Strength training increases insulin action in healthy 50- to 65-yr-old men

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Division of Gerontology, Department of Medicine, University of Maryland at Baltimore, and Baltimore Geriatric Research, Education and Clinical Center, Baltimore Veterans Affairs Medical Center, Baltimore 21201, and Departments of Kinesiology and of Human Nutrition and Food Systems, University of Maryland, College Park, Maryland 21218

Miller, John P., Richard E. Pratley, Andrew P. Goldberg, Patricia Gordon, Michelle Rubin, Margarita S. Treuth, Alice S. Ryan, and Ben F. Hurley. Strength training increases insulin action in healthy 50- to 65-yr-old men. J. Appl. Physiol. 77(3): 1122–127, 1994.—The insulin resistance associated with aging may be due, in part, to reduced levels of physical activity in the elderly. We hypothesized that strength training increases insulin action in older individuals. To test this hypothesis, 11 healthy men 50–65 yr old [mean 58 ± 1 (SE) yr] underwent a two-step hyperinsulinemic-euglycemic glucose clamp with concurrent indirect calorimetry and an oral insulin tolerance test (OGTT) before and after 16 wk of strength training. The training program increased overall strength by 47% (P < 0.001). Fat free mass (FFM; measured by hydrodensitometry) increased (62.4 ± 2.1 vs. 63.6 ± 2.1 kg; P < 0.05) and body fat decreased (27.2 ± 1.8 vs. 26.6 ± 1.9%; P < 0.001) with training. Fasting plasma glucose levels and glucose levels during the OGTT were not significantly lower after training. In contrast, fasting plasma insulin levels decreased (85 ± 25 vs. 55 ± 10 μu/ml, P < 0.05) and insulin levels decreased (P < 0.05, analysis of variance) during the OGTT. Glucose infusion rates during the hyperinsulinemic-euglycemic glucose clamp increased 24% (13.5 ± 1.7 vs. 16.7 ± 2.2 μu/m kg FFM⁻¹·min⁻¹; P < 0.05) during the low (20 μU·m²·min⁻¹) insulin infusion and increased 22% (55.7 ± 3.9 vs. 67.7 ± 3.0 μu/m kg FFM⁻¹·min⁻¹; P < 0.05) during the high (100 μU·m²·min⁻¹) insulin infusion. These increases were accompanied by a 40% increase (n = 7; P < 0.05) in nonoxidative glucose metabolism during the high insulin infusion. These results demonstrate that strength training increases insulin action and lowers plasma insulin levels in middle-aged and older men.

exercise; aging; glucose tolerance; body composition; weight lifting

THE INSULIN RESISTANCE associated with aging (5, 10, 25) may contribute to the high prevalence of impaired glucose tolerance and non-insulin-dependent diabetes mellitus in the elderly (13). Although age related, the impairment in insulin action in older individuals may not be primarily due to the aging process per se. Other factors such as physical inactivity and obesity are associated with insulin resistance (3), are more common in older individuals (11), and thus may contribute to the apparent decrease in insulin sensitivity that can be demonstrated even in otherwise healthy older individuals (3, 5, 10, 25).

To further understand the contribution of decreased levels of physical activity to the age-associated decline in insulin sensitivity, a number of recent investigations have examined the effects of exercise training in older individuals. Most studies to date have focused on aerobic exercise training, which increases insulin action, improves glucose tolerance, and decreases hyperinsulinemia in older individuals (18, 19, 28). However, because isometric contractions produce insulin-like effects on glucose uptake in isolated muscle (15), we hypothesized that strength training also increases insulin action in older individuals. Recent reports from our laboratory (26) and others (4, 29) provide some support for this hypothesis. Insulin responses to an oral glucose challenge are lower in both younger (4, 23) and older (4, 26) individuals after strength training, and, in some cases, glucose tolerance is improved as well (26). Although these findings suggest that strength training improves insulin action, this aspect was not directly measured in those studies. Thus, the purpose of the present investigation was to determine the effects of strength training on in vivo insulin action in middle-aged and older individuals.

METHODS

Subjects. Healthy nonsmoking 50- to 65-yr-old men were recruited to take part in this study. All subjects provided written informed consent according to the guidelines of the Institutional Review Boards of the University of Maryland and Francis Scott Key Medical Center before participation. None of the subjects exercised regularly, and all had been weight stable (±2.5 kg) for at least 6 mo before enrollment. Subjects underwent a thorough medical screening including a history and physical examination, a fasting blood profile, a graded exercise treadmill test, and a 2-h oral glucose tolerance test (OGTT) before entering the study. Individuals with significant abnormalities (including diabetes or other endocrine disorders, hypertension, evidence of cardiovascular disease, and orthopedic limitations) on screening were excluded. Eleven men, ranging in age from 50 to 63 yr [mean 58 ± 1 yr (SE)], entered the study.

Body composition. Body mass index was calculated by dividing weight by height squared (in kg/m²). Body density was determined by hydrostatic weighing and was corrected for residual lung volume, which was measured by the closed-circuit oxygen dilution method (29) using a mass spectrometer (model 2000, Airspec, Kent, UK). Body fat and fat free mass (FFM) were calculated from body density values (2). The waist-to-hip ratio, an index of the pattern of regional fat distribution, was calculated by dividing the minimal circumference of the abdomen by the circumference of the buttocks at the maximal gluteal protuberance.

Maximal aerobic power. Maximal oxygen consumption (VO₂ max) was determined during a treadmill test to subjective exhaustion as previously described (20). Expired air was collected in meteorological balloons at 1-min intervals during exercise. Fractional concentrations of oxygen and carbon dioxide in the expired gases were measured by mass spectrometry (model 2000, Airspec), and gas volumes were measured with a 120 liter Tissot spirometer. To establish that a true VO₂ max was obtained, at least two of the following three criteria were met.
for all VO_{2\,\text{max}} tests: 1) a plateau (\(-2 \, \text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}\) increase) in oxygen uptake with increasing workload, 2) a respiratory quotient of \(>1.10\), and 3) a heart rate within 10 beats/min of predicted maximum.

Dietary control. Subjects met individually with a nutritionist who instructed them in a diet that followed American Heart Association recommendations (1), and the subjects were weight stable on this diet for 6 wk before initial testing. They were instructed to maintain this dietary pattern as well as their baseline body weight during training. Compliance was monitored by analyzing 7-day food records before and after training and 24-h dietary recalls during the training phase (Nutritionist III, Silverton, OR). In addition, weekly weights were reviewed. All subjects were provided isocaloric weight-maintaining diets for 3 days before the hyperinsulinemic-euglycemic glucose clamp and for an additional 2 days before the OGTT. These diets, which were based on calculated energy requirements and 7-day food records, also followed American Heart Association recommendations (1) and provided \(50-55\%\) of calories as carbohydrate, 15-20\% as protein, and 30\% as fat. All metabolic testing was performed in the morning after a 12-h overnight fast. Studies conducted after the strength-training intervention were performed 22-24 h after the last exercise session.

OGTT. After two baseline blood samples 10 min apart were obtained for measurement of glucose and insulin, subjects drank a lemon-flavored solution containing 40 g glucose/m² body surface area. Blood samples were collected at 30-min intervals for an additional 2 h to determine glucose and insulin responses. Plasma glucose levels were measured using the glucose oxidase method (Yellow Springs Instruments, Yellow Springs, OH). Aliquots of plasma were frozen at \(-70^\circ\text{C}\) until measurement of insulin levels by radioimmunoassay (31). Samples obtained at baseline and after training were measured in a single insulin assay to eliminate interassay variation. The intra-assay coefficient of variation for this assay is 8\%. Mean values of the fasting glucose and insulin samples were used in subsequent statistical analyses.

Hyperinsulinemic-euglycemic glucose clamp. Insulin action was measured using a two-step modification of the hyperinsulinemic-euglycemic glucose clamp technique of DeFronzo et al. (7). Briefly, an intravenous catheter was inserted into an antecubital vein for infusion of insulin, glucose, and potassium. A second catheter was inserted into a dorsal hand vein for blood sampling. The hand was then placed in a warming box thermostatically controlled at 70°C to arterialize the blood and was allowed to equilibrate for 30 min before baseline samples for glucose and insulin were obtained. Insulin (Humulin-R, Eli Lilly, Indianapolis, IN) was administered as a primed continuous infusion at a rate of 20 \(\mu\text{U} \cdot \text{m}^{-2} \cdot \text{min}^{-1}\) for 90 min. This infusion was immediately followed by a second primed continuous infusion of insulin at a rate of 100 \(\mu\text{U} \cdot \text{m}^{-2} \cdot \text{min}^{-1}\) for an additional 90 min. Potassium chloride was simultaneously infused at a rate of 4 mmol/h to prevent hypokalemia. Plasma glucose levels were measured (Beckman Instruments, Fullerton, CA) at 5-min intervals during the clamp and were maintained at basal levels with a variable infusion of 20\% glucose, which was adjusted according to a computerized algorithm. Samples were obtained at 10-min intervals during the clamps for subsequent measurement of plasma insulin by radioimmunoassay (31). The higher insulin infusion was not completed in one subject after training because of technical difficulties.

Calculations. Mean glucose infusion rates (GIR) were calculated from minutes 60 to 90 of the 20 \(\mu\text{U} \cdot \text{m}^{-2} \cdot \text{min}^{-1}\) insulin infusion and from minutes 150 to 180 of the 100 \(\mu\text{U} \cdot \text{m}^{-2} \cdot \text{min}^{-1}\) insulin infusion. Mean plasma insulin levels were also calculated during these intervals. On the basis of earlier reports (10), hepatic glucose output is \(75\%\) suppressed during the low insulin infusion. Thus, GIR at this level of hyperinsulinemia represents the net effect of insulin on increasing insulin-mediated glucose uptake and suppressing hepatic glucose output. However, during the high insulin infusion hepatic glucose output should be almost completely suppressed in these healthy subjects. Therefore, at the high dose the GIR closely approximates the rate of tissue glucose disposal. Rates of glucose oxidation were calculated from measurements of oxygen consumption and carbon dioxide production with use of standard equations (9) and estimates of protein oxidation derived from 24-h urine urea nitrogen measurements obtained 1 day before the clamp. Nonoxidative glucose metabolism was calculated as the difference between total glucose disposal and glucose oxidation during the high insulin infusion. Because total glucose disposal cannot be approximated by GIR during the low insulin infusion, nonoxidative glucose disposal was not calculated at this dose.

Strength testing and training. Strength training and testing were performed on Keiser K-300 pneumatic variable-resistance machines. Subjects were familiarized with the equipment during at least four low-intensity exercise sessions before initial strength testing. Strength, indexed as the three repetition maximum (3 RM), was measured in six major muscle groups (leg press, leg extension, chest press, latissimus pull down, upper back row, and military press) before and after training.

Training sessions began with a 3-min warm-up period of low-intensity cycling followed by 10 min of static stretching exercises. The strength-training program consisted of the following 14 exercises: seated leg press, seated chest press, leg curl, latissimus pull down, leg extension, military press, hip abduction, hip adduction, upper back row, seated triceps extension, lower back, abdominal crunch, seated dumbbell curls, and supine abdominal crunches. The first three to four repetitions of each exercise were performed at \(>90\%\) of the 3 RM, after which resistance was gradually reduced without interruption of the normal cadence of exercise to permit subjects to complete 10 repetitions. A 1- to 2-min rest was allowed between exercises. One set of all exercises was performed in each session except for the lower body exercises, which were repeated at the end of the first circuit. Each training session lasted \(-1\) h. Subjects trained three times a week for 16 wk.

Statistical analyses. All data were analyzed with commercial statistical software packages (SAS, Cary, NC, and Statview II, Abacus Concepts, Berkeley, CA). Plasma insulin levels from the OGTT were log transformed to yield a normal distribution before parametric analyses. All other data were normally distributed. The effects of strength training on the major dependent variables were tested with paired t tests. The effects of training on glucose and insulin responses to the OGTT and glucose oxidation during the clamp were tested with repeated-measures analysis of variance models. \(P < 0.05\) was considered significant. Values are expressed as means \(\pm SE\).

RESULTS

Strength and body composition. The strength-training program was well tolerated. Attendance at scheduled
TABLE 1. Strength (3 RM values) before and after strength training

<table>
<thead>
<tr>
<th></th>
<th>Before Training</th>
<th>After Training</th>
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<tbody>
<tr>
<td>Upper body</td>
<td>162±8</td>
<td>296±11*</td>
</tr>
<tr>
<td>Lower body</td>
<td>413±26</td>
<td>560±57*</td>
</tr>
<tr>
<td>Total</td>
<td>575±30</td>
<td>846±42*</td>
</tr>
</tbody>
</table>

Values are means ± SE in kg. 3 RM, 3 repetition maximum. Upper body exercises include chest press, back row, shoulder press, and lateral-simps pull down; lower body exercises include leg press and leg extension; and total is sum of upper and lower body exercises. * P < 0.001.

Strength training sessions was >95%, and all of the subjects completed the intervention. Training resulted in substantial increases in strength in both arms and legs (Table 1). Upper body strength (sum of 3 RM of 4 upper body exercises) increased 64% (P < 0.001), and lower body strength (sum of 3 RM of 2 lower body exercises) increased 40% (P < 0.001). Overall strength (total 3 RM) increased 47% (P < 0.001).

Strength training increased FFM by a mean of 1.2 kg (P < 0.05, Table 2) and decreased body fat from 27.2 to 25.6% (P < 0.001) but did not significantly change body mass. There were no significant changes in VO2max or in the pattern of regional body fat distribution, indexed by the waist-to-hip ratio, with strength training (Table 2).

Analysis of food records indicated that subjects maintained the prescribed dietary pattern before, during, and after the training program. There were no significant differences in total energy consumed or percentage of calories derived from carbohydrate, fat, or protein with training (Table 3).

Glucose tolerance. At baseline, eight subjects had normal glucose tolerance tests and three were nondiagnostic (24). None of the subjects was impaired or diabetic. After training, all subjects were normal. However, in the group as a whole, strength training did not significantly lower fasting plasma glucose levels (5.3 ± 0.2 vs. 5.1 ± 0.1 mmol/l; NS) or glucose levels during the OGTT (F = 2.0, NS; Fig. 1). In contrast, both fasting plasma insulin levels (85 ± 25 vs. 55 ± 10 pmol/l; P < 0.05) and insulin levels during the OGTT were significantly lower after strength training (F = 4.9, P < 0.05; Fig. 2).

Insulin action. Mean plasma glucose levels during the hyperinsulinemic-euglycemic glucose clamps were comparable before and after training (4.9 ± 0.3 vs. 5.1 ± 0.2 mmol/l; NS). Plasma insulin concentrations also were similar before and after training during both the low insulin infusion (320 ± 25 vs. 335 ± 20 pmol/l; NS) and the high insulin infusion (1,705 ± 155 vs. 1,660 ± 95 pmol/l; NS; Fig. 3).

The mean GIR necessary to maintain euglycemia was higher after strength training at both physiological and supraphysiological levels of hyperinsulinemia (Fig. 4). During the 20 mU·m−2·min−1 insulin infusion the mean GIR was 24% higher (13.5 ± 1.7 vs. 16.7 ± 2.2 μmol·kg FFM−1·min−1, P < 0.05), and during the 100 mU·m−2·min−1 insulin infusion the mean GIR was 22% higher (55.7 ± 3.3 vs. 67.7 ± 3.9 μmol·kg FFM−1·min−1; P < 0.05). Nine of 11 subjects showed improvement at the lower insulin dose, and 9 of 10 subjects showed improvement at the higher insulin dose.

Basal rates of glucose oxidation measured by indirect calorimetry were not significantly different after strength training (6.9 ± 2.7 vs. 8.5 ± 3.3 μmol·kg FFM−1·min−1, NS). Glucose oxidation increased from the low dose to the high dose of insulin infusion (F = 19.4, P < 0.001) from 15.3 ± 2.9 to 21.7 ± 2.0 μmol·kg FFM−1·min−1 before training and from 19.8 ± 2.1 to 24.5 ± 1.6 μmol·kg FFM−1·min−1 after training, but there was no effect of training (F = 1.7, NS). Nonoxidative glucose disposal during the 100 mU·m−2·min−1 insulin infusion increased in six of the seven men in whom it was measured by an average of 40% (34.9 ± 4.2 vs. 48.9 ± 4.7 μmol·kg FFM−1·min−1; P < 0.08).

**DISCUSSION**

The results of this study demonstrate that strength training increases in vivo insulin action in sedentary

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**FIG. 1.** Plasma glucose responses to oral glucose tolerance test (40 g/m2 body surface area) before (○) and after (●) 16-wk strength-training program. There were no significant differences in fasting glucose levels or in glucose levels in response to oral glucose challenge.
STRENGTH TRAINING INCREASES INSULIN ACTION

0 30 60 90 120
Time (min)

FIG. 2. Plasma insulin responses to oral glucose tolerance test (40 g/m² body surface area) before (○) and after (●) 16-wk strength-training program. Fasting plasma insulin levels were lower after training (85 ± 25 vs. 55 ± 10 pmol/l; P < 0.05), as were insulin levels in response to oral glucose challenge (F = 4.9, P < 0.05, analysis of variance).

0 200 1000 1500 2000
Plasma Insulin (pmol/l)

FIG. 3. Steady-state plasma insulin levels during last 30 min of 20 mU·m⁻²·min⁻¹ and 100 mU·m⁻²·min⁻¹ insulin infusions before (open bars) and after (solid bars) 16-wk strength-training program. There were no significant differences with training in insulin levels attained at either low or high dose.

middle-aged and older individuals. In these men, glucose disposal during the hyperinsulinemic-euglycemic glucose clamp increased by >20% at both physiological and supraphysiological levels of hyperinsulinemia after 16 wk of strength training. In addition, fasting insulin levels and insulin levels during the OGTT were significantly lower after training.

Previous studies of the effects of strength training on glucose tolerance have suggested that strength training increases insulin sensitivity. In some cases glucose tolerance improved with strength training (26), whereas in others it did not change (4, 23). However, in most (4, 23, 26) but not all studies (12), insulin responses were lower after training. The results of the present study are similar. Although plasma glucose levels were not significantly lower, fasting plasma insulin levels and insulin responses to the oral glucose challenge fell significantly with strength training. The decreases in plasma insulin levels in these men were comparable to reductions that we (26) and others (4) have reported in older individuals as well as to changes that have been reported for younger individuals (4, 23). The differences among studies with respect to the effect of training on glucose tolerance may relate to subject selection. In the present study, changes in fasting and 2-h plasma glucose levels were related to initial levels (r = 0.86, P < 0.001 and r = 0.59, P < 0.08, respectively) such that individuals with higher initial glucose levels had relatively larger decreases with training. It is possible that the relatively normal glucose tolerance of this group precluded our finding a significant decrease in plasma glucose levels with strength training. This possibility may also explain why an earlier study from our laboratory, which included individuals with impaired glucose tolerance, was able to demonstrate an improvement in glucose tolerance (26). Similar considerations may apply to differences among studies with respect to changes in plasma insulin levels with training.

Although improvements in insulin and glucose responses to an OGTT provide indirect evidence that strength training increases insulin action, they do not, by themselves, prove that this is the case. The hyperinsulinemic-euglycemic glucose clamp technique used in the present study overcomes many of the limitations inherent in an OGTT. Using this technique, it was possible to measure increases in insulin action at both physiological and supraphysiological insulin levels after strength training. Thus, these results provide direct evidence supporting the hypothesis that strength training increases insulin action.

Although this is the first demonstration that strength training increases insulin action, an earlier cross-sectional study reported increased rates of glucose disposal in young bodybuilders compared with age- and weight-matched sedentary control subjects (30). In contrast to the results of the present study, glucose disposal rates were not significantly higher in the bodybuilders after correction for the large differences in FFM between groups. In addition to differences in study design and subject selection, these two studies differ with respect to
the duration and type of training. Thus, further investiga-
tions are necessary to resolve these disparate findings.

The improvements in glucose metabolism seen in this
study are similar to improvements reported after aerobic
exercise training in older individuals. For example, in-
creases in insulin sensitivity ranging from 13 to 36% (18,
19, 28) have been reported after 3–6 mo of aerobic exer-
cise training. It has been speculated that the improve-
ments seen with aerobic exercise training are related to
increases in VO2max and decreases in body fat, particu-
larly of upper body depots (21). These mechanisms are
unlikely to account for the increase in insulin action ob-
erved in the present study, since neither VO2max nor the
waist-to-hip ratio changed significantly with strength
training. Although body fat decreased from 27.2 to 25.6%
in these men, this decrease, too, is an unlikely explana-
tion for the improvement in insulin action. On the basis
of data obtained in our laboratory in a comparable group
of subjects (3), a decrease in body fat of this magnitude
would be expected to increase glucose disposal by <2%
during the high insulin infusion.

Most of the glucose administered during a clamp is
metabolized in muscle (6). However, it is doubtful that the
improvements demonstrated in the present study are
due solely to the increase in FFM. Glucose disposal
increased significantly at both physiological and supra-
physiological insulin levels even after the correction for
FFM in these older men. Furthermore, even if the aver-
age increase in FFM of 1.2 kg were entirely attributable
to an increase in muscle cell mass, this would represent
only an ~5% increase in total muscle mass (assuming
muscle to be ~40% of FFM) and would be quantitatively
insufficient to account for the 20% increase in glucose
disposal that was observed. Thus, although the increase
in muscle mass with strength training may contribute to
increased rates of glucose disposal, it is unlikely to be
the major factor explaining the improvement in insulin
action.

Oxidative glucose metabolism measured during a hy-
perinsulinemic-euglycemic glucose clamp is not different
in aerobically trained individuals and sedentary control
subjects (8). Thus, the higher rates of total body glucose
disposal observed in aerobically trained subjects are pri-
marily due to increases in nonoxidative glucose disposal
(8). It appears that the effect of strength training is simi-
lar. Oxidative glucose metabolism was not altered by
strength training. On the other hand, nonoxidative glu-
sucosis metabolism tended to be higher after strength
training, although this increase did not reach statistical
significance (perhaps because of the small sample size).

Glucose disposal through nonoxidative pathways dur-
ing glucose clamp experiments is largely due to glycogen
synthesis and is directly related to the fractional activity
of glycogen synthase in skeletal muscle (8). The activity
of this enzyme complex is higher in aerobically trained
individuals (8). It is possible that glycogen synthase activ-
ity is also increased by strength training, although it has
not been reported. It is known, however, that glycogen
depletion, which stimulates the activity of glycogen syn-
thase, occurs with acute bouts of resistive exercise (27)
and that strength training significantly increases skele-
tal muscle glycogen levels (22). Therefore, the effects of
strength training on glycogen storage and utilization are
consistent with an increase in the activity of glycogen
synthase.

Glucose disposal is directly related to levels of the in-
ulin-stimulatable glucose transport protein GLUT-4 in
skeletal muscle (8). Levels of this protein are higher in
endurance-trained individuals (8, 17). Thus, it is conceiv-
able that strength training increases insulin action by
increasing skeletal muscle GLUT-4 levels. Although the
effects of strength training on skeletal muscle GLUT-4
levels have not been investigated, skeletal muscle
GLUT-4 levels were unchanged despite a worsening of
insulin responses to OGTT in 12 young strength-trained
individuals who detrained for 14 days (16). Unfortu-
nately, the effect of detraining on the subcellular localiza-
tion of GLUT-4, an important determinant of trans-
porter activity, was not addressed in that study.

Acute bouts of aerobic exercise increase insulin action
and decrease insulin responses to an oral glucose chal-
lenge independently of training (14). From the results of
the present study it cannot be determined whether the
increase in insulin action with strength training is truly
a training effect or whether the results are due to a residual
effect of the last bout of exercise. However, lower insulin
responses to oral glucose were demonstrated 48–72 h
after the last exercise session in earlier studies (4, 23),
which suggests that the effect of strength training is a
true training adaptation and not simply an acute effect of
exercise.

In summary, we have demonstrated that strength
training increases insulin action and decreases insulin
levels in sedentary older individuals. These improve-
ments appear to be independent of changes in VO2max,
body composition, and body fat distribution. The effects
of strength training on insulin action are similar to those
produced by aerobic exercise training. This finding, when
considered with the early observation that isotonic and
isometric contractions are capable of stimulating glucose
transport to comparable degrees in isolated muscle prep-
ations (15), suggests that resistive and aerobic exerci-
esces increase insulin action by a common mechanism.
Additional studies focusing on the changes in skeletal
muscle glucose transport and metabolism produced by
strength training are required to further understand the
effects of this form of exercise. In addition to providing
insights into the basic mechanisms regulating glucose
and insulin metabolism, these studies also may lead to
more effective intervention strategies aimed at reversing
the insulin resistance of aging.

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