Progressive Improvement in Glucose Tolerance Following Lower-Intensity Resistance Versus Moderate-Intensity Aerobic Training in Older Women

Loretta DiPietro, Catherine W. Yeckel, and James Dziura

Background: Few studies have compared long-term moderate-intensity aerobic versus light-resistance training on serial improvements in glucose tolerance in older people. Methods: Healthy, inactive older (74 ± 5 [SD] years) women (N = 20) were randomized into either a high-volume, moderate-intensity aerobic (ATM, n = 12) or a lower-intensity resistance training (RTL, n = 8) group. Both groups exercised under supervision 4 times per week for 45- to 60-minute sessions over 9 months. Measurements of plasma glucose, insulin, and free fatty acid (FFA) responses to an oral glucose tolerance test (OGTT) were performed at baseline and at 3, 6, and 9 months 48 hours after the last exercise session. Results: We observed significant improvements in 2-hour glucose concentrations at 3, 6, and 9 months among women in the RTL (152 ± 42 vs 134 ± 33 vs 134 ± 24 vs 130 ± 27 mg · dL⁻¹; P < .05), but not the ATM (151 ± 25 vs 156 ± 37 vs 152 ± 40 vs 155 ± 39 mg · dL⁻¹) group. These improvements were accompanied by an 18% (P < .07) decrease in basal FFA concentrations in the RTL group, whereas basal and 30-minute FFA concentrations increased (P < .05) after training in the ATM group. Conclusions: These findings suggest that the net physiological benefits of exercise might have been blunted in the ATM group, owing to higher circulating levels of FFA, which might have temporarily interfered with insulin action.

Keywords: aging, exercise, diabetes, glucose metabolism

A constellation of factors associated with aging per se, as well as lifestyle, contributes to the decline in glucose tolerance commonly observed in older age.1–6 Data from the Diabetes Prevention Program (DPP),7 Studies of Targeted Risk Reduction Interventions Through Defined Exercise (STRRIDE),8 and the Finnish Prevention Program9 have strongly implicated lifestyle changes involving increased moderate or moderate-to-vigorous physical activity as an effective means of reducing the risk of type 2 diabetes in middle-age persons with impaired glucose tolerance or other metabolic risk factors. Even in older age, people who
Exercise regularly appear to be protected from the development of insulin resistance and glucose intolerance,10–14 and this protection might be independent of exercise-related changes in body composition.15–18 Training-related improvements in insulin sensitivity and glucose tolerance typically have been observed when subjects are studied between 12 and 72 hours after exercise,15,19–21 with higher-intensity exercise training providing more enduring benefits than moderate- and lower-intensity exercise, likely owing to greater transient effects.15,19 On the other hand, others have observed impairments in both insulin action and glucose tolerance from an oral glucose challenge performed immediately after a large volume of aerobic exercise (eg, ~75% VO2peak for 45 minutes) in healthy middle-age people.22,23 These metabolic impairments, then, were replaced within 24 hours with enhanced insulin action persisting up to 3 days.23 It is not clear, however, whether these latter results are generalizable to older people or to those with already impaired glucose tolerance owing to ß-cell defects or to peripheral insulin resistance.

Similar to the aims of the DPP, we were interested in the effectiveness of commonly prescribed and long-term exercise on improvements in glucose tolerance, but in older people at risk for type 2 diabetes. Data from our previous studies17,19 suggest that a higher dose or volume (ie, Frequency × Intensity) of exercise might be necessary to result in meaningful improvements in glucose tolerance in otherwise robust older people. Thus, we compared over 9 months the benefits of high-volume, moderate-intensity (240 min · wk−1; 65% to 75% VO2peak or 4.3 METs) aerobic exercise with those of a control condition comprising light resistance training (180 min · wk−1; 45% to 50% VO2peak or 2.5 METs) on glucose, insulin, and free fatty acid (FFA) responses to an oral glucose tolerance test (OGTT) in older women, with measurements performed every 3 months. Few serial data are available over the course of longer exercise training periods, and these data would be quite useful in determining the time course necessary for more chronic improvements in metabolic function to occur in older age—especially after possible decades of disuse. Because both aerobic and resistance exercise training have demonstrated their benefit to insulin action and glucose tolerance in aging,24 we hypothesized that both training regimens would be effective in improving glucose tolerance in these older women; however, we proposed that the high-volume, moderate-intensity training would result in even greater improvements in glucose tolerance over lower-intensity resistance training owing to a greater volume or dose of energy expenditure. Moreover, we expected that meaningful improvements in glucose tolerance would occur in a graded manner over the duration of the training program and, similar to our previous work,17,19 would occur independent of changes in body composition.

Methods

Subjects

Older (≥65 years) women were recruited by advertisement from private older adult residential communities in Connecticut and from local community senior centers. Eligible study subjects included those who reported no regular physical activity for the previous 6 months, were nonsmokers and not on hormone
replacement therapy or glucose-lowering medication, and were without class I obesity (ie, body mass index <30 kg · m⁻²). Older volunteers were screened by their personal physician for cardiovascular disease, neuroendocrine disorders, and other uncontrolled chronic disease. Potential study subjects were also screened with a 3-hour oral glucose tolerance test to rule out type 2 diabetes. The rationale for using a 3-hour test was to allow ample time for glucose concentrations to return to baseline in these older women. If glucose concentrations returned to baseline before 3 hours, the test was terminated. In addition, all eligible study subjects successfully completed an exercise tolerance test performed in the Department of Cardiology at Yale University–New Haven Hospital. Following these screening assessments, volunteers meeting the inclusion criteria completed all baseline assessments before being randomized. Randomization was achieved by assigning the RTL group an even number (ie, 4) and the ATₘ group an odd number (ie, 7). As subjects met inclusion criteria for the study, the next in a pile of sealed and serially numbered envelopes was opened. Each envelope contained a card indicating the group assignment. The ordering of these cards was determined by a random numbers table. Data analysis was conducted on only those subjects with complete data across all 4 time points: baseline, 3, 6, and 9 months (n = 20). The protocol was approved by the Human Investigations Committee of Yale University School of Medicine, and all eligible study subjects gave written informed consent before their participation.

**Exercise Training Protocol**

Subjects were randomized into either a high-volume, moderate-intensity (ATₘ: 240 min · wk⁻¹; 65% to 75% VO₂peak) aerobic training or a lower-intensity resistance training (RTL: 180 min · wk⁻¹; 45% to 50% VO₂peak) group, with the latter serving as a control group. Exercise intensity was based on a heart rate necessary to achieve this relative intensity during the graded exercise challenge. Thus, women in the ATₘ group exercised at an average (range) heart rate of 113 (102–123) beats · min⁻¹, and women in the RTL group exercised at about 90 (85–97) beats · min⁻¹. All exercise was supervised, and heart rate was monitored continuously during exercise (Polar Electro, Finland) and recorded every 10 minutes during each session. Both groups were identical with regard to exercise frequency (4 d · wk⁻¹) throughout the 9-month intervention. Subjects in the ATₘ group exercised on treadmills, whereas subjects in the RTL group participated in a program of 15 minutes of lower-intensity treadmill walking and stretching and 30 minutes of strengthening using Thera-Bands, Thera-Balls, and hand weights. After an initial 4- to 6-week lead-in period that allowed subjects to gradually attain their given exercise duration and intensity, exercise duration was set at 60 minutes for subjects in the ATₘ group and 45 minutes for those in the RTL group. Because we were interested in the independent effects of exercise on glucose metabolism, subjects were instructed to maintain their usual dietary intake throughout the 9-month period.
Determination of VO_{2peak}

Peak aerobic capacity (VO_{2peak}) was determined on a treadmill using a modified Balke protocol\textsuperscript{25} at baseline, 3, 6, and 9 months. Subjects were tested to volitional exhaustion, and all subjects met 2 of 3 criteria for determining VO_{2max}: a respiratory exchange ratio $\geq 1.15$, plateauing of the VO$_2$, or heart rate $>$ age-predicted max [220 – age (y)]. Heart rate was continuously recorded (Polar Electro, Finland), and blood pressure was measured by auscultation. Oxygen consumption was determined by sampling expired gas fractions of CO$_2$ and O$_2$ from a mixing chamber (Sensormedics, 2900; Sensormedics, Anaheim, CA). These measurements were corrected to standard conditions and used to determine oxygen consumption (VO$_2$) at 20-second intervals throughout the test. Peak VO$_2$ was determined by averaging values over the final minute of testing.

Oral Glucose Tolerance Test

A 3-hour, 75-g OGTT was performed at baseline and at 3, 6, and 9 months according to the guidelines of the American Diabetes Association.\textsuperscript{26} All subjects were instructed to eat a diet containing 150 g or more of carbohydrates per day for 3 days before the OGTT. A 21-gauge Intracath catheter was placed in an antecubital vein, and blood samples (5 mL each) were collected before (–15 and 0 minutes) and at 30-minute intervals following glucose ingestion for the determination of glucose, insulin, and FFA concentrations. If the glucose value for a given subject returned to within 10 mg · dL$^{-1}$ of baseline before 180 minutes, the OGTT was terminated and the last glucose value was carried forward. All subjects were tested in the early morning following a 12-hour fast. At 3, 6, and 9 months, the OGTT was performed 48 hours after exercise.

Blood Analyses

All blood samples were placed in prechilled test tubes. Samples were centrifuged at 4°C and the plasma stored at −70°C until analyzed in the Core Laboratory of the General Clinical Research Center at Yale University–New Haven Hospital. Serial samples for each subject were analyzed in duplicate within a single assay. Plasma glucose concentrations were analyzed using the glucose oxidase method (YSI 2300; Yellow Springs Instruments Co., Yellow Springs, OH). Plasma immunoreactive insulin concentrations were determined with a double antibody radioimmunoassay (Diagnostic, Webster, TX). Plasma concentrations of FFA were determined by standard microfluorimetric procedures (Sigma, Saint Louis, MO).

Calculations

Total areas under the glucose and insulin response curves (AUC$_G$ and AUC$_I$) were determined by the trapezoidal method. To evaluate glucose-stimulated responses in insulin secretion, we calculated the ratio of the initial change (0–30 minutes) in
insulin to that of glucose as $\Delta$insulin (0–30 min)/$\Delta$glucose (0–30 min). This insulinogenic index is a common indicator of $\beta$-cell function, with a lower ratio indicating poorer secretory function. The homeostatic model assessment (HOMA) was calculated from basal concentrations of glucose and insulin as $[(\text{glucose}_0 \times 0.056) \times (\text{insulin}_0)]/22.5$ and used as an indicator of basal insulin resistance. Lower HOMA values indicate lesser insulin resistance. The composite whole-body insulin sensitivity index (WBISI) was calculated from basal concentrations of glucose and insulin, as well as from values averaged over the first 2 hours of the OGTT as $10,000/\sqrt{(\text{glucose}_0 \times \text{insulin}_0) \times (\text{mean glucose}_{0-120} \times \text{mean insulin}_{0-120})}$. Higher WBISI values indicate greater insulin sensitivity.

Body Composition

Height and weight were measured on a balance-beam scale, and the abdominal circumference (cm) was measured in triplicate at the umbilicus by the same examiner before and after training. We have observed a strong correlation ($r = .80; P < .001$) between the abdominal circumference and the visceral fat area measured by computed tomography in our older populations. Overall body composition [whole body muscle (kg) and fat mass (kg)] scans were obtained using dual energy X-ray absorptiometry (DXA).

Analysis

Univariate statistics (mean ± SD) first were generated on all study variables. Simple correlations among the study variables were tested using the Spearman rank order correlation coefficient. As most study variables were normally distributed, cross-sectional differences at baseline in the levels of these variables were compared between groups using $t$ tests for independent samples. Within- and between-treatment group differences in the physiological variables before and at 3, 6, and 9 months of the exercise training intervention were tested using repeated-measures analysis of variance (ANOVA), respectively. Comparisons of specific time points of interest were tested using orthogonal contrast statements. Polynomial contrast statements were used to test the specific hypothesis of a graded response over time. Data were analyzed using SAS Windows—8.04 (SAS Institute, Inc, Cary, NC).

Results

Retention to the 9-month program (144 sessions) was greater than 92% in the AT$_M$ and 95% in the RT$_L$ group. Adherence to the prescribed training heart rate (ie, intensity) was 100% in both groups, whereas adherence to the prescribed session duration was 87% and 96% in the AT$_M$ and RT$_L$ group, respectively. Although women in the RT$_L$ group were slightly older (77 ± 6 vs 72 ± 3 years, respectively) with a lower peak aerobic capacity (18.3 ± 4.4 vs 20.2 ± 3.0 ml · (kg · min)$^{-1}$, respectively) than women in the AT$_M$ group, these baseline differences were not statistically significant. Body composition was also similar between groups at baseline (Tables 1 and 2), and neither peak aerobic capacity nor body composition was altered over the course of the exercise intervention.
Fasting concentrations of glucose and insulin decreased marginally (P < .08) in both groups after training and contributed to a small improvement in the HOMA (22% and 20% in the RT_L and AT_M groups, respectively); however, these improvements in basal metabolism were not evident until 9 months (Tables 3 and 4). The whole-body insulin sensitivity index (WBISI) improved significantly between baseline and 9 months in the RT_L group (29%; P < .05), but it became worse in the AT_M group (–17%). Values for the insulinogenic index were considerably lower than those observed in younger obese populations, with values lower than 1.0 indicating a markedly inadequate early-phase insulin response relative to the postchallenge glucose response in these older women. We observed no clinically relevant changes in the insulinogenic index with either type of training.

Although these older women were considered healthy enough to participate in a long-term training study based on physician screening, most of the women in both the RT_L (63%) and the AT_M (54%) groups met the criterion for impaired glucose tolerance based on a 2-hour glucose concentration from the baseline OGTT of 140 to 199 mg · dL⁻¹. Surprisingly, although the 2 groups were similar at baseline, we observed a significant improvement in 2-hour glucose concentrations...
among women who participated in lower-intensity resistance exercise but not in women performing high-volume, moderate-intensity aerobic exercise. In fact, after 9 months of training, the prevalence of impaired glucose tolerance (as measured 48 hours after exercise) decreased to 25% in the RT_L group ($P < .05$) but increased marginally to 62% in the AT_M group. Figure 1 displays individual changes in 2-hour glucose concentrations before and after 9 months. These apparent improvements in 2-hour glucose concentrations among women in the RT_L group were evident after only 3 months of training but did not decrease further with an additional 6 months of exercise (Table 3). Among the entire study sample, the correlation between 2-hour glucose concentrations at baseline and the change in these 2-hour concentrations with training was modest and of marginal statistical

### Table 3  Metabolic Characteristics of the Study Population Over Training Period in the Lower-Intensity Resistance Exercise Group RT_L ($n = 8$)

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>3 months</th>
<th>6 months</th>
<th>9 months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basal glucose (mg · dL$^{-1}$)</td>
<td>93.0 ± 8.9</td>
<td>91.3 ± 4.5</td>
<td>88.4 ± 5.4</td>
<td>88.1 ± 6.6</td>
</tr>
<tr>
<td>Basal insulin (µU · mL$^{-1}$)</td>
<td>9.8 ± 4.5</td>
<td>10.0 ± 4.3</td>
<td>9.4 ± 4.1</td>
<td>8.1 ± 4.9</td>
</tr>
<tr>
<td>2-h glucose (mg · dL$^{-1}$)</td>
<td>152.0 ± 42.2</td>
<td>134.4 ± 33.3</td>
<td>133.9 ± 23.9</td>
<td>129.8 ± 27.4$^a$</td>
</tr>
<tr>
<td>Basal FFA (µmol · L$^{-1}$)</td>
<td>0.67 ± 0.15</td>
<td>0.56 ± 0.14</td>
<td>0.56 ± 0.21</td>
<td>0.55 ± 0.19</td>
</tr>
<tr>
<td>Total AUC glucose [(mg · dL$^{-1}$) · 180 min$^{-1}$ · 10$^{3}$]</td>
<td>22.3 ± 7.7</td>
<td>21.4 ± 6.1</td>
<td>19.7 ± 5.9</td>
<td>18.9 ± 5.3</td>
</tr>
<tr>
<td>Total AUC insulin [(µU · mL$^{-1}$) · 180 min$^{-1}$ · 10$^{3}$]</td>
<td>8.3 ± 1.6</td>
<td>7.9 ± 2.9</td>
<td>7.4 ± 1.9</td>
<td>7.2 ± 2.4</td>
</tr>
</tbody>
</table>

Abbreviations: FFA, free fatty acids; AUC, area under the response curve.

**Note.** Values are means ± SD.

$^a$ Significantly different from baseline, $P < .05$.

$^b$ Between-group differences at 9 months, $P < .05$.

### Table 4  Metabolic Characteristics of the Study Population Over Training Period in the Moderate-Intensity Aerobic Exercise Group AT_M ($n = 12$)

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>3 months</th>
<th>6 months</th>
<th>9 months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basal glucose (mg · dL$^{-1}$)</td>
<td>97.0 ± 10.0</td>
<td>95.2 ± 10.9</td>
<td>94.3 ± 10.5</td>
<td>93.2 ± 10.0</td>
</tr>
<tr>
<td>Basal insulin (µU · mL$^{-1}$)</td>
<td>9.3 ± 6.3</td>
<td>9.3 ± 5.7</td>
<td>9.5 ± 7.2</td>
<td>8.5 ± 5.5</td>
</tr>
<tr>
<td>2-h glucose (mg · dL$^{-1}$)</td>
<td>150.9 ± 25.1</td>
<td>155.9 ± 37.1</td>
<td>152.3 ± 39.5</td>
<td>154.8 ± 38.9</td>
</tr>
<tr>
<td>Basal FFA (µmol · L$^{-1}$)</td>
<td>0.67 ± 0.24</td>
<td>0.62 ± 0.16</td>
<td>0.64 ± 0.11</td>
<td>0.71 ± 0.09</td>
</tr>
<tr>
<td>Total AUC glucose [(mg · dL$^{-1}$) · 180 min$^{-1}$ · 10$^{3}$]</td>
<td>24.2 ± 6.1</td>
<td>24.6 ± 6.2</td>
<td>23.8 ± 7.2</td>
<td>24.5 ± 6.7</td>
</tr>
<tr>
<td>Total AUC insulin [(µU · mL$^{-1}$) · 180 min$^{-1}$ · 10$^{3}$]</td>
<td>7.3 ± 3.1</td>
<td>7.5 ± 3.1</td>
<td>8.0 ± 3.6</td>
<td>8.4 ± 3.0</td>
</tr>
</tbody>
</table>

Abbreviations: FFA, free fatty acids; AUC, area under the response curve.

**Note.** Values are means ± SD.
significance ($r = -.38; P < .07$), suggesting that level of initial impairment in glucose tolerance only partially accounted for any exercise-related improvements in this older sample. In addition, both glucose and insulin responses to the OGTT improved significantly during the last hour of the OGTT (120–180 minutes) in the RTL, but not the ATM, group (Figure 2). In contrast to the observed improvements in the HOMA, WBISI, and 2-hour glucose levels, however, these improvements in late-phase glucose and insulin responses appeared in a graded manner over the course of the training period (Figure 3), although the test for trend was not statistically significant.

Basal concentrations of FFA improved marginally (18%; $P < .07$) in the RTL, but not the ATM, group, and similar to 2-hour glucose concentration, these small improvements occurred in the first 3 months of training, with no additional decline (Tables 3 and 4). However, FFA concentrations over the course of the OGTT at baseline and at 9 months demonstrated a significantly diminished insulin suppression of FFA during the early phase of the OGTT (0–30 minutes) following high-volume, moderate-intensity training (Figure 4; $P < .05$). In fact, at 9 months, insulin-stimulated suppression (%) of FFA concentrations between baseline and 30 minutes of the OGTT was 31% in the RTL group but only 3% in the ATM group ($P < .05$). Overall, we observed a moderate correlation between the change in basal FFA and change in 2-hour glucose concentrations ($r = .49; P < .05$).

**Discussion**

Contrary to our initial hypotheses, we observed that 180 min · wk$^{-1}$ of lower-intensity resistance training was significantly more effective in improving glucose tolerance in the short term (ie, within 48 hours of exercise) than was 240 min · wk$^{-1}$.
Figure 2 — Longitudinal changes in glucose (A) and insulin (B) responses to the OGTT over the training period in older women. OGTT = 3-hour oral glucose tolerance test. * $P < .05$, within-group difference between baseline and 9 months; † $P < .05$, between-group difference at 9 months.
of moderate-intensity aerobic training in our older women. Indeed, we observed significant improvements in 2-hour glucose concentrations and consequent prevalence of IGT among women in the RTL group but not among women in the ATM group. These improvements in glucose tolerance were accompanied by a marginal (18%) decline in basal FFA concentrations in the RTL group alone and were independent of improvements in body composition. Perhaps this weekly amount of resistance training (even though of lower intensity) resulted in beneficial adaptations in muscle quality related to transient improvements in insulin action (increased GLUT-4 translocation, muscle fiber alterations, etc), which would not be detected using DXA scanning.

Alternatively, the stress response to a large volume of exercise at relative intensity levels >65% of VO2peak might activate counter regulatory hormones such as catecholamines,32 cortisol,33 growth hormone,34 and glucagon,32 which interfere with the action of insulin both to suppress hepatic glucose production and to promote peripheral glucose uptake during the physiological oral glucose challenge. Concentrations of these counter regulatory hormones tend to stabilize within 24 hours of exercise in younger people35; however, it is not clear whether this remains so in older age. Tuominen and colleagues35 observed that serum concentrations of glucagon, cortisol, and growth hormone returned to basal levels the...
morning after a marathon; however, fat metabolism remained elevated and was associated with impaired insulin-stimulated glucose disposal in their younger male subjects. Older women in the current study had significantly diminished suppression of circulating FFA during the first 30 minutes of the OGTT after high-volume, moderate-intensity exercise training, which appeared to interfere with insulin action up to 48 hours following exercise, thus altering (at least temporarily) the metabolic benefit-to-stress ratio of the exercise bout. In partial support of these findings, King et al\textsuperscript{23} observed significant impairments in insulin action and glucose tolerance immediately following a large volume (45 minutes) of higher-intensity (~75% VO\textsubscript{2peak}) aerobic exercise in a sample of healthy middle-age people. This insulin resistance improved dramatically by 24 hours, however, and was replaced by enhanced insulin action that persisted up to 3 days. The authors attributed the insulin resistance observed immediately after exercise to transient elevations in circulating FFA concentrations, which then inhibited glucose uptake in the muscle.\textsuperscript{36} Therefore, the fact that we did not observe improvements in glucose tolerance with high-volume, moderate-intensity aerobic training (in contrast to the findings of other studies of older people\textsuperscript{8,17,37,38}) is likely the result of differences in the metabolic benefit-to-stress ratio of the exercise, which changes over the time course of evaluation.

Of question is the relevance of changes in FFA suppression during the first 30 minutes of the OGTT to impaired glucose tolerance over the subsequent 2.5 hours of testing. Using either acipimox to reduce\textsuperscript{39} or lipid infusions to increase\textsuperscript{40}
circulating FFA, other investigators have demonstrated that early-phase (0–30 minutes) alterations in FFA suppression have a significant impact on 2- or 3-hour glucose tolerance in younger people at risk for type 2 diabetes. In fact, similar to our findings using exercise, one study observed no change in fasting glucose concentrations after treatment with acipimox; indeed, the observed improvements in glycemic control (ie, area under the glucose response curve) were accounted for entirely by postprandial (2–3 hour) glucose excursions.

In one of our previous studies, we observed a 16% decrease in basal FFA concentrations and a 25% decrease in the glucose response curve to an OGTT following 4 months of moderate-intensity (75% VO$_{2peak}$) aerobic training in older men and women. More recently, we demonstrated the more enduring benefits of higher (80% VO$_{2peak}$)—compared with moderate (65% VO$_{2peak}$) or low (55% VO$_{2peak}$)—intensity aerobic exercise to peripheral insulin sensitivity, which was tested using a 2-step euglycemic-hyperinsulinemic clamp. The finding of the greater benefits of higher-intensity aerobic training to insulin sensitivity in older people was also reported by Coker et al. In all 3 of these earlier studies, however, glucose tolerance and/or insulin sensitivity were determined ~72 hours after exercise, and thus, it is very likely that any elevated FFA and stress hormone concentrations resulting from ~50 to 55 minutes of either moderate- or higher-intensity aerobic exercise decayed by 72 hours—indeed, we demonstrated that even with higher-intensity exercise, basal FFA concentrations measured 72 hours later were similar to those following moderate- or low-intensity exercise. Moreover, any remaining high plasma FFA concentrations in response to higher-intensity aerobic exercise would be abolished with a constant insulin infusion during the hyperinsulinemic clamp, especially at the higher insulin dose (40 mU · m$^{-2}$ · min$^{-1}$), thus resulting in little interference with insulin action and perhaps unmasking the improved peripheral insulin sensitivity with higher-intensity training. Together these findings suggest that the timing of the transient expression and the decay in metabolic benefits is a function of age, as well as the dose of the exercise bout. For instance, the benefits of lower-intensity exercise might be observed closer to the time of exercise (owing to a greater metabolic benefit-to-stress ratio) but might decay very quickly in older people. Alternatively, a large volume of moderate- or higher-intensity exercise might lower this proposed benefit-to-stress ratio, in part because of a transient increase in FFA and various counter regulatory hormones, which might last up to 48 hours in older age. Initial impairments in insulin action after moderate- or higher-intensity exercise more than likely are replaced by improvements in insulin sensitivity lasting as long as 72 hours after exercise even in older age.

Few studies have investigated the time course for more chronic improvements in glucose tolerance and insulin sensitivity with long-term exercise training. Among women performing lower-intensity exercise, the slowest improvements were observed for basal concentrations of glucose and insulin, which were not evident until 9 months of lower-intensity training and were not statistically significant. Basal FFA and 2-hour glucose concentrations improved within 3 months in this same group, with no additional change over the remainder of the training period. Interestingly, late-phase (120–180 minutes) glucose and insulin responses to the OGTT (expressed as the areas under the curve for that late phase) were the only metabolic parameters that appeared to improve in a graded manner over the
9 months of training in the RT_L group. Perhaps improvements in metabolic function at 2 hours and later are indicative of improved peripheral insulin sensitivity from exercise training, whereas the inability to change basal or early-phase concentrations of glucose and insulin might be a consequence of impairments in β-cell function in older age, which might not be as amenable to change from exercise alone or might require a longer period of intervention.21

We observed no alterations in body composition after 9 months of training. This is consistent with our previous findings17,19 and helps to emphasize that the improvement in glucose tolerance among women performing lower-intensity resistance training was likely the result of the exercise stimulus itself and not weight or fat loss. Neither did we observe improvements in VO_{2peak} after 9 months of high-volume, moderate-intensity aerobic training, which is also contrary to other studies of older people. Given the low level of aerobic fitness [ie, 18 to 20 mL ∙ (kg ∙ min)−1] in our study subjects, however, even a relative stimulus of 75% VO_{2peak} translates into an absolute stimulus of only 3.9 to 4.3 metabolic equivalents, which might not be sufficient to improve maximal aerobic capacity in robust older women not on hormone replacement therapy.41,42 Indeed, our study subjects were a full decade older than subjects described in other studies of exercise and aging.16,37,38 Finally, the small number of study subjects in the RT_L group might have compromised the precision of the estimates. However, overall adherence over 9 months to the full training prescription (frequency, duration, and intensity) was greater than 95% in that group; baseline levels of all influential study variables were similar between groups, and training-related alterations in 2-hour glucose and FFA concentrations occurred in opposite directions between the 2 groups, thereby supporting the validity of the findings despite the low statistical power.

We conclude that the greater short-term (ie, 48-hour) effectiveness of lower-intensity resistance exercise compared with high-volume, moderate-intensity aerobic training on improvements in glucose tolerance (including a dramatic decrease in the prevalence of impaired glucose tolerance) might be explained, in part, by the positive changes in muscle quality resulting from resistance training that are not hindered by a persistent stress response. We propose that the metabolic benefit-to-stress ratio of lower-intensity resistance exercise is higher compared with high-volume, moderate-intensity exercise; however, these benefits might also decay more quickly, thus requiring this mode of exercise to be performed more frequently to result in improved metabolic function. The clinical relevance of lower-intensity resistance training is substantial because older people are far more likely to perform such activity on a regular basis. Thus, a combined program of walking, stretching, and light resistance using Thera-Bands and/or hand weights that is performed for 45 minutes in duration on most days of the week is easily achievable by most older people and should be incorporated gradually into their lifestyle.

Acknowledgments

We thank Jodi L. Crimmins, Anne Marie Cheatham, Jennifer Fawcett, Andrew Grabarek, Lynsey Teulings, and the nursing and technical staffs of the Yale University–New Haven General Clinical Research Center and the Yale University Diabetes Endocrinology Research Center for their technical expertise, and the study subjects for their commitment to this
research. In addition, we thank Robert S. Sherwin, MD, for his thoughtful comments on an earlier draft of this manuscript. James Dziura, PhD, currently holds the position of Research Scientist at the Yale University–New Haven General Clinical Research Center. This work was supported by RO1 AG.17163 (LDP), MO1 RR.00125, P30 AR.46032, and P30 DK.45735.

References


