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1 **Exercise management in type 1 diabetes: a consensus statement**

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47 **Abstract**

48 Type 1 diabetes (T1D) is challenging condition to manage for a variety of physiological and behavioural
49 reasons. Regular exercise is important, however management of the different forms of activity is a
50 particular struggle for both the individual with T1D and the health care provider. People with T1D tend
51 to be at least as inactive as the general population, with a large percentage of individuals not
52 maintaining a healthy body mass nor achieving the minimum number of minutes per week of moderate-
53 to-vigorous aerobic activity. Regular exercise can improve health and well-being and can help individuals
54 to achieve their lipid, body composition, fitness and glycaemic goals. However, several additional
55 barriers to exercise may exist for the person with diabetes including fear of hypoglycaemia, loss of
56 glycaemic control, and inadequate knowledge around exercise management. This review provides an up
57 to date consensus on exercise management for individuals with T1D who exercise regularly, including
58 glucose targets for safe and effective exercise, and nutritional and insulin dose adjustments to protect
59 against exercise-related glucose excursions.

60 Introduction

61 Despite tremendous advances since the discovery of insulin almost 100 years ago, type 1
62 diabetes (T1D) remains a challenging disease to manage (1,2). A majority of patients living with T1D are
63 not at a healthy body weight (~60% are overweight or obese), suffer from hypertension (~40%) and/or
64 dyslipidaemia (~60%) (3) and are not engaging enough regular physical activity (4). Regular exercise
65 helps patient achieve a number of goals. It improves the cardiovascular disease risk profile in paediatric
66 patients (5) and reduces HbA1c (-0.3%) in that particular segment of the patient population (6). Body
67 composition, cardiorespiratory fitness, endothelial function and blood lipid profile (i.e. triglycerides,
68 total cholesterol) all improve with regular physical activity in children and young people with T1D (7).
69 These cardiometabolic improvements are all important, given that cardiovascular disease is the leading
70 cause of morbidity and mortality in persons with T1D (8). In adults, both retinopathy and
71 microalbuminuria are less common in those who are more physically active (9). Active adults with T1D
72 tend to have better chance of achieving target HbA1c levels, blood pressure levels and a healthier body
73 mass index when compared to inactive patients (3). Regular exercise also lowers total daily insulin needs
74 (10). Having a high exercise capacity in adulthood with T1D is associated with less risk for coronary
75 artery disease, myocardial ischaemia and stroke if you have diabetes or not (11). In a large cross
76 sectional study of 18,028 adults with T1D, patients who fall in the most active category of physical
77 activity levels (exercising two or more times per week) had better HbA1c levels, a more favourable body
78 mass index, less dyslipidaemia, hypertension and fewer diabetes-related complications (retinopathy,
79 microalbuminuria), compared to those who were less habitually active (3). In general, patients with T1D
80 who are more active tend to have less diabetic ketoacidosis and less risk for developing severe
81 hypoglycaemia with coma (3), except for with older women where this latter relationship is reversed;
82 those most active have higher rates of severe hypoglycaemia (with coma) when compared with those
83 who are inactive (3). However, several barriers may exist for exercise including: a fear of hypoglycaemia;
84 a loss of glycaemic control, lack of time; access to facilities; lack of motivation; issues around body image
85 and a general lack of knowledge around exercise management (12–14).

86 The physical activity prescription for all adults living with diabetes, including those living with
87 T1D, is 150 minutes of accumulated physical activity each week, with no more than 2 days in a row with
88 no activity. Resistance exercise is also recommended two to three times a week. Getting this much
89 exercise is difficult for a large majority of patients; with less than 20% of patients performing aerobic
90 exercise more than two times per week and 60% of the patient population performing no structured
91 exercise at all (3). For children and adolescent, at least 60 minutes of physical activity should be
92 performed per day (15). Physical inactivity and prolonged sitting times increase gradually with age and
93 are linked to high HbA1c levels in youth with T1D (16) and inactivity appears to be more common in
94 females than in males (3).

95 Regular exercise should be encouraged and supported by health care professionals (HCPs), for a
96 number of reasons, but primarily because the overall cardiometabolic benefits outweigh the immediate
97 risks if certain precautions are made. In this review, the basic categories of exercise are described from a
98 physiological perspective as are the starting points for nutritional and insulin dose adjustments to keep
99 patients in a targeted glycaemic range. This review summarizes our consensus on the available

100 strategies that help incorporate exercise safely into the daily T1D management plan for those adults
101 who are regularly engaging in exercise, sport and/or competitive events. It is hoped that these new
102 guidelines for exercise management will improve patient control and engage more individuals with T1D
103 to be more physically active.

104

105 **Search strategy and selection criteria**

106 We searched PubMed.gov and other relevant biomedical databases for articles pertaining to
107 'type 1 diabetes' OR 'insulin-dependent diabetes AND 'exercise' OR 'physical activity'; published
108 between 01/1990 to 07/2016 and filtered for human and restricted to English publications. Additional
109 searches using the search terms 'nutrition' OR 'dietary carbohydrate' OR 'dietary protein' OR 'glycemic
110 index' OR 'hypoglycaemia' OR 'energy expenditure OR 'glycemic control' OR 'management' OR
111 'hypoglycemia' OR 'hyperglycemia' OR 'prevention & control' were conducted for various subtopics
112 within this review.

113

114 **Physiology of Physical Activity and Exercise**

115 Modalities of exercise

116 Understanding the metabolic and neuroendocrine responses to the various types of exercise undertaken
117 by people with T1D is critical for determining appropriate nutritional and insulin management
118 strategies. Exercise is generally classified as *aerobic* or *anaerobic*, depending on the predominant energy
119 systems used to support the activity, although a majority of exercise activities include a mix of energy
120 systems. Aerobic exercise involves repeated and continuous movement of large muscle groups (e.g.
121 walking, cycling, jogging, and swimming) that rely primarily on aerobic energy-producing systems.
122 Resistance (strength) training is a type of exercise using free weights, weight machines, body weight, or
123 elastic resistance bands that rely primarily on anaerobic energy-producing systems. High intensity
124 interval training (HIIT), involves alternating between brief periods of vigorous exercise and recovery
125 periods at low-to-moderate intensity (e.g., from 20 seconds to 4 minute intervals of exercise and rest,
126 for up to ~10 cycles) (17). Both aerobic and resistance type activities are recommended for a majority of
127 people living with diabetes (15,18) and recent guidelines also now incorporate HIIT as a training
128 modality with established benefits for individuals with prediabetes or type 2 diabetes (18). In some
129 studies, HIIT has been shown to be more effective than continuous aerobic training in improving
130 cardiovascular fitness and various parameters related to glucose metabolism including insulin sensitivity
131 and glycaemic control in type 2 diabetes (19). At present, it is unclear what form(s) of exercise are best
132 for improving cardiometabolic control in type 1 diabetes (20).

133 Neuroendocrine and metabolic responses to exercise

134 *Individuals without diabetes*

135 The metabolic responses to different forms of exercise are distinct. However, in almost all forms of
136 exercise, no matter the intensity or duration, blood glucose concentrations are normally held within a
137 tight range (4-6 mmol/l). During aerobic exercise, insulin secretion drops and glucagon secretion rises in
138 the portal vein to facilitate glucose release from the liver to match the rate of glucose uptake into the
139 working muscles (21). Exercise can increase glucose uptake into muscle by up to 50-fold; a phenomenon
140 independent of insulin signalling (22), so the drop in insulin in the circulation does not limit glucose
141 provision to the working body. Although the main determinant of glucose production for aerobic
142 exercise is a rise in glucagon levels, there is also neural control of glucose release and other
143 counterregulatory hormones play a supportive role (23). With increased exercise duration, there is
144 reduced reliance on muscle glycogen as fuel and a greater reliance on lipid oxidation and plasma-derived
145 glucose (24). If insulin levels do not fall during aerobic exercise, the rise in counterregulatory hormones
146 is less effective in promoting hepatic glucose production (21).

147 As the intensity of exercise increases above ~50-60% of maximal oxygen consumption (VO_2max),
148 fat oxidation decreases, particularly in those who are untrained, and CHO are the preferred fuel (25).
149 Prolonged high-intensity exercise is supported by both muscle glycogen and blood glucose utilization
150 with minimal contributions from lipid and protein (26). During predominantly anaerobic activities (27)
151 and during a HIIT session (28), circulating insulin concentrations do not drop as markedly as compared to
152 purely aerobic activities, in part because the duration of activity is typically shorter. High rates of
153 external power output during HIIT increase reliance on muscle phosphagens and glycogen, with lactate
154 levels rising markedly in the circulation (28). Insulin levels increase above baseline levels in early
155 recovery from a HIIT session to offset the rise in glucose caused by the elevations in counterregulatory
156 hormones and other metabolites (27).

157

158 *Dysglycaemia during exercise in individuals with T1D*

159 In T1D, the glycaemic responses to exercise are influenced by the location of insulin delivery, the
160 amount of insulin in the circulation, the pre exercise blood glucose concentration, the composition of
161 the last meal or snack, as well as the intensity and duration of the activity (29) (Figure 1).

162 During aerobic exercise, most individuals with T1D have a drop in glycaemia, unless
163 carbohydrates (CHO) are ingested, because insulin levels cannot be lowered rapidly enough at the start
164 of the activity, and levels may rise in the systemic circulation (30), perhaps because of increased
165 subcutaneous adipose tissue blood flow during exercise (31). Even if basal insulin infusion rates are
166 halved 60-min before the start of exercise in patients on continuous subcutaneous insulin infusion (CSII),
167 circulating free insulin levels do not drop at exercise commencement and levels tend to rise transiently
168 during the activity (32). Higher insulin levels in circulation during exercise promotes increased glucose
169 disposal relative to hepatic glucose production, and may delay lipolysis, another feature that increases
170 the muscles reliance on glucose as a fuel. Hypoglycaemia develops in a majority of patients within ~45
171 minutes of activity (33,34). Trained individuals with T1D have greater reductions in blood glucose
172 concentrations during aerobic exercise when compared to less fit patients (35), possibly because the

173 overall work rate is higher in those more aerobically conditioned. As such, both trained and untrained
174 individuals with T1D typically require increased CHO intake, and/or insulin dose reduction, for prolonged
175 aerobic exercise (see below). High intensity interval sprint training promotes increased oxidative
176 capacity of skeletal muscle in T1D and attenuates the rates of glycogen breakdown (36), which may
177 protect against post-exercise hypoglycaemia, at least in theory. Perhaps in line with this, individuals who
178 are aerobically conditioned have reduced glucose variability compared to those unconditioned (37). Low
179 insulin levels due to aggressive reductions in administration or a skipped insulin dose can cause
180 hyperglycaemia prior to and during aerobic exercise (38) and ketosis may develop, even with mild
181 activity (39).

182 Compared to continuous moderate-intensity aerobic exercise, resistance exercise is associated
183 with better glucose stability (40), although it may cause a modest rise in some individuals (41).
184 Compared to aerobic exercise, performing a HIIT session attenuates the drop in glycaemia (42), as does
185 performing resistance exercise before aerobic exercise (43), possibly because of increases in
186 counterregulatory hormones and various metabolites that limit glucose disposal (44). In situations of
187 brief and intense anaerobic exercise (e.g. sprinting, weight lifting, some competitive sports) (41,45), or
188 during HIIT (28), glucose levels typically rise.

189

190 *Dysglycaemia post-exercise in individuals with T1D*

191 Immediately after aerobic exercise, glucose uptake into muscle drops but overall glucose disposal
192 is still elevated for hours in recovery to help replenish glycogen stores (46). Hypoglycaemia risk is
193 elevated for at least 24 hours in recovery from exercise with the greatest risk for nocturnal
194 hypoglycaemia occurring after afternoon activity (47). As mentioned above, weight lifting, sprinting and
195 intense aerobic exercise can promote elevations in glycaemia that may last for hours in recovery.
196 Although a conservative insulin “correction” post-exercise may be prudent in some situations (48), over-
197 correction with insulin can promote severe nocturnal hypoglycaemia and death (49). HIIT appears to
198 increase risk for nocturnal hypoglycaemia compared to continuous aerobic exercise in some (50), but
199 not all (51,52) studies.

200

201 **Exercise Goals and Glycaemic Targets**

202 Individuals with T1D should perform exercise for a variety of health reasons. The evidence that
203 regular exercise training improves metabolic control in adults with T1D is somewhat limited (20,53),
204 although in youth it appears to be helpful (7). Exercise readiness questionnaires for adults with diabetes
205 who may be at increased risk for adverse events can be found at eparmedx.com. Patient goals for
206 exercise should be considered before making management decisions (e.g. metabolic control and
207 prevention of complications, fitness, weight loss, competition/performance). This is a critical element of
208 the diabetes management plan. For example, exercise for weight loss requires strategies that focus on
209 reducing insulin levels during and after exercise, as opposed to consuming additional CHOs. By contrast,

210 if maximising sports and exercise performance is the primary goal, then sport-specific nutritional
211 guidance is needed and a modified insulin plan to match increased nutritional requirements should be
212 considered (54). For all patients, blood glucose monitoring before, during and after exercise is critical for
213 informing strategies and maintaining stable and safe glycaemia.

214 The appropriate blood glucose concentration for the start of exercise should be individually
215 tailored. Based on consensus, a reasonable starting range for most patients doing aerobic exercise
216 lasting up to an hour is between 7-10 mmol/l. This range balances performance considerations against
217 hypoglycaemia risk. Higher levels may be acceptable in some situations where added protection against
218 hypoglycaemia is needed. Achieving and maintaining circulating glucose in this range is challenging. The
219 glycaemic response to exercise is variable and based on several factors including the duration and
220 intensity of exercise (44,55), the starting level of glycaemia (34), the individual's aerobic fitness (35) and
221 the amount of insulin in circulation (56,57) (Figure 1). Anaerobic and a HIIT session can be initiated with
222 a lower starting glucose level (5-7 mmol/l) since glucose concentrations tend to remain relatively stable,
223 fall to a lesser extent compared to continuous aerobic exercise, or rise slightly (Figure 1). Strategies to
224 cope with a range of glucose concentrations near the start of exercise are provided in Table 1. If glucose
225 level is too high because of insulin omission, risk of ketosis and further hyperglycaemia can occur (39)
226 and work effort probably rises. Although it is unclear if there is an optimal glycaemic range for exercise
227 performance, clinical experience and limited field study investigation (58) suggest that maintaining a
228 concentration between ~6.0-8.0 mmol/l may be ideal.

229

230 **Contraindications and cautions for exercise**

231 While few exercise limitations should be placed on patients, some considerations are important:

232 A. Ketones

233 Elevated blood ketones (≥ 1.5 mmol/l) before a bout of exercise should be addressed prior to
234 the start of the session via insulin administration and/or CHO feeding (Table 1). The cause of
235 elevated ketone levels should be identified (illness, diet manipulation, a recent bout of
236 prolonged exercise, insulin omission, etc.). Both prolonged endurance type activities
237 (marathons, trekking, etc.) and very low CHO diets can elevate blood ketone levels in
238 patients and the HCP should define appropriate levels and provide tailored guidance for
239 each individual. Blood ketone levels of ≥ 3.0 mmol/l should be managed immediately by a
240 qualified HCP (e.g. emergency department, physician, etc.).

241 B. Recent hypoglycaemia

242 Severe hypoglycaemia (defined here as a blood glucose ≤ 2.8 mmol/l or a hypoglycaemic
243 event requiring assistance from another individual) within the previous 24 hours is a
244 contraindication to exercise, due to the significant increased risk of a more serious episode
245 during the exercise (59). Where minor hypoglycaemia (blood glucose 2.9-3.9 mmol/l, with

246 the ability to self-treat) has occurred, the increased risk of a recurrence must be taken into
247 account (60). Vigilance around monitoring should be stressed and exercise should be
248 avoided if the setting is deemed particularly unsafe (e.g. swimming/trekking alone).

249 C. Diabetes-related complications

250 Overall the health benefits of being physically active outweigh the risks of being sedentary
251 for people with diabetes. Those with complications can derive numerous health benefits
252 from lower intensity physical activities, with little risk for any adverse events (61). In those
253 with long-standing disease, or with HbA1c levels well above target, vigorous exercise, heavy
254 weight-bearing activities and competitive endurance events are contraindicated, particularly
255 if the patient has unstable proliferative retinopathy, severe autonomic dysfunction or renal
256 failure (61).

257 D. Failure to be prepared for exercise-associated hypoglycaemia

258 In preparation for exercise, individuals with T1D should be aware of their starting glucose
259 concentrations, have blood glucose monitoring equipment and snacks to treat
260 hypoglycaemia. They should also be advised to wear/carry diabetes identification.

261

262 **Nutritional Management**

263 Goals for nutritional management

264 Nutritional management for people with T1D should incorporate strategies that optimise
265 glycaemic control, while promoting long-term health (62). The main strategies around nutrition for
266 exercise and sport discussed in this section are primarily to maximise athletic performance and are
267 based largely on studies conducted in highly trained healthy individuals without diabetes (63), with
268 limited studies in people with T1D. The application of these strategies must consider the individual's
269 insulin management plan and specific advice targeting nutrition for both athletic performance and
270 glycaemic management (see Glycaemic Management section below). A registered dietitian with
271 specialist diabetes and sports knowledge is the most qualified to help active people with T1D.

272 An individualised meal planning approach is central to improving performance and glycaemic
273 outcomes. Daily CHO intake should relate to the fuel cost of training in the athletic subpopulation and
274 hypoglycaemia prevention for all active people. Balancing insulin dose to CHO intake during exercise is
275 essential. A variety of CHO and insulin adjustment strategies can be used, such as reducing the pre-
276 exercise bolus insulin dose by 30-50% up to 90 minutes before aerobic exercise (64), consuming high
277 glycaemic index (GI) CHO (30-60g /hour) during sport or replacing CHO post-exercise for anaerobic
278 exercise. Personal tolerance of ingested CHO particularly during exercise is a key factor in individualising
279 recommendations. The distribution of macronutrient intake over the day should take into account the
280 timing of exercise so that liver and muscle glycogen stores are maximised before the activity and

281 replenished in early recovery (63). This strategy should include CHO feeding well before exercise (~4
282 hours) and early in recovery (63,65).

283

284 Daily energy and macronutrient balance

285 Athletes with T1D need sufficient energy to meet the demands of their daily activity. These will
286 vary with age, sex, body composition and activity type (66). Total energy requirements differ with
287 individual aims. Predictive equations can be used to estimate resting energy expenditure (67); however
288 they should serve only as a guide as they may over or underestimate actual requirements. An
289 appropriate macronutrient balance and micronutrient intake (63), coupled with a glycaemic control
290 strategy, is required to maximise performance. The optimal macronutrient distribution will vary
291 depending on an individualised assessment and exercise goals. A guide to the distribution of the total
292 daily energy intake is 45-65% CHO, 20-35% fat and 10-35% protein, with higher protein intakes indicated
293 for individuals wanting to lose weight (68).

294 The major nutrients required to fuel performance are CHOs and lipids, while the addition of
295 protein is needed to help foster recovery and maintain nitrogen balance (63,69). Protein requirements
296 range from 1.2- 1.6 g/kg body weight (BW) /day and will vary with training type and intensity and CHO
297 availability (63,70). Higher intakes may be needed for recovery from injury or for individuals on energy
298 restricted diets (71) to maintain lean body mass.

299

300 CHO needs before, during and after exercise

301 Distinction should be made between CHO needs for performance and CHO required for
302 hypoglycaemia prevention (Table 2). CHO requirements will alter insulin management strategies and
303 vice versa. The majority of studies in T1D investigate the amount and distribution of CHO to prevent
304 hypoglycaemia rather than to optimise performance, although the two may be at least partially related
305 (34,64,72,73). As an example, although only 15-20 grams/hr of CHO may be required to prevent
306 hypoglycaemia in people who reduce their insulin levels in anticipation of exercise; this amount of CHO
307 may be insufficient for performance. It has been shown that it is possible to implement larger CHO
308 supplementation (up to 75g/hr) for prolonged competition greater than 2.5 hours (marathons and other
309 endurance type races) without adversely impacting glycaemia as long as insulin dose is titrated
310 appropriately (54). In general, CHO requirements during shorter, intermittent high intensity and
311 anaerobic activities can be much less (Table 2).

312

313 Nutritional needs for recovery

314 Post-exercise nutrition requirements to maximise muscle recovery and muscle protein synthesis
315 have been well studied in the athletic population without diabetes (74). For replenishment of glycogen

316 content after exercise, CHO intake is essential (63). For athletes with T1D, it is important to ensure rapid
317 and adequate replenishment of muscle and liver glycogen stores to help prevent late-onset
318 hypoglycaemia. Glycogen replacement strategies may also be important to help prevent euglycaemic
319 ketosis in exercise recovery (75). Ingesting protein (~20-30 grams) in addition to CHO in the post-
320 exercise period is beneficial for muscle protein synthesis, but it does not appear to facilitate glycogen
321 replenishment, at least in non-diabetic athletes (63).

322

323 Role of high and low GI foods for maintenance of euglycaemia

324 The GI of a CHO-rich food can be used to assist with the selection of CHO type for exercise; with
325 high GI sports drinks and gels providing rapidly released CHO to increase blood glucose levels during
326 endurance events and for the treatment of hypoglycaemia. Low GI foods have been suggested pre-
327 exercise to sustain CHO availability and maintain euglycaemia, while higher GI meals/snacks consumed
328 post-exercise may enhance recovery. Low and moderate GI snacks may also be preferred for long
329 distance activities (like trekking and long distance cycling) at low to moderate workloads. Low GI CHO
330 (isomaltose) consumed 2 hours before a high intensity run showed improved blood glucose responses
331 during exercise compared to a high GI CHO (dextrose) (76). A low GI meal and bedtime snack consumed
332 after evening exercise prevented postprandial hyperglycaemia compared to a high GI meal and snack,
333 with both meal types protective against hypoglycaemia for ~8 hours (77). Protection beyond 8 hours
334 with a snack is lost and hypoglycaemia risk remains significant (77).

335

336 Fluid Replacement

337 Adequate fluid intake before, during and after exercise is necessary to avoid dehydration and for
338 optimal performance (65). Water is the most effective drink for low intensity and short duration sports
339 (i.e. \leq ~45 min), as long as glucose levels are at or above target (\geq 7 mmol/l). Sports beverages containing
340 CHO (6-8%) and electrolytes are useful for athletes with T1D in longer duration, higher intensity exercise
341 as a hydration and fuel source and to prevent hypoglycaemia (34,78). However, it is important to ensure
342 these are not over consumed as this can result in hyperglycaemia. Milk-based drinks containing CHO and
343 protein can assist recovery and prevent delayed hypoglycaemia (73).

344

345 Low-CHO high-fat diets and exercise

346 People with T1D may choose a low-CHO high-fat (LCHF) diet for a variety of reasons. A recent
347 review on LCHF diets and sports performance in subjects without T1D concluded that despite increasing
348 the muscles' ability to utilise fat over time, there was no evidence of performance benefits (79). Long-
349 term studies have yet to be conducted on the health, glycaemia, or performance effects of LCHF diets in
350 T1D. A concern with these diets is that they may impair the capacity for high intensity exercise (80).

351 Variation in CHO intake (i.e. periodisation throughout the training cycle according to fuel needs
352 and performance) has been suggested by some researchers as a way to help promote skeletal muscle
353 adaptation to training (81). Additionally, various exercise-nutrient protocols (i.e. training in a fasted
354 state or withholding CHO intake at meal before or after exercise) are used to manipulate CHO
355 availability. These approaches have not been studied in individuals with T1D where manipulation of
356 dietary CHO as part of training presents unique challenges for insulin therapy and requires careful
357 glucose monitoring.

358

359 Sports nutritional aids and T1D

360 The use of ergogenic aids is a widespread performance enhancement strategy used by athletes.
361 The evidence for ergogenic aids on performance is limited in athletes with T1D.

362 Caffeine intake in athletes without diabetes has shown improvements in endurance capacity
363 and power output (82). Caffeine intake (5-6 mg/kg body mass) before exercise attenuates the drop in
364 glycaemia during exercise in individuals with T1D but may increase late-onset hypoglycaemia risk (83).

365

366 **Glycaemic Management Recommendations**

367 There is high between- and within-patient variability in glucose responses to the various forms
368 and intensities of exercise (Figure 1); therefore glycaemic management is based on frequent glucose
369 monitoring, adjustments to both basal and/or bolus insulin dosing and the consumption of CHOs during
370 and after exercise. These recommendations are intended to serve as a starting point for insulin
371 adjustments and CHO intake that can then be individualised (Figure 2).

372 Clinical management strategies should be built around exercise types and individual aims and
373 implemented, taking into account the factors summarised in Table 3. Generally, sustained aerobic
374 exercise requires more substantial reductions in insulin dose and/or higher CHOs than a shorter-term
375 HIIT session. In stark contrast, brief anaerobic exercise (sprinting, weight lifting) may require increased
376 insulin delivery, which is typically given in early recovery rather than before exercise for obvious safety
377 reasons (48). Strategies for insulin dose adjustments and/or CHO intake during and after planned
378 exercise are presented in Table 4.

379

380 Insulin adjustment for prolonged activities: bolus insulin approaches

381 Pre-exercise meal insulin bolus dose reductions and/or additional CHO consumed during
382 exercise are typically needed to avoid hypoglycaemia during prolonged exercise (>30 minutes)
383 (34,55,64,84–86). Bolus dose reductions require pre-planning and are probably only appropriate for
384 exercise with a predictable intensity performed within 2-3 hours after a meal. As shown in Table 5, the

385 extent of mealtime dose reduction is proportional to both the intensity and duration of the activity. This
386 approach is safe and effective; even reducing the bolus insulin dose by as much as 75% does not appear
387 to increase ketone production during exercise (86).

388 Another strategy is to combine the reduction of the pre-exercise insulin bolus dose (by 75%)
389 with the ingestion of a low GI snack/meal (87). Importantly, this method also reduces the risk of pre-
390 exercise hyperglycaemia. However, protection against hypoglycaemia with this approach is lost if the
391 exercise is performed an hour or more after the snack (87). As such, this combined approach may be
392 preferable only for early postprandial exercise.

393

394 Basal insulin approaches

395 Late postprandial hypoglycaemia (4+ hours after a meal) following aerobic exercise is driven
396 partly by circulating basal insulin concentrations. Elevated insulin sensitivity post-exercise, and perhaps
397 a blunting of glucose counterregulation appear to place individuals at risk for at least 12 hours. Reducing
398 circulating basal insulin levels can ameliorate this risk. For patients on multiple daily insulin injections
399 (MDI), clinical observations and limited experimental data (88) demonstrate that reducing long acting
400 basal (as well as prandial) insulin before exercise reduces hypoglycaemia risk during and after the
401 activity, but may promote hyperglycaemia at other points during the day. Therefore reduction in basal
402 insulin dose for MDI patients should not be routinely recommended but may be a therapeutic option for
403 those having unusual days with considerably more planned activity (e.g. camps, tournaments). In
404 general, basal insulins with a relatively short half-life such as NPH-insulin or insulin detemir seem to lead
405 to less hypoglycaemia in conjunction with exercise when compared to longer basal insulins such as
406 glargine (89), although the mechanism for this is unclear. While ultra-long acting insulins (e.g. insulin
407 degludec with a 25hr half-life) pose similar risks for hypoglycaemia with endurance exercise to that of
408 insulin glargine (90), dose reductions for exercise would have to be implemented at least 48 hours
409 before planned exercise. This is not recommended, as it would compromise overall control.

410 CSII offers flexibility to modify basal infusion delivery and to obtain a relatively quick effect
411 (within ~1-2hrs) (91). Suspension of basal insulin infusion at the onset of 60-min exercise reduces
412 hypoglycaemia risk during the activity, but it may increase post-exercise hyperglycaemia risk (92).
413 Moreover, glucose levels may still drop 2-3 mmol/l over 30-60 minutes even when basal insulin is
414 dramatically reduced (or completely suspended) (64,92,93), due to the lag time in the change in
415 circulating insulin levels. Where practical, a basal rate reduction, rather than suspension, should be
416 attempted well before the start of exercise (60-90 minutes). An 80% basal reduction at the onset of
417 exercise helps mitigate post-exercise hyperglycaemia, compared to basal suspension, and appears to be
418 associated with reduced hypoglycaemic risk both during and after the activity (64). However, the
419 optimal timing of basal rate insulin reductions for aerobic and HIE activities and the maximal safe
420 duration for insulin pump suspension is unclear and remains open to debate. To limit the risk of
421 compromised glycaemic control and ketosis a time limit of <2hours is proposed based on rapid acting
422 insulin pharmacokinetics (91).

423 Post-exercise hyperglycaemia is a common complaint for patients doing intense exercise,
424 particularly if insulin levels are reduced. CSII seems to offer advantages over MDI in managing early
425 post-exercise hyperglycaemia (94) and late-onset post-exercise hypoglycaemia (95), due to the
426 increased flexibility around basal insulin adjustments. Overcorrection of post-exercise hyperglycaemia
427 via repeated insulin dose administration results in increased risk for severe late-onset hypoglycaemia,
428 which may even be fatal (49).

429

430 Strategies to reduce the risk of post-exercise late-onset hypoglycaemia

431 Increased insulin sensitivity lasts up to 24-48 hours following exercise (46). Very few studies
432 have tested various nutrient or insulin dose adjustments to prevent hypoglycaemia after exercise.
433 Nocturnal hypoglycaemia after exercise is a major occurrence for individuals with T1D (96), with
434 increased risk for afternoon exercise (47,97). Immediate increases in post-exercise insulin sensitivity can
435 be accommodated for by reductions in the bolus insulin at the meal after exercise by ~50%, along with a
436 low GI snack at bedtime (77). In one study of 16 youth, a ~20% temporary pump basal rate reduction
437 from bedtime for 6 hours reduced nocturnal hypoglycaemia risk (95). Similarly, in another study of ten
438 males on MDI, a 20% basal rate reduction on the exercise day along with a “free” CHO snack at bedtime
439 (0.4 g CHO/kg body mass) reduced hypoglycaemia risk overnight (88). Individuals at high risk of severe
440 nocturnal hypoglycaemia (e.g., recurrent hypoglycaemia, and those sleeping alone), should take
441 additional preventive measures including blood glucose checks at 2-3AM and/or use a real time CGM
442 system with alarms and automatic pump suspension (98). A snack alone, without changes to basal
443 insulin therapy, does not appear to entirely eliminate nocturnal hypoglycaemia risk (77) and alcohol
444 intake may increase risk (99).

445

446 **Glucose monitoring, CGM and other emerging tools for exercise management**

447 A range of treatment regimens exists for people with T1D. CSII offers better flexibility in basal
448 insulin adjustments and the management of exercise-associated hyperglycaemia (100). CSII is associated
449 with reduced post-exercise hyperglycaemia compared to MDI (94), but can create frustrating challenges
450 for sports requiring pump disconnection (101). CSII can also contribute to a greater sense of being
451 “diseased” for some individuals and may promote stigma (101). Prolonged pump disconnect (> 60
452 minutes) should be managed with reconnecting, testing and re-infusion if necessary, or a change to
453 basal insulin provision by needle. CGM provides comprehensive information on blood glucose levels,
454 real-time trends in glucose levels and rates of glucose change in glucose, which can be used to prevent
455 lows during exercise (102), even in unique settings when self-monitoring of blood glucose (SMBG) is
456 difficult to perform (103). Current sensors are reasonably accurate for exercise (104,105); however, the
457 lag time in glucose equilibrium with the interstitial space and the rapid turnover in glucose during
458 exercise may impact accuracy (i.e. overestimate glucose value when levels are dropping and
459 underestimate it when levels are rising) (106,107).

460 Structured educational sessions can be implemented using downloads of SMBG, CGM and CSII
461 (108). CGM now offers the option to add “followers” who can view glucose levels in real time and
462 potentially alert the patient while he/she is playing sports. Threshold suspension of insulin delivery in
463 CSII may offer additional protection against exercise-associated hypoglycaemia according to some
464 limited data (109). The development of a fully artificial pancreas for exercise remains an elusive goal
465 (110).

466 **Summary**

467 Regular physical activity should be a routine objective for patients with type 1 diabetes for a
468 variety of health and fitness reasons. Considerable challenges remain for the person with T1D, and their
469 HCP team, in exercise/sports management. A number of small observational studies and a limited
470 number of clinical trials have been published to date that help to inform the consensus
471 recommendations here. More studies are needed to determine how to best prevent exercise-associated
472 hypoglycaemia with basal rate insulin dose adjustments and how to manage in the post-exercise
473 recovery period. In general, aerobic exercise is associated with reductions in glycaemia while anaerobic
474 exercise may be associated with a transient rise in glucose levels. Both forms of exercise can cause
475 delayed-onset hypoglycaemia in recovery. A sound understanding of the physiology of different forms of
476 exercise and the variables that can influence glycaemia during exercise and sport should underpin the
477 implementation of safe and effective glycaemic management strategies. For aerobic exercise, reductions
478 in insulin administration before the activity (basal and/or bolus) can help ameliorate hypoglycaemia risk,
479 as can increasing CHO intake to 60 grams per hour or more. For anaerobic exercise, conservative insulin
480 dose corrections may be required, although this too may increase the risk for nocturnal hypoglycaemia,
481 particularly if the exercise is performed late in the day. In all instances, more vigilance around glucose
482 monitoring is needed before, during and after the activity.

483

484 **Contributors**

485 The literature search was conducted by MCR, IWG and CES. All authors (MCR, IWG, CES, CET, PA,
486 ANL, AK, RR-L, RM, CH, FA, PF, CG, BB, PG, TWJ, ISM, TH, AP, AP, and LML) contributed to the original
487 draft of the manuscript. MCR, FA and CES edited the revised manuscript. All authors approved the final
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489 **Declaration of interest**

490 The authors declare no relevant conflicts of interests that influence the content of this consensus
491 review.

492

493 Table 1. Pre-exercise blood glucose concentrations and initial glucose management strategies.

| Starting blood glucose concentrations | General Recommendations* |
|--|--|
| Below Target (<5 mmol/l) | <ul style="list-style-type: none"> ▪ Ingest 10–20 g of glucose before starting exercise ▪ Delay exercise until blood glucose > 5mmol/l (90 mg/dL) and monitor closely for hypoglycaemia |
| Near target (5-6.9mmol/l) | <ul style="list-style-type: none"> ▪ Ingest 10 g of glucose before starting aerobic exercise ▪ Anaerobic exercise and HIIT sessions can be started |
| Target (7-10mmol/l) | <ul style="list-style-type: none"> ▪ Aerobic exercise can be started ▪ Anaerobic exercise and HIIT sessions can be started but glucose levels may rise |
| Slightly above target 10.1-15.0 mmol/l) | <ul style="list-style-type: none"> ▪ Aerobic exercise can be started ▪ Anaerobic exercise can be started but glucose levels may rise |
| Above target (>15 mmol/l) | <ul style="list-style-type: none"> ▪ If the hyperglycaemia is unexplained (not associated with a recent meal), check blood ketones. If ketones are modestly elevated (up to 1.4 mmol/l), exercise should be limited to a light intensity for only a brief duration (<30 minutes) and a small corrective insulin dose may be needed before the exercise begins. If blood ketones are elevated (≥ 1.5mmol/l), exercise is contraindicated and management should be initiated rapidly as per the advice of the HCP/team. ▪ Mild to moderate aerobic exercise may be started if blood ketones are low (<0.6 mmol/l) or if urine ketones are less than 2+. Blood glucose levels should be monitored during exercise to help notify if glucose is rising further. ▪ Intense exercise should be initiated only with caution as it may promote a further rise in glycaemia. |

494 *Note: The CHO intake amounts shown here are to help with glucose stability at the start of exercise. For aerobic
 495 activities lasting greater than 30 minutes, additional CHOs will likely be needed (see Table 2). Blood glucose levels
 496 at the start of exercise must also be viewed within a wider context. Factors to consider include directional trends in
 497 glucose concentrations, insulin levels, patient safety and individual patient preferences based on experience. CHO
 498 intake will need to be higher if circulating insulin levels are high at the onset of exercise. See Nutritional
 499 Management section. HIIT= high intensity interval training.

500

501 Table 2 CHO requirements for endurance (aerobic) exercise performance and hypoglycaemia prevention

| Situation | Endurance exercise performance (Athletes with and without diabetes) | Hypoglycaemia prevention under low insulin conditions | Hypoglycaemia prevention under high insulin conditions |
|---|--|--|---|
| Pre-exercise meal (low fat, low GI) | A minimum of 1g CHO/kg BW according to exercise intensity and type | A minimum of 1g CHO/kg BW according to exercise intensity and type | A minimum of 1g CHO/kg BW according to exercise intensity and type |
| Immediately pre-exercise (high GI) | No CHO required for performance | If BG < 5mmol/l ingest 10-20g CHO | If BG < 5mmol/l ingest 20-30g CHO |
| Up to 30 min duration | No CHO required for performance | If BG < 5mmol/l ingest 10-20g CHO | May require 15-30g CHO to prevent or treat hypoglycaemia |
| 30- 60 min duration | Small amounts of CHO (10-15 g/hr) may enhance performance | <u>Low- moderate intensity (aerobic):</u> Small amounts of CHO (10-15 g/hr) depending on the exercise intensity and BG | May require up to 15-30g CHO/30 min to prevent hypoglycaemia |
| | | <u>High intensity (anaerobic):</u> No CHO required during exercise unless BG is < 5 mmol/l then ingest 10-20g CHO. Replace CHO needs post-exercise. | |
| 60- 150 min duration | 30-60g CHO/hr | 30-60g CHO/hr to prevent hypoglycaemia and enhance performance | Up to 75 g CHO/hr to prevent hypoglycaemia and enhance performance* |
| > 150 min duration (Mixture of CHO sources) | 60-90g CHO/hr spread across the activity (e.g. 20-30g CHO/20 min) Use CHO sources that utilize different gut transporters (e.g. glucose and fructose) | Follow sports nutrition guidelines (60-90g/hr) with appropriate insulin adjustment for glycaemic management | |
| Post- exercise meal | 1-1.2g CHO/kg body BW | Follow sports nutrition guidelines to maximise recovery with appropriate insulin adjustment for glycaemic management | |

502 Note: These guidelines are based on the following references (63,111,112) and on the expert opinion of the
 503 authors. BW= body weight, BG= blood glucose concentration. * Note: CHO consumption at a high rate may cause
 504 gastric upset in some individuals and may contribute to hyperglycaemia during and after the activity. To increase
 505 CHO absorption rate during exercise, and maintain hydration status, sport beverages containing glucose and
 506 fructose may be preferable.

507 Table 3 Examples of factors that need to be considered before making adjustments for exercise.

| Factor | Effect |
|---|--|
| Subcutaneous insulin injection and its adjustments | <ul style="list-style-type: none"> • Difference in injection site and depth affect insulin absorption characteristics (113,114). • Lipodystrophy. • Misunderstanding of insulin pharmacokinetic often leads to inappropriate insulin adjustments, including excessive insulin corrections (stacking), which may be particularly dangerous after exercise. • Rapid acting (30), regular and intermediate acting (115,116), but likely not long acting (117) insulin absorption rates are increased with exercise. |
| CHO intake | <ul style="list-style-type: none"> • Variation in CHO quantity (including inaccuracy to evaluate intake) and type will impact glycaemic excursions (118). |
| Self-monitored capillary glucose measurements and CGM | <ul style="list-style-type: none"> • Errors in SMBG sampling or measurement errors (SMBG, CGM) may result in inappropriate insulin dose estimations (119,120). • CGM accuracy, while improving, can be compromised by poor SMBG accuracy and calibrations methods (121). • Lag time in CGM may impact accuracy during exercise (104,106). |
| Medications/ alcohol | <ul style="list-style-type: none"> • Insulin sensitivity may be impacted (99) as might glucose monitoring tools (120). |
| Physiological cycles | <ul style="list-style-type: none"> • Diurnal endocrine variation, menstrual cycle and pregnancy impact insulin sensitivity and impact glycaemic patterns (122). |
| Changes in work and sleep patterns | <ul style="list-style-type: none"> • Require changes in timing of insulin basal dose administration. • Timing of exercise should be considered relative to insulin sensitivity and nocturnal hypoglycaemia risk (47). |
| Intercurrence illness and stress | <ul style="list-style-type: none"> • May require changes in both basal and bolus insulin dose (123). • Vigorous exercise contraindicated. |

508
509

510 Table 4. Therapeutic adjustment options (insulin and/or food intake) to minimize glycaemic excursions for
 511 prolonged aerobic and brief high intensity aerobic/anaerobic exercise.

| Adjustment | Prolonged endurance exercise (predominantly aerobic) | Brief intense exercise (aerobic and anaerobic) |
|--|---|--|
| Pre-exercise meal bolus dose insulin reduction | Advised when exercise occurs within ~120min of bolus dose The magnitude of reduction vary according to timing, type, duration and intensity of exercise (see Table 5) | Bolus reduction not advised May require additional conservative bolus dose correction if hyperglycaemia develops |
| Pre-exercise basal insulin dose reduction in (MDI patients) by ~20% | Useful especially if exercise occurs less than every 3 days or if exercise levels are elevated throughout the day May also be useful if on twice daily intermediate insulin | Basal reduction not advised |
| Basal nocturnal insulin dose reduction (MDI & CSII) following exercise by ~20% to reduce nocturnal hypoglycaemia | Particularly important if the exercise occurred in the afternoon or early evening | Useful for helping limiting post-exercise hypoglycaemia after a HIIT session |
| Temporary basal rate change (CSII) | Reduce basal rate to as low as total suspension of normal basal during exercise To take into account rapid acting insulin pharmacokinetics, this basal rate reduction should ideally occur well before exercise start (up to 90 minutes before) Normal basal rates can be resumed either at the end of exercise, or later in recovery depending on glucose trends | Increased basal rate may be needed to help prevent/treat hyperglycaemia either during or immediately after exercise |
| Pre-exercise CHO intake | See Table 2 | Not usually needed |
| Intra-exercise CHO intake | Typically up to 60g/h if no insulin dose adjustments have been made See Table 2 for additional information | Not usually needed |
| Pre-exercise or post-exercise sprint | May help reduce hypoglycaemia risk | May increase hyperglycaemia risk Consider a prolonged aerobic cool down |
| Post-exercise CHO intake | Useful to reduce risk of hypoglycaemia and enhance recovery (see Nutritional Management section) May need a specified insulin bolus depending on length and intensity of exercise (may need a reduced insulin to CHO ratio) | Useful to reduce risk of hypoglycaemia and enhance recovery but should be delayed if hyperglycaemia is initially observed (see Nutritional management section) May need a specified insulin bolus strategy (e.g. may need a reduced insulin to CHO ratio) |

512 Table 5: Suggested pre-exercise meal bolus percent reduction for exercise started within 90min of a meal.

| Exercise intensity | Exercise duration | |
|---|--------------------------|------------|
| | 30 minutes | 60 minutes |
| Mild aerobic (~25%VO ₂ max) | - 25%* | - 50% |
| Moderate aerobic (~50% VO ₂ max) | - 50% | - 75% |
| Heavy aerobic (70-75% VO ₂ max) | - 75% | N-A |
| Intense aerobic/anaerobic (>80% VO ₂ max) | No reduction recommended | N-A |

513 Notes: Recommendations based on the following references (51,55,72,124); N-A: Not assessed, since the exercise
 514 intensity is typically too high to sustain for 60min for most individuals; * Estimated from the 60min study.

515

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858 **Figure 1: Blood glucose trends and different forms of exercise.** High patient variability exists in the
859 blood glucose responses to different form of exercise, as denoted by the arrows and grey shading. In
860 general, aerobic exercise lowers glycaemia, anaerobic exercise raises glycaemia and mixed activities is
861 associated with relative glucose stability. The individual responses depend on a number of additional
862 factors including the duration/intensity of the activity; initial blood glucose level; individual fitness;
863 levels of insulin, glucagon, other counterregulatory hormones in circulation; and the nutritional status of
864 the individual.

865

866 **Figure 2: Decision tree for aerobic exercise and mixed aerobic and anaerobic activities lasting 30 min**
867 **or longer.** This decision tree can serve as a starting point for decision-making for aerobic exercise.

868 Notes: ¹ Mixed activities that include anaerobic bursts of exercise may require less carbohydrate intake
869 and/or less insulin dose reductions compared continuous moderate aerobic activities. If both resistance
870 and aerobic exercise are to be performed, suggest performing resistance first to help attenuate the drop
871 in glycaemia. ² In some situations, increased carbohydrate feeding rather than insulin dose reduction
872 may help improve endurance performance in prolonged activities. ³ In other situations, both bolus and
873 basal insulin dose reductions may be preferred to help limit CHO needs. Consider CGM where patient or
874 parent preference dictates, or with history of nocturnal or severe hypoglycaemia.