Resistance Exercise in Type 1 Diabetes

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Running title: Resistance exercise in type 1 diabetes

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Word Count: 4631
Abstract: 113 words
Main text: 4518
Tables and Figures: 2 tables, 4 figures

Key words: weight lifting, blood glucose control, hypoglycemia, diabetes

Abstract

It is relatively well-known that moderate intensity aerobic exercise increases the risk of hypoglycemia in individuals with type 1 diabetes. Conversely, brief high intensity (anaerobic) activity can cause post-exercise hyperglycemia. Recent evidence indicates that including small amounts of anaerobic activity, either in the form of short sprints or as resistance exercise (weight-lifting), during aerobic exercise sessions may decrease the fall in blood glucose associated with moderate intensity aerobic exercise. This review discusses the recent developments in the area of exercise and type 1 diabetes, with a particular focus on the effects of resistance exercise. Practical exercise recommendations, as well as suggestions for the future direction of research in this area are also provided.

Introduction

Physical activity is strongly recommended for individuals with type 1 diabetes, as regular exercise is associated with greater life expectancy and a lower frequency of diabetic complications in this population (1). Higher levels of physical activity are associated with improved physical fitness, lower insulin requirements, more favorable lipid profiles, decreased cardiovascular disease risk, improved endothelial function, delayed onset and/or progression of peripheral neuropathy and higher self-reported quality of life in people with type 1 diabetes (1). In spite of this, most individuals with type 1 diabetes fail to achieve recommended levels of physical activity (2). In addition to the usual barriers to exercise cited by the general population, such as lack of time and/or energy, or lack of convenient/affordable facilities, type 1 diabetic individuals generally list fear of hypoglycemia as an important barrier (3). While it is clear that aerobic exercise generally increases the risk of hypoglycemia in type 1 diabetes, a handful of recent acute exercise studies indicate that anaerobic forms of exercise (weight lifting, sprinting, etc.) may reduce this risk (4, 5). In the present review article, we discuss the energy systems involved in these types of activities, and provide an overview of recent studies related to resistance exercise in type 1 diabetes. We also discuss the current exercise guidelines for individuals with type 1 diabetes, provide further recommendations with respect to resistance exercise, and propose a direction for future research in the area.

Exercise types and energy systems

Aerobic Exercise

The terms “anaerobic” and “aerobic” refer mainly to the metabolic energy sources that dominate the activity. Aerobic exercise, such as walking, cycling, jogging or swimming, typically involves the repeated and continuous movements of the same large muscle groups over an extended duration of time (minimum 10 minutes at a time) at a moderate intensity [~40 to 60% of an individual’s aerobic capacity (VO_{2peak})] (6). In non-diabetic individuals, the first 5-10 minutes of aerobic exercise are fueled mostly by muscle glycogen. After this initial period, glucose and non-esterified fatty acids (NEFA) become the main source

of fuel, as they are broken down in the presence of oxygen in the mitochondria of the muscle cells to produce energy in the form of ATP. As the duration of moderate aerobic exercise increases, so does reliance on NEFA and circulating glucose as the primary fuel sources (7). Throughout this time, release of insulin from pancreatic β-cells decreases and glucagon concentration increases. The balance of these two hormones ensures that fuels are released from storage in order to meet the elevated energy demands of the exercising muscles. Glucose, stored mainly as glycogen in the liver, and NEFA, stored mainly in adipocytes, is released into circulation for uptake and use in the exercising muscles (8). As a result, blood glucose levels during exercise in people without type 1 diabetes remain essentially unchanged. Once exercise has stopped, glucose production and utilization both return to baseline levels, as do the levels of insulin and glucagon. Where pancreatic function is normal, hypoglycemia only occurs if exercise lasts for several hours without food intake, resulting in glycogen depletion, and hepatic glucose production falling short of glucose utilization (9).

For individuals with type 1 diabetes, autoimmune destruction of the insulin-producing β-cells of the pancreas eventually results in a complete or near-complete lack of endogenous insulin production. As such, circulating insulin levels during exercise depend on the timing and quantity of insulin introduced (either by injection or insulin pump infusion) into the individual's system prior to exercise. Without careful planning and adjustments to insulin dosage prior to exercise, circulating insulin levels are often too high (hyperinsulinemia) or too low (hypoinsulinemia). Hyperinsulinemia stimulates glucose uptake by muscle, adipose and hepatic cells for storage and/or oxidation, and inhibits the release of glucose from the liver. Conversely, hypoinsulinemia increases hepatic glucose production and limits glucose uptake in the periphery. In most cases aerobic exercise occurs while the type 1 diabetic participant is in a hyperinsulinemic state, resulting from an inability to lower circulating insulin levels at the start of exercise. This generally results in large declines in blood glucose during the activity, resulting in hypoglycemia unless sufficient quantities of carbohydrate are consumed before, during and after exercise.

A summary of the response to aerobic exercise in individuals with and without type 1 diabetes can be found in Table 1.

Anaerobic Exercise

When exercise is very intense (exceeding 85% of aerobic capacity) anaerobic metabolism, which breaks down glucose quickly in the absence of oxygen to produce ATP and lactate, supplies most of the energy. Under these conditions, the roles of insulin and glucagon are diminished (10). High intensity causes substantially increased levels of catecholamines (epinephrine and norepinephrine), which have an overriding influence on glucose release by the liver (11). Under the influence of the catecholamines, hepatic glucose production can increase 5 to 10-fold, often exceeding the rate of utilization and resulting in an increase in blood glucose concentration (11, 12). This may cause hyperglycemia when activity ends, as glucose utilization returns to baseline faster than glucose production (11, 12). In individuals without diabetes the hyperglycemia stimulates normal mechanisms of glucose control, leading to the release of insulin to promote glucose storage and return blood glucose levels to normal. In one study of non-diabetic athletes exercising for 15 minutes at ~90% of their maximal aerobic capacity (an intensity level associated with elevated catecholamines and increased lactate production) circulating insulin levels doubled at the end of exercise and remained elevated for ~ 40 minutes (13). Thus, it would appears that insulin requirements increase at the end of intense aerobic/anaerobic exercise to help reestablish glucose homeostasis.

The powerful effects of epinephrine and norepinephrine on glucose production are also present in individuals with type 1 diabetes. Brief (10-15 minutes), very high intensity exercise causes increases in glucose production during exercise. After the cessation of exercise, glucose production does not diminish as quickly as does glucose utilization, resulting in post-exercise hyperglycemia (14, 15). In individuals with type 1 diabetes, because there is no endogenous insulin secretion, hyperglycemia can persist for several hours post-exercise unless a correction bolus of insulin is administered (16). When applied in

short bursts, however, anaerobic activity in the form of short (4-10 seconds) sprints can be used to attenuate declines in blood glucose during moderate aerobic exercise (4). Such sprints reduce hypoglycemia due to decreased glucose disposal rather than increased glucose production (17). Studies differ regarding whether or not exercise sessions involving intermittent high intensity intervals lead to a greater risk of nocturnal hypoglycemia, resulting from muscle and liver glycogen stores being replenished for up to 12 hours post-exercise (18-20). A summary of the response to anaerobic exercise in individuals with and without type 1 diabetes can be found in Table 2.

Resistance Exercise

Resistance exercise also relies mostly on anaerobic sources of fuel, and as such, elicits very similar hormonal and metabolic responses to that of anaerobic exercise such as high intensity running or cycling (21, 22). The design of each training protocol and the resulting hormonal responses depends on the goals of the individual performing them. The speed of the movement, along with the amount of weight lifted (as a percentage of the person's maximum lifting ability), the number of repetitions (times the weight is lifted), the number of sets of each exercise as well as the rest interval between the sets affect the body's response to the activity (22, 23).

During moderate-intensity resistance exercise in non-diabetic individuals, insulin and glucagon responses are the main regulators of blood glucose levels. More intense resistance exercise (faster or heavier lifts) will result in a greater release of catecholamines (24). Hepatic glucose production increases in proportion to the concentration of catecholamines present, increasing blood glucose (sometimes to the point of hyperglycemia) when glucose supply exceeds demand (24, 25). Within an hour of completing a resistance exercise session, the balance of insulin and glucagon restores blood glucose levels to baseline in individuals without diabetes.

Very few studies to date have examined the acute effects of resistance exercise in individuals with type 1 diabetes. Two recent publications indicate that, similar to other forms of anaerobic activity, resistance exercise causes less of a decline in blood glucose during exercise and a more stable blood glucose profile immediately post-exercise, without increasing the risk of nocturnal hypoglycemia (5, 26). These studies will be discussed in more detail below along with resistance exercise recommendations for individuals with type 1 diabetes, after an overview of the health benefits of resistance training and its impact on longer-term blood glucose control in individuals with type 1 diabetes.

The health benefits of resistance training

Recent decades have seen the transition of resistance exercise as a form of training primarily performed for competition weight lifting and body building, to a training tool for fitness, strength and balance in most sports, and a prescription for healthy living in the general population. With the aging of the population, a great deal of emphasis has been placed on the role of resistance training in the maintenance of muscle mass, strength and metabolic health (27), along with improved physical functioning and longer-lasting independence among elderly individuals (28). The therapeutic and prophylactic properties of resistance exercise training have also been recognized: studies have shown that this type of training can augment resting energy expenditure (29), increase bone mineral density (30), improve body composition by increasing lean muscle mass and decreasing fat mass (31), reduce the risk of type 2 diabetes through improvements in insulin sensitivity (32), lower resting blood pressure (33), ameliorate blood lipid profiles (34) and generally improve cardiovascular health (31, 33). In addition, resistance training has been associated with mental health benefits including improvements in self-rated quality of life (35), cognition (36), and self-esteem (37). Overall, resistance training offers a multitude of benefits for individuals of all ages and all fitness levels.

Resistance training and blood glucose control type 1 diabetes

While individuals with type 1 diabetes will experience all of the same health benefits of resistance training as people without diabetes, it remains to be conclusively shown whether or not resistance exercise has a positive effect on blood glucose control, as measured by hemoglobin A_{1c} (HbA_{1c}) in this population. Some studies found that resistance exercise, either on its own or combined with aerobic activity, reduced HbA_{1c} (38-41), while others did not find any positive effects on blood glucose control (42, 43). These studies have generally involved small sample sizes, and often lack a non-exercising control group with type 1 diabetes.

Among these studies, there are only two that have been published examining the chronic effect of resistance exercise training by itself on blood glucose control in type 1 diabetes (38, 39). Durak et al. (38) randomized eight subjects in a crossover design into two groups: one performing a 10-week resistance training program before taking a six-week break, and the second spent six weeks without exercise before performing the 10-week resistance training program (n=4 per group). The training consisted of three sessions weekly (approximately an hour each) of weight-lifting exercises. After the six weeks without training, mean HbA_{1c} was 6.9±1.4%, while post-training it was measured at 5.8±0.9% (P=0.05) (38). Additional benefits of the exercise included decreases in serum cholesterol and self-monitored blood glucose.

In a separate study, Ramalho et al. (39) randomized 16 previously sedentary type 1 diabetic participants to either 12 weeks of aerobic exercise three times per week, or 12 weeks of resistance exercise three times weekly. While the decrease in HbA_{1c} found in the resistance training group was not statistically significant (from 8.2±2.9% to 7.6±1.6%), aerobic training produced a significant increase in HbA_{1c} (from 8.7±1.6% to 9.8±1.8%; $P<0.05$) (39). It is possible that those performing aerobic exercise had a greater tendency to compensate with excessive carbohydrate intake in order to avoid hypoglycemia both during and after exercise, however these data were not reported by the study's authors. All participants in the study were following a regimen of multiple daily insulin injections (as opposed to an insulin pump), which has also

be associated with worse post-exercise blood glucose outcomes after aerobic exercise (44). Overall, both training programs reduced mean waist circumference, insulin dosage and self-monitored blood glucose, but these changes were only statistically significant in the aerobic exercise group.

The studies (40-43) involving combined aerobic and resistance training are also small in number and generally have small sample sizes (n=8 to 13, except for one study (43) where n=73). In addition, the lack of concurrent non-exercise control groups with diabetes in some of the studies complicates interpretation of the outcomes. In an early study, Petersen et al.(40) measured a significant decrease in HbA_{1c} (from 10.3% to 7.6%), a decrease in blood pressure, heart rate and mean body fat, and improvements in nerve conduction in 10 young adults with type 1 diabetes. The eight-month training program consisted of a five-minute warm-up, 15 minutes of cycling and 15 minutes of resistance exercise, in addition to monthly medical examinations, strict glucose monitoring instructions and weekly group meetings. Without a concurrent control group, it is difficult to know whether improvements in blood glucose control can be attributed to the exercise program, or simply to the improvements in patient blood glucose monitoring and other aspects of self-care. Similarly, while a study by Mosher et al. (41) found improved strength and cardiorespiratory endurance, increased lean body mass and significant improvements in HbA_{1c} (from 7.72±1.26% to 6.76±1.07%) in 10 adolescents with type 1 diabetes after 12 weeks of circuit training (45 minutes of combined endurance and strength activities three times weekly), it too lacked a non-exercising control group with type 1 diabetes.

Two recent studies, involving type 1 diabetic adolescents performing both aerobic and resistance training, included non-exercise control groups (42, 43). A small (n=8 per group) study by D'Hooge et al. (42) found that a combination of supervised aerobic (30 minutes) and strength (30 minutes) training performed twice weekly, improved muscular strength and endurance, and decreased insulin dosage, but had no significant effect on body composition or HbA_{1c} in children with type 1 diabetes. However, study participants had low compliance rates (mean attendance of 63%) and did not have their diet monitored

during the study, both of which could have negatively affected the outcome. A larger study by Salem et al. (43) in Egyptian children and adolescents with type 1 diabetes involved a combination of aerobic exercise (cycling/treadmill at 65 to 85% of target heart rate for 30 minutes including warm-up and cool-down), anaerobic exercise (1-2 minutes at >85% maximal heart rate) and resistance exercise (~20 minutes of lower body exercises involving sets of 10 repetitions at between 50 and 100% of the individual's 10 repetition maximum) and looked more closely at the importance of exercise frequency. Of the two exercise groups, one performed the exercise protocol once per week (n=75), while the other group exercised three times per week (n=73). A non-exercise type 1 diabetic control group (n=48) was also included. The published outcomes, however, must be viewed with caution, as it seems that the 24% of participants who did not adhere to the required protocol were not included in an intention-to-treat analysis, thereby increasing the likelihood of false positives. The amount of attrition for each group in the study is also not explicitly stated. Of the individuals analyzed, the control group showed a non-significant increase in HbA_{1c} (from 8.3±2.1 to 8.9±1.4%) while both exercise groups experienced significant decreases. Greater improvements were found in the group performing exercise more frequently [from 8.9±1.6 to 7.8±1% (P=0.03) versus 8.9±1.4 to 8.1±1.1% (P=0.01)]. Similarly, improvements in weight, body mass index (BMI), waist circumference, lipid profiles and insulin dosage were found in both exercise groups, with greater improvements being associated with higher exercise volume (43). The outcomes for the lipid profiles should be viewed with caution, though, as the more frequently exercising group had higher low density lipoprotein (P=0.01) and total triglycerides (P=0.001) at baseline.

Acute effects of resistance exercise on blood glucose levels in type 1 diabetes

Until very recently, there were no studies examining the acute effects of resistance exercise on blood glucose levels in type 1 diabetes. A recent study by our group (26) examined the acute glycemic effects of a resistance exercise protocol consisting of three sets of eight repetitions, of seven different exercises at the individual's pre-determined eight repetition maximum (8 RM), in comparison to aerobic exercise [45 minutes of treadmill running at 60% of their pre-determined maximal aerobic capacity (VO_{2peak})] and no

exercise (upright sitting for 45 minutes) in physically fit individuals with moderate to good control of their type 1 diabetes (HbA_{1c} = 7.1±1.1%). Participants wore continuous glucose monitoring (CGM) devices for 24 hours before the testing session, during the exercise session, and for 24 hours post-exercise. They also consumed the same foods (self-selected) for three straight days (the day before, the day of, and the day after testing) at the same time of day for all three testing sessions and matched their insulin intake for each day of monitoring as closely as possible.

Plasma glucose decreased rapidly during aerobic exercise resulting in significantly lower levels than the no-exercise condition within 10 minutes of exercise. Declines during resistance exercise were more gradual and of a smaller magnitude (Figure 1), with differences only being significant after 45 minutes of resistance exercise when compared to the no-exercise session. During exercise, two out of 12 participants needed carbohydrate supplementation (glucose tablets) due to low blood glucose levels in the no-exercise trial, nine out of 12 in the aerobic exercise trial and three out of 12 for the resistance exercise session (26). Post-exercise, blood glucose levels remained unchanged in the one-hour recovery period after the resistance exercise and no-exercise sessions, while a significant increase in blood glucose was observed after the aerobic exercise session. Less late (three to six hours) post-exercise hyperglycemia (as measured by CGM) was also found after resistance exercise than after aerobic exercise, with blood glucose trends after resistance exercise mirroring those from the no-exercise control session (Figure 2) (26).

Combining Aerobic and Resistance Exercise

Many individuals who perform both resistance and aerobic exercise regularly tend to combine them into a single session. In type 1 diabetic individuals, recent studies by us indicate that including resistance exercise alongside aerobic exercise affects blood glucose levels differently than performing aerobic exercise alone. Specifically, performing resistance exercise (three sets of eight repetitions of seven different exercises at the participants' 8 RM, session duration of approximately 45 minutes) prior to aerobic exercise (45 minutes at 60% VO_{2peak}) may attenuate the declines in blood glucose associated with

moderate aerobic activity (Figure 3). In one of our studies, the participants' plasma glucose concentration decreased significantly over the course of the exercise session when aerobic exercise was performed alone (from 9.2±3.4 to 5.8±2.0 mmol/l, P=0.001). When the participants performed resistance exercise prior to the same aerobic exercise protocol on a separate occasion, changes in plasma glucose concentration were much smaller (from 9.2±4.0 to 6.9±3.1 mmol/l, P=0.04). The declines in blood glucose during the aerobic exercise session may have been even more pronounced had fast acting glucose supplements (Dex 4®, AMG Medical, Montreal) not been provided: participants were given 16 g of glucose in tablet form when blood glucose levels dropped below 4.5 mmol/L during the exercise session. More participants required carbohydrate supplementation during the session that involved aerobic exercise on its own (nine out of 12 as compared to five out of 12 where resistance exercise preceded the running), in spite of the greater energy demands associated with the combined exercise session. Performing the resistance exercise in addition to the aerobic activity also did not increase the risk of nocturnal hypoglycemia, as frequency of low blood glucose, average low blood glucose, and area under the curve were similar for both exercise sessions (unpublished).

When aerobic and resistance exercise are combined into a single exercise session, the order in which the exercises are performed also affects blood glucose levels in type 1 diabetic individuals (5). When regularly active individuals with type 1 diabetes (n=12) performed aerobic exercise (45 minutes of running at 60% VO_{2peak}) prior to resistance exercise (three sets of eight repetitions of seven different exercises at the participants 8RM, session duration of approximately 45 minutes) blood glucose levels were lower throughout exercise, with differences reaching statistical significance between 30 and 60 minutes of exercise, than when resistance exercise was performed first (Figure 4). Post-exercise, blood glucose levels increased significantly during the one-hour recovery where aerobic exercise preceded resistance exercise (5). No increases were found when the opposite order of exercise took place. In addition, 10 out of 12 participants required supplementation to avoid hypoglycemia during the aerobic then resistance exercise session, while only six out of 12 participants required carbohydrate intake when

resistance exercise preceded the aerobic activity (5). These data indicate that individuals with type 1 diabetes who frequently experience hyperglycemia associated with high intensity or resistance exercise may wish to perform their aerobic exercise first, while those who have difficulties with exercise-induced hypoglycemia should perform resistance-type activities before aerobic ones in a combined exercise session.

Resistance exercise recommendations for type 1 diabetes

The Canadian Diabetes Association Clinical Practice Guidelines currently recommends that individuals with diabetes perform resistance training at least twice (preferably three times) per week in addition to 150 minutes of moderate to vigorous aerobic activity (spread over at least three days of the week) (45). For individuals undertaking a resistance exercise program for the first time, it is generally recommended to begin under the supervision of a certified personal trainer or exercise specialist in order to ensure good form and progression and thereby prevent overtraining and/or injury. Where insulin and carbohydrate adjustments are concerned, declines in blood glucose during resistance exercise programs similar to those we examined (sets of 8 to 10 repetitions, 1.5 to 2 minutes between sets) are likely to be smaller than those experienced during aerobic exercise. As a result, undertaking this type of activity, especially if performed on its own, may require minimal adjustments to insulin dosage or carbohydrate intake. While high volume resistance exercise protocols (i.e. 15 to 20 repetitions with low to moderate resistance and rests of 30 to 60 seconds between sets) have not been studied in individuals with type 1 diabetes, it is likely that these will be associated with a steeper decline in blood glucose, due to the more aerobic nature of the activity. Likewise, training protocols involving short sets (i.e. three to five repetitions) with heavy resistance may be associated with a higher epinephrine response (22) and therefore a greater likelihood of high blood glucose levels. The fitness level of the individual performing resistance exercise could also impact acute blood glucose responses, as highly trained individuals are known to have higher epinephrine secretion, and consequently greater increases in blood glucose, in response to exercise than untrained individuals (46).

When combining aerobic and resistance activities within a single exercise session, it is advisable to perform resistance exercise prior to aerobic exercise if low blood glucose during exercise is a concern. It should be noted that these recommendations are based on studies involving relatively young individuals with type 1 diabetes, and that the effects of resistance exercise in older adults with type 1 diabetes remain to be examined. With age-related declines in muscle mass (47) the glucose lowering effect of exercise may be attenuated in older individuals. In addition, hormonal responses to resistance exercise will probably be less pronounced (48), which could potentially decrease the glucose stabilizing effect of resistance exercise in older individuals with type 1 diabetes. As with beginning any type of exercise program, individuals with type 1 diabetes should check their blood glucose levels frequently and be prepared to make adjustments both during exercise, and in the 12 to 24 hours following activity. In addition, it is highly recommended that individuals with type 1 diabetes undergo screening for diabetic retinopathy with a dilated retinal exam or retinal photographs prior to starting a resistance training program, if it has not been done in the previous year. Pre-proliferative or proliferative retinopathy, if present, should be treated and stabilized before starting a resistance exercise program.

Perspective

There is still a great deal to learn about the effects of resistance exercise on acute blood glucose responses in individuals with type 1 diabetes, and the effects of different frequencies, intensities and durations of resistance exercise to prescribe. The only type of protocol that has been examined in this population so far is a relatively high-intensity protocol consisting of three sets of eight repetitions at the maximum weight that can be lifted eight times. Blood glucose responses for moderate-intensity programs aimed at increasing muscular endurance (i.e. consisting of three or more sets of 15 or more repetitions) still need to be quantified. An examination of shorter weight lifting sets consisting of three to five repetitions where much heavier loads are lifted and longer rest periods are provided between sets (designed for maximizing strength and muscle hypertrophy) is also warranted. Finally, a study examining the effects of alternating

resistance and aerobic exercises for short periods of time (i.e. circuit training, as is often performed in fitness “boot camps”) would also be beneficial.

To be able to generalize the results of these studies, there are several factors that must be examined more closely. The responses of several exercise-related hormones (cortisol, growth hormone, catecholamines, etc.) vary depending on the age (24), sex (24, 49), and fitness level (11) of the individual, thereby warranting studies of these various subgroups. There is also recent evidence to indicate that blood glucose responses to exercise might be different depending on whether the individual is using an insulin pump, or multiple daily injections for their insulin delivery (44), the reasons for which need to be explored in greater detail.

Considering the technology that is currently available (i.e. continuous glucose monitoring systems), we now have the potential to extend the window of observation associated with these exercise sessions to include data for the overnight period, and even for a few days post-exercise, without requiring subjects to remain in a lab. The effects of exercise on blood glucose homeostasis may extend well beyond the 12-hour period in individuals with type 1 diabetes, although the myriad of factors that influence blood glucose levels make examining the prolonged effects of exercise on glucose control challenging. Continuous glucose monitoring systems have been identified as a useful and accurate (50) tool for monitoring blood glucose trends during exercise, recovery, and overnight post-exercise. The ability to observe overnight trends will allow a closer examination of the lasting effects of an exercise session, as well as providing the ability to compare with the nights where exercise has not been performed. In theory, this may eventually enable us to provide better recommendations for exercise in terms of the type, duration and intensity of exercise, and to refine algorithms for adjustment of insulin and carbohydrate intake for individuals with type 1 diabetes. While being vigilant of blood glucose levels will always be necessary when performing resistance exercise, this type of activity has numerous benefits and should be recommended as an important activity for health and well-being in individuals with type 1 diabetes.

Author Disclosure

R. Sigal is supported by a Health Senior Scholar award from the Alberta Heritage Foundation for Medical Research. G. Kenny is supported by a University of Ottawa Research Chair. B. Perkins is supported by a Canadian Diabetes Association Research Scholar Award and has received consultation fees from Glaxo Smith Kline, honoraria from Johnson and Johnson, Sanofi-Aventis, Medtronic and Novo-Nordisk and grant support from Boehringer Ingelheim and Medtronic. M. Riddell has received speakers' fees from Medtronic Canada.

Contributions

The manuscript was drafted by J. Yardley. G. Kenny, B. Perkins, M. Riddell, and R. Sigal provided content advice, and reviewed/edited the manuscript.

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TABLES AND FIGURES

Table 1 – Responses to aerobic exercise in individuals with and without type 1 diabetes

Table 2 – Response to anaerobic exercise in individuals with and without type 1 diabetes

Figure 1. Mean (±SE) plasma glucose during exercise and 60 minutes of recovery (n = 12). □ = control session, ♦ = resistance exercise session, ▲ = aerobic exercise session. a = statistically significant change from baseline in aerobic exercise; b = statistically significant change from baseline in resistance exercise; c = statistically significant difference between control session and aerobic session; d = statistically significant change throughout recovery after aerobic exercise. Differences were only considered statistically significant if still significant after Bonferroni corrections for multiple comparisons. Copyright 2012 American Diabetes Association. From Diabetes Care®, Vol.36, 2013;537-542. Modified by permission of *The American Diabetes Association.*

Figure 2. Mean glucose as measured by continuous glucose monitoring (CGM) from 1 to 12 hours post-exercise. The solid line represents the control session, the dotted line represents the aerobic exercise session and the dashed line represents the resistance exercise session. The box represents the period of time where glucose was significantly higher after aerobic exercise as compared to resistance exercise ($p < 0.05$). n=11 (control), n=10 (aerobic), n=12 (resistance). Copyright 2012 American Diabetes Association. From Diabetes Care®, Vol.36, 2013;537-542. Modified by permission of *The American Diabetes Association.*

Figure 3 –Plasma glucose during 45 minutes of aerobic exercise on its own (AE – dashed line with open symbols ○) or after resistance exercise (RA – solid line with closed symbols ●). Data are presented as means and error bars represent SE (n=12 for aerobic only session, n=11 for combined resistance then aerobic session). * indicates statistical significance for changes from baseline (after Holm-Bonferroni adjustment). † indicates statistical significance for changes from the end of exercise (after Holm-Bonferroni adjustment).

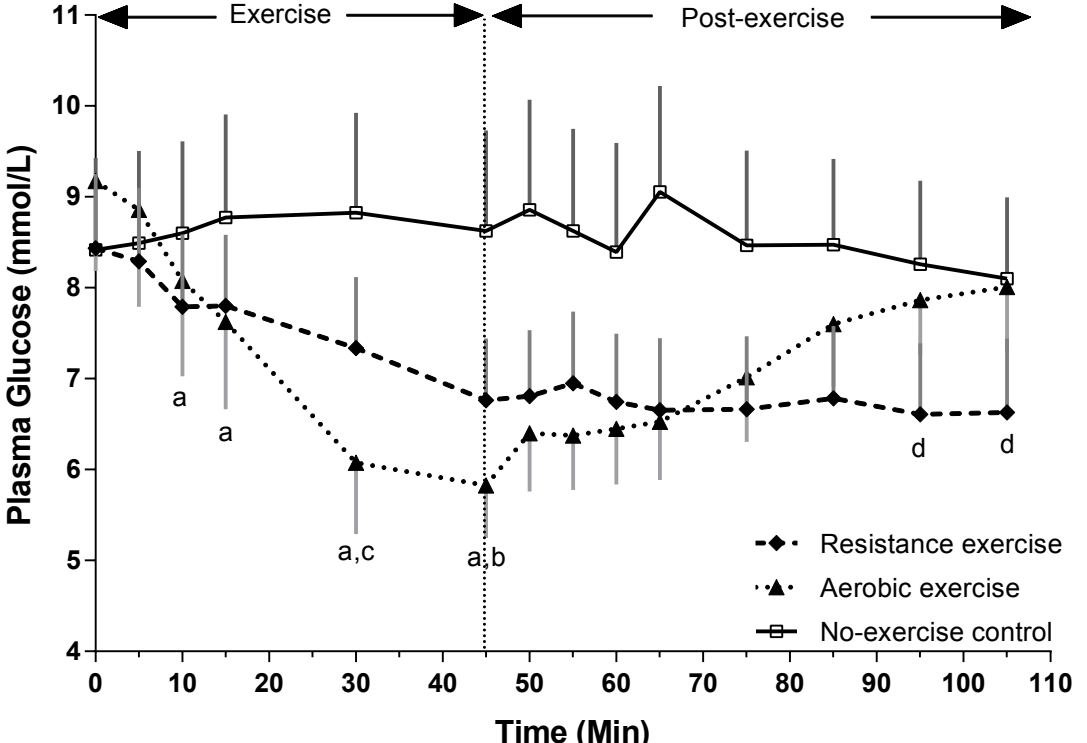
Figure 4 – Mean (±SE) plasma glucose during exercise and recovery for aerobic exercise performed before resistance exercise (**AR** – dashed line with open symbols) and resistance exercise performed before aerobic exercise (**RA** – solid line with closed symbols) (n=11). * denotes difference from baseline during exercise where $P<0.05$. † denotes difference between conditions where $P<0.05$. ‡ denotes change throughout recovery from end-exercise level where $P<0.05$.

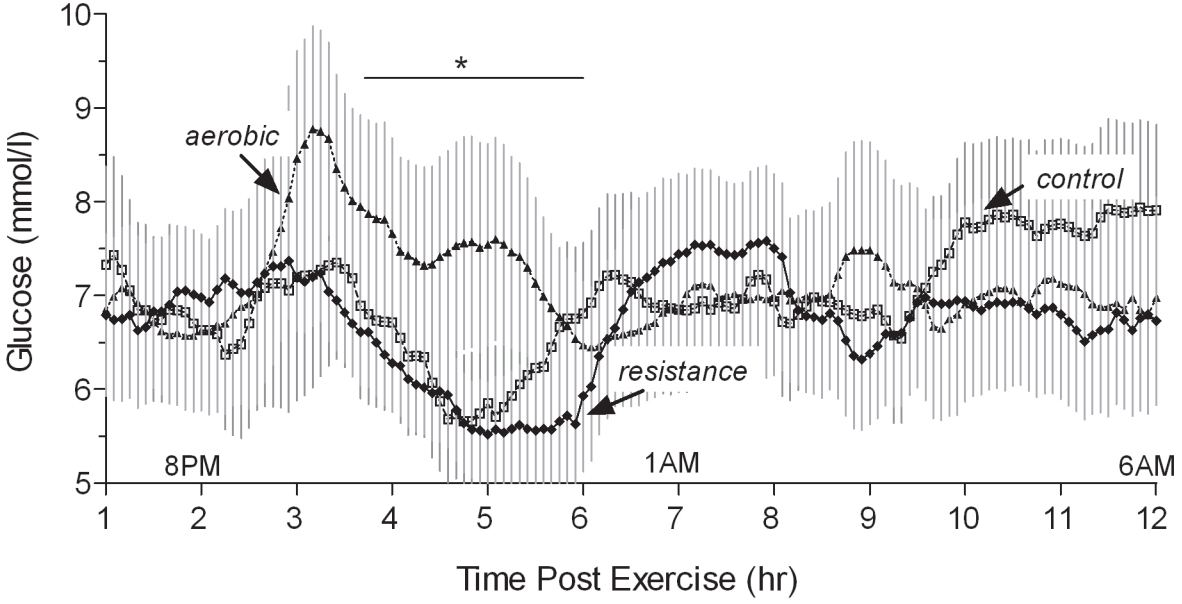
Table 1 – Responses to aerobic exercise in individuals with and without type 1 diabetes

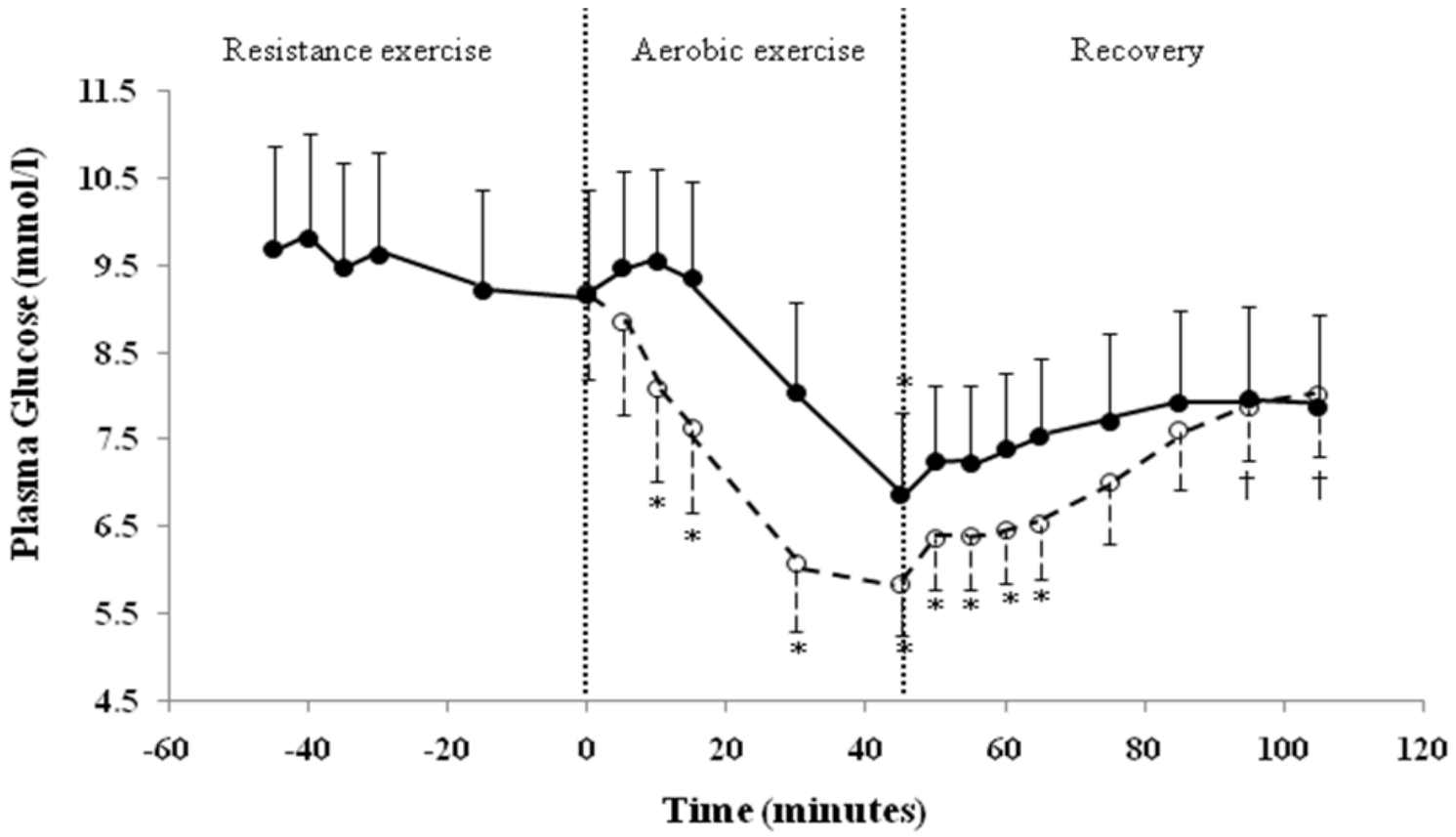
EXERCISE RESPONSE	**NO DIABETES**	**TYPE 1 DIABETES**
Change in Glucose Uptake	↑↑↑	↑↑↑
Initial Blood Glucose Response	↓	↓
Insulin Response	**↓↓**	**↔**
Glucagon Response	**↑↑**	**↑ or ↔**
Catecholamine Response	↑	↑
Hepatic Glucose Production	**↑↑↑**	**↑**
Resulting Blood Glucose Levels	**↔** **(euglycemia)**	**↓↓** **(hypoglycemia)**

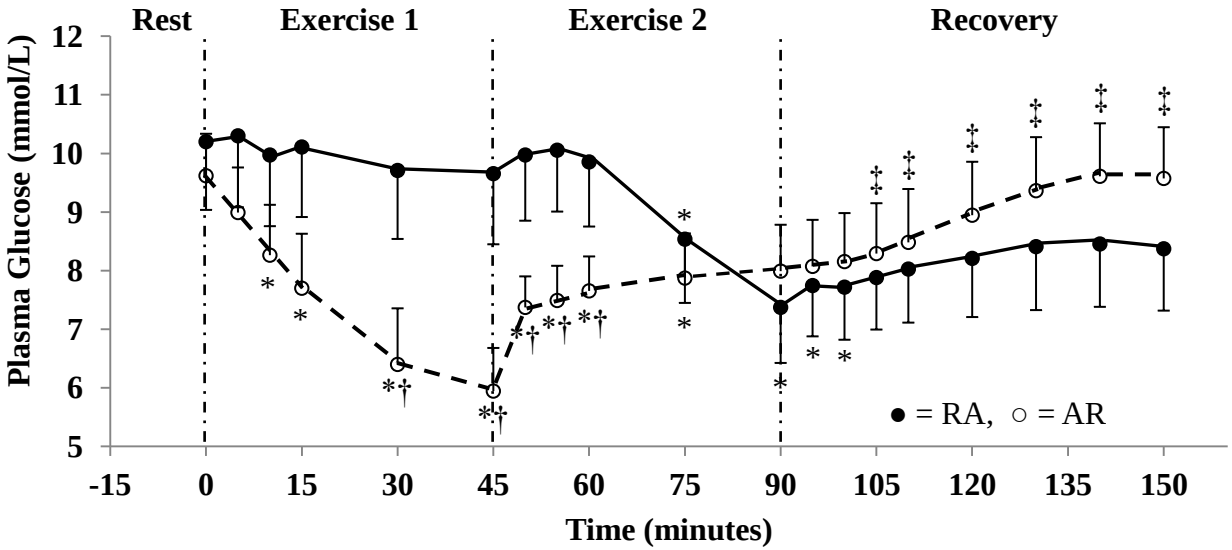
Table 2 – Response to anaerobic exercise in individuals with and without type 1 diabetes

EXERCISE RESPONSE	**NO DIABETES**	**TYPE 1 DIABETES**
Change in Glucose Uptake	↑↑↑	↑↑↑
Catecholamine Response	↑↑↑↑	↑↑↑↑
Insulin Response (exercise)	↓	↔
Glucagon Response (exercise)	↑↑	↑ or ↔
Hepatic Glucose Production	↑↑↑↑	↑↑↑↑
Insulin Response (post-exercise)	↑↑	↔
Resulting Blood Glucose Levels	↔ **(euglycemia)**	↑↑ **(hyperglycemia)**


Exercise
Post-exercise
Plasma Glucose (mmol/L)
Time (Min)
11
10
9
8
7
6
5
4
0
10
20
30
40
50
60
70
80
90
100
110
a
a
a,c
a,b
d
d
Resistance exercise
Aerobic exercise
No-exercise control


10
9
8
7
6
5
Glucose (mmol/l)
*
aerobic
control
resistance
8PM
1AM
6AM
1
2
3
4
5
6
7
8
9
10
11
12
Time Post Exercise (hr)


Resistance exercise
Aerobic exercise
Recovery
Plasma Glucose (mmol/l)
11.5
10.5
9.5
8.5
7.5
6.5
5.5
4.5
-60
-40
-20
0
20
40
60
80
100
120
Time (minutes)


Rest
Exercise 1
Exercise 2
Recovery
Plasma Glucose (mmol/L)
12
11
10
9
8
7
6
5
-15
0
15
30
45
60
75
90
105
120
135
150
Time (minutes)
● = RA, ○ = AR