20 h after the last chronic bradykinin treatment can be ascribed to a long-lasting acute effect of this last bradykinin administration, as bradykinin has a rela- tively short half-life (35).

Oral glucose tolerance tests. Animals were food-restricted (4 g of chow given at 5 PM, which was immediately consumed) the evening before the experiment. Between 8 and 10 AM, ~20 h after the most recent treatment, the animals underwent an oral glucose tolerance test (OGTT) using a 1 g/kg body wt glucose feeding by gavage (6). Blood was drawn from a cut at the tip of the tail at 0, 15, 30, and 60 min after the glucose feeding. This whole blood was thoroughly mixed with EDTA (18 mM final concentration) and centrifuged at 13,000 g to separate the plasma. Plasma samples were frozen at ~70°C and subsequently analyzed for glucose (Sigma), Insulin (Linco Research, St. Charles, MO), and free fatty acids (Wako, Richmond, VA). Immediately after the completion of the OGTT, all animals received 2 ml of sterile 0.9% saline subcutaneously to compensate for plasma loss, and vehicle or bradykinin treatments were resumed for 2 further days.

Glucose transport activity. At 8 AM, ~20 h after the final treatment and again having been restricted to 4 g of chow in the previous 15 h, animals were deeply anesthetized with pentobarbital sodium (Nembutal, 50 mg/kg ip). Both epitrochlearis muscles were surgically removed and prepared for in vitro incubation. Epitrochlearis muscles were initially incubated (without tension throughout) for 60 min in 3 ml of oxygenated Krebs-Henseleit buffer (KHB) containing 8 mM glucose, 32 mM mannitol, and 0.1% BSA (radioimmunoassay grade). In experiments investigating the effect of bradykinin treatment on insulin action, one muscle from each animal was incubated in the absence of insulin, while the contralateral muscle was incubated in medium containing a maximally effective concentration of pork insulin (2 mU/ml; Eli Lilly, Indianapolis, IN). The flasks were shaken in a Dubnoff incubator at 37°C and had a gas phase of 95% O2-5% CO2. Following the initial treatments, all muscles were rinsed for 10 min at 37°C in 3 ml of oxygenated KHB containing 40 mM mannitol, 0.1% BSA, and, if present previously, insulin. The muscles were then transferred to flasks containing 2 ml of oxygenated Krebs-Henseleit buffer (KHB) containing 8 mM glucose, 32 mM mannitol, and 0.1% BSA (radioimmunoassay grade). In experiments investigating the effect of bradykinin treatment on insulin action, one muscle from each animal was incubated in the absence of insulin, while the contralateral muscle was incubated in medium containing a maximally effective concentration of pork insulin (2 mU/ml; Eli Lilly, Indianapolis, IN). The flasks were shaken in a Dubnoff incubator at 37°C and had a gas phase of 95% O2-5% CO2. Following the initial treatments, all muscles were rinsed for 10 min at 37°C in 3 ml of oxygenated KHB containing 40 mM mannitol, 0.1% BSA, and, if present previously, insulin. The muscles were then transferred to flasks containing 2 ml of oxygenated KHB, 0.1% BSA, 1 mM 2-deoxy-[1,2-3H]glucose (300 mCi/ml) and 39 mM [U-14C]mannitol (0.8 mCi/ml) (ICN Radiochemicals, Irvine, CA), and insulin, if present previously. After this final 20-min incubation period at 37°C, muscles were trimmed of fat, extraneous muscle, and connective tissue; frozen between aluminum blocks cooled to the temperature of liquid N2; and weighed. The whole heart was also removed, frozen, and weighed.

The frozen incubated muscles were divided into two pieces, and each piece was weighed. One piece was dissolved in 0.5 ml of 0.5 N NaOH, and used to determine glucose transport activity, as described by Henriksen and Ritter (18). Incubated epitrochlearis muscles of this size remain metabolically viable (14), and this method for assessing glucose transport activity in the epitrochlearis muscles has been validated (15). The remaining piece was used in biochemical assays, as described below.

Electrical stimulation of muscle contractions. In experiments investigating the effect of bradykinin treatment on contraction-stimulated glucose transport, one muscle from each animal served as an unstimulated control, and the contralateral muscle underwent the electrical stimulation protocol. For electrical stimulation of muscle contractions, the distal end of the epitrochlearis muscle was attached to a vertical Lucite rod containing two platinum electrodes. The proximal end was clipped to a jeweler’s chain and attached to a Grass model FTO3 isometric force transducer. The mounted muscle was immersed in 25 ml KHB containing 8 mM glucose and 32 mM mannitol and continuously oxygenated with 95% O2-5% CO2 at 37°C. The muscle was stimulated with supramaximal square wave pulses of 0.2 ms duration using a Grass S11 stimulator. Ten tetanic contractions were produced by stimulating at 50 Hz for 10 s at a rate of 1 contraction/min. Glucose transport activity was then assessed as described above.

Muscle biochemistry. The remaining muscle piece was homogenized in 40 volumes of ice-cold buffer containing 20 mM HEPES (pH 7.4), 1 mM EDTA, and 250 mM sucrose. The homogenates were then frozen at ~70°C until analysis of total protein concentration (bicinchoninic acid method, Sigma), GLUT-4 protein (16), total hexokinase activity (33), and citrate synthase activity (29).

Statistical analysis. All data are presented as means ± SE. The significance of differences between two groups was determined by an unpaired Student’s t-test, whereas the significance of differences between multiple groups was assessed by analysis of variance with Duncan’s multiple-range post hoc tests. Statistical significance was set at the 0.05 probability level.

RESULTS

Plasma glucose, insulin, and free fatty acids. Final body weights, epitrochlearis muscle and heart wet weights, and plasma glucose values within the lean and obese groups were not significantly affected by the chronic bradykinin treatment (Table 1). In the lean group, chronic administration of bradykinin did not significantly affect plasma insulin or free fatty acids. In contrast, the chronic administration of bradykinin to obese animals resulted in a 20% decrease (P < 0.05) in plasma insulin and a 26% decline (P < 0.05) in plasma free fatty acids relative to the obese vehicle-treated control group.

OGTT responses. In the lean animals, treatment with bradykinin had no significant effect on disposal of the

<table>
<thead>
<tr>
<th>Group</th>
<th>Body Wt, g</th>
<th>Epitrochlearis Wt, mg</th>
<th>Heart Wt, mg</th>
<th>Glucose, mg/dl</th>
<th>Insulin, µU/ml</th>
<th>Free Fatty Acids, mM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lean vehicle treated</td>
<td>165 ± 2</td>
<td>35.6 ± 1.3</td>
<td>479 ± 14</td>
<td>130 ± 11</td>
<td>14 ± 1</td>
<td>0.52 ± 0.05</td>
</tr>
<tr>
<td>Lean chronic bradykinin treated</td>
<td>159 ± 2</td>
<td>31.4 ± 0.9</td>
<td>472 ± 5</td>
<td>125 ± 5</td>
<td>12 ± 1</td>
<td>0.52 ± 0.05</td>
</tr>
<tr>
<td>Obese vehicle treated</td>
<td>359 ± 7*</td>
<td>36.2 ± 0.6</td>
<td>694 ± 10</td>
<td>147 ± 5</td>
<td>183 ± 19*</td>
<td>1.53 ± 0.13*</td>
</tr>
<tr>
<td>Obese chronic bradykinin treated</td>
<td>360 ± 8*</td>
<td>36.6 ± 1.3</td>
<td>672 ± 6</td>
<td>136 ± 5</td>
<td>147 ± 13†</td>
<td>1.13 ± 0.05†</td>
</tr>
</tbody>
</table>

Values are means ± SE for 5–10 animals (lean) or 10–15 animals (obese) per group. Bradykinin was administered subcutaneously twice daily at 40 µg/kg for 14 days. *P < 0.05 vs. lean vehicle-treated animals; †P < 0.05 vs. obese vehicle-treated animals.
glucose load during the OGTT (Fig. 1, top left; Fig. 2A, left). In addition, the insulin response to this glucose load was not substantially affected by chronic bradykinin treatment in the lean animals (Fig. 1, bottom left; Fig. 2A, middle). Chronic treatment of the obese animals with bradykinin resulted in uniformly lower (P < 0.05) plasma glucose values during the OGTT (Fig. 1, top right), and the incremental area under the glucose curve was 21% smaller (P < 0.05) compared with obese control values (Fig. 2B, left). Moreover, insulin values in plasma from the bradykinin-treated obese animals were also 20–31% less (P < 0.05) during the OGTT (Fig. 1, bottom right), and the incremental area under the insulin curve was 29% smaller (P < 0.05) in this group compared with obese controls (Fig. 2B, middle). The glucose-insulin index, the product of the glucose and insulin areas under the curve and an indirect index of in vivo peripheral insulin action (6), was 52% lower (P < 0.05) in the bradykinin-treated obese group compared with the obese control group (Fig. 2B, right).

Muscle glucose transport activity. No alteration in basal 2-deoxyglucose uptake due to prior chronic bradykinin treatment was observed in epitrochlearis muscles from either the lean animals (140 ± 19 vs. 160 ± 8 pmol·mg muscle⁻¹·20 min⁻¹) or the obese animals (123 ± 7 vs. 110 ± 11 pmol·mg muscle⁻¹·20 min⁻¹). Insulin-mediated (Fig. 3A) and contraction-mediated (Fig. 4A) increases in 2-deoxyglucose uptake above basal in the epitrochlearis muscle were not significantly different in the lean bradykinin-treated group compared with the lean control group. Following chronic administration of bradykinin to obese animals, insulin action on muscle glucose transport activity was 52% greater (P < 0.05) relative to the obese control group (Fig. 3B). In addition, glucose transport activity stimulated by muscle contractions was 35% greater (P < 0.05) in the bradykinin-treated obese group compared with obese controls.

Muscle biochemistry. There were no changes induced by bradykinin treatment of lean or obese animals in the epitrochlearis muscle activities for total hexokinase and citrate synthase, nor were total homogenate GLUT-4 protein levels altered by this intervention in epitrochlearis muscle from lean or obese animals (data not shown).
A beneficial effect of chronic treatment with bradykinin for this process (Fig. 4). It is noteworthy that glucose transport but also the contraction-dependent chronically bradykinin administration enhances not only stimulated insulin secretion (Figs. 1 and 2), and enhanced insulin action on glucose disposal at both the whole body (Fig. 2) and skeletal muscle (Fig. 3) levels. In addition, we have presented the novel finding that enhanced insulin action on glucose disposal at the isolated epitrochlearis muscles from vehicle-treated (open bars) and bradykinin-treated (solid bars) animals. Data are means ± SE for 5 animals per group. *P < 0.05 vs. vehicle-treated group.

**DISCUSSION**

In the present investigation, we have demonstrated for the first time that chronic administration of the nonapeptide bradykinin can ameliorate several metabolic abnormalities present in the obese Zucker rat. These beneficial effects of bradykinin treatment include significant reductions in hyperinsulinemia and elevated plasma free fatty acids (Table 1), improved glucose tolerance (Figs. 1 and 2), decreased glucose-stimulated insulin secretion (Figs. 1 and 2), and enhanced insulin action on glucose disposal at both the whole body (Fig. 2) and skeletal muscle (Fig. 3) levels. In addition, we have presented the novel finding that chronic bradykinin administration enhances not only the insulin-dependent pathway for skeletal muscle glucose transport but also the contraction-dependent pathway for this process (Fig. 4). It is noteworthy that the beneficial effects of chronic treatment with bradykinin were observed only in the obese animals and not in the lean animals. These findings indicate that treatment with bradykinin overcomes a defect specific to the insulin-resistant animal. Although this specific defect remains unclear, it may involve systemic and/or local kallikrein-kinin systems.

Several animal model and human clinical investigations have demonstrated that chronic administration of ACE inhibitors can improve insulin-stimulated whole body and skeletal muscle glucose disposal in insulin-resistant subjects (13, 17, 19, 22, 24, 25, 28, 30, 31, 34). One contention from these investigations has been that the elevation in circulating bradykinin levels, resulting from the inhibition of bradykinin degradation (10), underlies the beneficial metabolic effects of ACE inhibitors (6, 17, 31). The present investigation, in which bradykinin was directly administered to insulin-resistant rats, supports this hypothesis that bradykinin can modulate the effect of insulin to stimulate skeletal muscle glucose transport and improve whole body glucose tolerance.

Additional evidence in the scientific literature supports a role of kinins, such as bradykinin or one of its metabolic products, in the regulation of insulin-dependent skeletal muscle glucose transport. For example, Wicklmayr and Dietze (35) showed that bradykinin, provided with an otherwise ineffective dose of insulin, had a marked blood glucose-lowering effect in alloxan-diabetic rats. Henriksen and Jacob (17) showed that acute and chronic oral treatment with the ACE inhibitor captopril causes a significant improvement in insulin-mediated glucose transport activity in skeletal muscle. Moreover, this acute ACE inhibitor-induced improvement in insulin action could be completely prevented by pretreatment with HOE-140, a selective B2-bradykinin receptor antagonist that blocks the formation and metabolism of bradykinin. Similar findings have been reported by Uehara et al. (31) using a diabetic dog model. Importantly, it has been shown recently that bradykinin B2 receptors are present in the sarcolemmal membrane of skeletal muscle (12), indicating that bradykinin can act directly on skeletal muscle. Indeed, several studies have demonstrated that direct bradykinin administration can improve insulin action on glucose uptake by muscle (9, 22, 23), although this is not a uniform finding (5).

Although the mechanism of action of bradykinin on muscle glucose transport is not directly addressed in the present study, several possibilities exist. Stimulation of the translocation of the glucose transporter isoform GLUT-4 is defective in muscle from the obese Zucker rat (11, 21), and recent investigations indicate that bradykinin administration can stimulate GLUT-4 translocation in skeletal muscle (32) and cardiac muscle (27). This stimulation of GLUT-4 translocation in muscle by bradykinin may be attributed to the interactions of the bradykinin and insulin intracellular signaling pathways. Carvalho et al. (3) recently demonstrated in insulin-resistant skeletal muscle from aged rats that bradykinin can enhance insulin-induced phosphorylation of insulin receptors and insulin receptor sub-

---

**Fig. 3.** Effect of chronic treatment with bradykinin on insulin-mediated skeletal muscle glucose transport activity in lean (A) and obese (B) Zucker rats. Net increase in 2-deoxyglucose uptake due to insulin was assessed in the isolated epitrochlearis muscles from vehicle-treated (open bars) and bradykinin-treated (solid bars) animals. Data are means ± SE for 5 animals per group. *P < 0.05 vs. vehicle-treated group.

**Fig. 4.** Effect of chronic treatment with bradykinin on contraction-mediated skeletal muscle glucose transport activity in lean (A) and obese (B) Zucker rats. Net increase in 2-deoxyglucose uptake due to contractions was assessed in the isolated epitrochlearis muscles from vehicle-treated (open bars) and bradykinin-treated (solid bars) animals. Data are means ± SE for 5 animals per group. *P < 0.05 vs. vehicle-treated group.
mediated glucose transport activity in skeletal muscle.

that bradykinin treatment can increase contraction-
glucose transport. In addition, we have demonstrated
and enhanced glucose tolerance and insulin action on
reductions in plasma insulin and free fatty acid levels
about significant metabolic improvements, including
insulin resistance, hyperinsulinemia, glucose intoler-
tance.

We have found previously that chronic administra-
tion of the ACE inhibitor trandolapril is associated with
increased muscle levels of GLUT-4 protein and hexoki-
ase activity. These findings support the possibility that the
increase in insulin action seen with chronic bradykinin
treatment was secondary to the reduction in plasma
free fatty acids elicited by this intervention.

We have found previously that chronic administra-
tion of the ACE inhibitor trandolapril is associated with
increased muscle levels of GLUT-4 protein and hexoki-

REFERENCES

1. Alberti, K. G. The clinical implications of impaired glucose
2. Boden, G. Role of fatty acids in the pathogenesis of insulin
Velloso, and M. J. A. Saad. Effect of captopril, losartan, and
bradykinin on early steps of insulin action. Diabetes 46: 1950–
4. Cheatham, B., and C. R. Kahn. Insulin action and the insulin
Bradykinin does not mediate activation of glucose transport by
Insulin resistance of obese Zucker rats exercise trained at two
difference intensities. Am. J. Physiol. 261 (Endocrinol. Metab.
7. Decarle, A., A. Adam, and R. Couture. Effects of captopril and
Icatibant on bradykinin (BK) and des [Arg9] BK in carrageenan-
multifaceted syndrome responsible for NIDDM, obesity, hyperten-
sion, dyslipidemia, and atherosclerotic cardiovascular disease.
Henriksen. Potential role of bradykinin in forearm muscle
10. Erdös, E. Angiotensin I converting enzyme. Circ. Res. 36:
and E. J. Henriksen. Effects of captopril and Icatibant on bradykinin
and E. J. Henriksen. Effects of captopril and Icatibant on bradykinin
and E. J. Henriksen. Effects of captopril and Icatibant on bradykinin
and E. J. Henriksen. Effects of captopril and Icatibant on bradykinin
and E. J. Henriksen. Effects of captopril and Icatibant on bradykinin
and E. J. Henriksen. Effects of captopril and Icatibant on bradykinin


