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Extent and prevalence of post-exercise and nocturnal hypoglycemia following peri-exercise bolus insulin adjustments in individuals with type 1 diabetes

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Abstract *Aim:* To detail the extent and prevalence of post-exercise and nocturnal hypoglycemia following peri-exercise bolus insulin dose adjustments in individuals with type 1 diabetes (T1D) using multiple daily injections of insulins aspart (IAsp) and degludec (IDeg).
Methods and results: Sixteen individuals with T1D, completed a single-centred, randomised, four-period crossover trial consisting of 23-h inpatient phases. Participants administered either a regular (100%) or reduced (50%) dose (100%; 5.1 ± 2.4, 50%; 2.6 ± 1.2 IU, $p < 0.001$) of individualised IAsp 1 h before and after 45-min of evening exercise at 60 ± 6% VO_{2max}. An unaltered dose of IDeg was administered in the morning. Metabolic, physiological and hormonal responses during exercise, recovery and nocturnal periods were characterised. The primary outcome was the number of trial day occurrences of hypoglycemia (venous blood glucose ≤ 3.9 mmol L^{-1}). Inclusion of a 50% IAsp dose reduction strategy prior to evening exercise reduced the occurrence of in-exercise hypoglycemia ($p = 0.023$). Mimicking this reductive strategy in the post-exercise period decreased risk of nocturnal hypoglycemia ($p = 0.045$). Combining this strategy to reflect reductions either side of exercise resulted in higher glucose concentrations in the acute post-exercise ($p = 0.034$), nocturnal ($p = 0.001$), and overall ($p < 0.001$) periods. Depth of hypoglycemia ($p = 0.302$), as well as ketonic and counter-regulatory hormonal profiles were similar.
Conclusions: These findings demonstrate the glycemic safety of peri-exercise bolus dose reduction strategies in minimising the prevalence of acute and nocturnal hypoglycemia following evening exercise in people with T1D on MDI. Use of newer background insulins with current bolus insulins demonstrates efficacy and advances current recommendations for safe performance of exercise.
Clinical trials register: DRKS00013509.

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Introduction

Individuals with type 1 diabetes (T1D) on multiple daily injection (MDI) regimens are reliant on insulin replacement therapy for managing blood glucose. However, exogenously administered insulin is not subject to autoregulation, thus hyperinsulinemia [1,2], and therefore hypoglycemia [3,4], remain major limitations in the current therapeutic management of diabetes. This becomes particularly relevant around physical exercise, which can rapidly increase intramuscular glucose uptake through mechanisms mediated by, but also independent of, insulin [5–10]. Thus, the additive effects of peripheral hyperinsulinemia and exercise in promoting tissue permeability and uptake of glucose [11–14], accentuate the risk of exercise-related hypoglycemia in people with T1D. Beyond these acute effects, exercise-induced increases in tissue sensitisation to insulin may persist for many hours following cessation [15–20], with evidence of a second peak occurring several hours later [21]. In the case of evening exercise, this may bring an already chronically hyperinsulinemic individual with T1D into a nocturnal period in a supra-insulin-sensitised state. As such, the window of hypoglycaemic risk is often expanded to include the nocturnal hours [21–24], at a time when self-blood glucose monitoring is inherently difficult [25]. In appreciation of these factors, careful adjustments in bolus insulin therapy around physical exercise are advised for individuals with T1D, and general recommendations across many diabetes associations and peer-reviewed outlets are available [26–28]. However, intra-individual variation in blood glucose responses to the same exercise is large [29], which only adds to the complexity of developing an effective glycemic management strategy around physical activity in those with T1D. Furthermore, despite the endorsed integration of insulin dose reduction strategies, research continues to demonstrate that individuals with T1D frequently begin exercise hyperinsulinemic [24,30–32], a situation worsened by the apparent rise in systemic insulin concentrations during aerobic activities [12,24,32], likely due to the associated subcutaneous insulin washout, hyperaemia and blood/interstitial volume redistribution [33]. A key source of variance in research pertaining to recommended MDI alterations around exercise is the diversity of bolus and basal insulins employed within and between studies [30,32,34–37], most of which have relied on home-based interstitial glucose monitoring for confirmation of hypoglycemia leading into and throughout the nocturnal hours, a method with recognised limitations due to device inaccuracy when glucose deviates from the physiologic range [38]. Given the distinct pharmacokinetic profiles of different insulins, the range used in existing research makes for difficulty in interpreting findings, particularly when now outdated analogues have previously been used and overnight sampling is scarce. Modern insulin analogues are in clinical practice, and the incorporation of ultra-long acting insulin analogues as conventional basal therapies with established bolus insulins is common within primary and secondary healthcare. Therefore, there remains a need to explore combinations of current generation insulins as part of a basal-bolus glycemic management strategy that, not only strengthens the efficacy of current exercise strategy recommendations pertinent to those with T1D, but also encourages safe exercise performance by limiting the potential for post-exercise and nocturnal hypoglycemia.

Materials

Study design

This study involved a primary analysis of a single-centre, randomised, open-label, four-period cross over clinical trial (German Clinical Trials Register; DRKS00013509). The study was performed in accordance with good clinical practice and the Declaration of Helsinki (1996). Approval was granted by both the national research ethics committee (16/WA/0394) and the local health authority (EudraCT number: 2017-004774-34; UTN: U1111-1174-6676).

Screening visit

Ahead of trial inclusion, participants were screened for anthropometric, cardiovascular and T1D specific markers prior to the performance of a cardio-pulmonary exercise test on a semi-recumbent cycle ergometer (Corival Recumbent, Lode, NL) [39]. After successful completion against the reference inclusion criteria, participants were switched from their usual basal/bolus insulin therapies ($n = 8$; glargineU100/aspart, $n = 1$; glargineU300/aspart, $n = 1$; degludec/aspart, $n = 6$; detemir/aspart) to ultra-long-acting insulin degludec ([IDeg], Tresiba®, NovoNordisk, Denmark) in 3 mL pre-filled investigational pens (PDS290) and rapid-acting insulin aspart ([IAsp], NovoRapid® NovoNordisk, Denmark) in 3 mL pre-filled investigational pens (FlexPen®). Once titrated, the total daily basal insulin dose (TDBD) was 20% less for the once-daily-morning dosing for IDeg than detemir, glargineU100 and glargineU300. Participants were required to achieve a mean overnight-fasted morning capillary blood glucose (cBG) value of 4.4–7.2 mmol L^{-1} over 3 consecutive days within 4 weeks after first trial basal insulin dose. If glycemic instability persisted for $\geq$3 days following titration, a dose adjustment alteration was made until criteria was met. A run-in period of >7 days was required to assure optimal adaptation to IDeg prior to the experimental period. All participants were using IAsp ahead of trial inclusion, thus were instructed to maintain their usual bolus insulin regime in accordance with their individualised meal-time insulin dose requirements (Mean insulin: carbohydrate [CHO] ratio = 1 IU:10 ± 4 g).

Experimental trial visits

A schematic overview of experimental trial visits is illustrated in Fig. 1. Between 08:00 and 16:00, participants undertook a standardised period during which they

received set breakfast, brunch and lunch meals that were matched in macronutrient content to their habitual dietary preferences. Low glycaemic index (G1) meals were provided at each feeding timepoint to control the influence of high GI foods on blood glucose over the 23-h in patient stays. With each of these meals, participants injected their routine dose of IAsp based on their individualised carbohydrate factor (CarbF) calculated by means of an algorithm (CarbF = 5.7*kg/TDD) [40]. One hour before and after exercise (Ex), participants administered either a full (100%) or reduced (50%) dose (100%; 5.1 ± 2.4 vs 50%; 2.6 ± 1.2 IU, $p < 0.001$) of individualised IAsp alongside the consumption of an identical low glycemic index (brown rice based vegetable dish), carbohydrate rich meal equating 1 g CHO kg bm^{-1} (Total energy; 496 ± 62 kcals, Fat; 9 ± 5 g [20%], Protein; 19 ± 11 g [15%], CHO 80 ± 10 [65%]). If pre-exercise fingertip cBG was <6 mmol L^{-1}, the exercise test was delayed, and participants consumed a standardised 10 g CHO gel (Glucogel®, BBI healthcare Ltd, UK) with subsequent 10-minutely monitoring until cBG was above a target threshold.

On the basis of block randomisation, trials were allocated the following identifiable codes; PreEx **F**ull − PostEx **F**ull (**FF**), PreEx **F**ull − PostEx **R**educed (**FR**), PreEx **R**educed − PostEx **F**ull (**RF**) and PreEx **R**educed − PostEx **R**educed dose (**RR**). The evening (17:00) exercise test consisted of 45 min (3-min warm up @ 20 W, 42-min @ target workload) of continuous cycling on a semi-recumbent ergometer at 60 ± 6% VO_{2max}. The workload intensity was computed as the mid-point between the first and second lactate turn points as previously described [39]. During exercise, heart rate (HR [s410, Polar®, Finland]) respiratory exchange ratios (METAMAX® 3B; Cortex Biophysik GmbH, GER) and power metrics were collected continuously. Respiratory exchange ratios were used to calculate the rates of carbohydrate and lipid oxidation via the principles of indirect calorimetry as described previously [41]. Prior to retiring to bed, participants consumed a small CHO-rich snack (0.4 g CHO kg bm^{-1}) with omission of IAsp (21:45). Glycemia was determined via capillary (08:00−15:59) and venous (16:00−07:00) BG monitoring over the 23-h inpatient stays. Venous derived samples were taken hourly leading into (16:00) and acutely post-exercise (17:45−21:45), then obtained two-hourly leading into, and throughout the nocturnal period (00:00−05:59). During exercise, 20 μl capillary samples were collected every 6 min from the right earlobe and used for within-exercise metabolic analysis. Following obtention, BG was analysed immediately via an enzymatic-amperometric method (Biosen C-Line, EKF Diagnostic, GER). Hypoglycemia was identified as a venous BG (vBG) value of ≤3.9 mmol L^{-1}. Hypoglycemia was treated via the oral administration of a standardised 10 g containing CHO gel (Glucogel®, BBI healthcare Ltd, UK). cBG was subsequently monitored every 10 min, and if necessary, the treatment procedure was repeated until cBG was restored to euglycemic concentrations.

Metabolic and counter-regulatory hormonal biomarkers

The Randox Daytona Plus RX series analyser (Randox Laboratories, Ltd, UK) was used for determination of β-

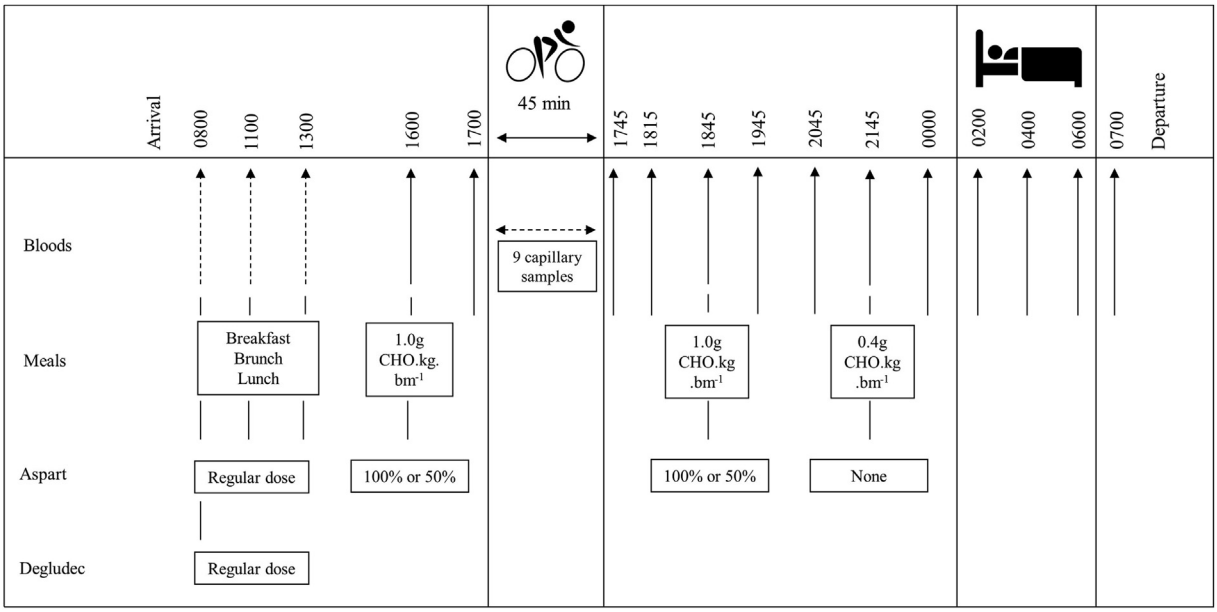

Figure 1 Experimental visit flow chart for each 23-h in patient trial. Dashed black arrows indicate capillary blood glucose sampling. With the breakfast, brunch and lunch feedings, blood glucose was collected from the fingertip and assessed via the inbuilt glucometer (Freestyle libre, Abbott Laboratories Limited, UK). During exercise, capillary blood glucose sampling was collected from the right earlobe and analysed via the fully enzymatic-amperometric method ([FEA] Biosen C-Line, EKF Diagnostic, GER). Solid black lines represent venous sampling from which blood glucose was assessed via FEA. Solid black arrows with a gap indicate the provision of a meal and an accompanied insulin dose. Cycling icon indicates the 45-min moderate intensity (@ 60% VO_{2max}) continuous exercise period. Bed icon indicates the night-time period during which venous blood glucose was sampled every 2 h 100%; Unaltered bolus dose. 50%; reduced bolus dose.

hydroxybutyrate ([β-OHB] RB4067). ELISA assays were used for the quantification of plasma glucagon (DGCG0, R&D Systems, Inc. Minneapolis, USA) and catecholamines (epinephrine [EPI] and norepinephrine [NE] ECT31-K02, Eagle biosciences, Inc. New Hampshire, USA]). Venous derived blood lactate (vBLa) concentrations were measured via the fully enzymatic-amperometric method (Biosen C-Line, EKF Diagnostic, GER).

Data analysis

All statistical analyses were carried out using SPSS 26.0 statistical software (SPSS, Chicago, Illinois, USA) and $p \leq 0.05$ (two sided) was considered statistically significant. Data were treated via repeated measures ANOVA and uni-or multi-variate analysis techniques with bonferroni-corrected pairwise comparisons used in post-hoc analysis to determine time and treatment effects. The total daily dose (TDD) [inclusive of basal and bolus amounts] of insulin taken during the control period and exercise duration were accounted for as covariates in the model where appropriate. Cross tabulation analysis was used to identify estimated risk ratios (ERR) between nominal variables, with fishers exact testing and chi-square values used to report significance. Data were stratified into distinct phases i.e. the day-time control period (08:00–15:59), the pre-exercise period (16:00–16:59), the exercise period (17:00–17:45), the post-exercise period (17:46–23:59), the nocturnal period (00:00–05:59) and the fasted morning period (06:00–07:00).

Results

Participant characteristics and pre-intervention study standardisation

Baseline physiological and diabetes characteristics are displayed in Table 1. During the day-time control period (08:00–15:59), carbohydrate (CHO) intake ([inclusive of standardised and treatment amounts] **FF** 169.3 ± 46.7, **FR** 168.6 ± 43.6, **RF** 168.5 ± 37.8, **RR** 165.3 ± 34.3 g, $p = 0.993$) and total daily insulin dosages (**FF** 0.50 ± 0.22, **FR** 0.48 ± 0.20, **RF** 0.50 ± 0.20, **RR** 0.49 ± 0.22 IU kg bm^{-1}, $p = 0.995$) were identical between trials.

Table 1 Baseline characteristics of study participants.

Characteristic	$n = 16$
Gender M vs F (n)	13 vs 3
Age (years)	34.5 ± 13.9
BMI (kg m^2)	26.0 ± 3.4
Lean mass (%)	23.4 ± 3.3
HbA_{1c} (%)	7.2 ± 1.3
HbA_{1c} (mmol/mol)	56 ± 15
Diabetes duration (years)	14.4 ± 11.1
Pre study TDD (IU kg bm^{-1})	0.6 ± 0.3
Pre study TDBD (IU kg bm^{-1})	0.4 ± 0.2
$\dot{V}O_{2max}$ (ml kg^{-1} min.$^{-1}$)	40.3 ± 10.3

Data are presented as mean ± SD.
n, number of participants; M, Male; F, Female; BMI, body mass index; kg, kilograms; m, meters; TDD, total daily insulin dose (inclusive of basal and bolus amounts) ; TDBD, total daily basal insulin dose; bm, body mass; ml, millimetres; min, minutes; $\dot{V}O_{2max}$, maximum volume of inhaled Oxygen; $HbA_{1c,\ glycated\ haemoglobin}$.

23-h hypoglycemia

Trial day vBG concentrations were highest in the **RR** trial, which differed from all other arms (**FF** 8.0 ± 3.6, **FR** 8.0 ± 3.3, **RF** 7.8 ± 3.3, **RR** 9.2 ± 3.8 mmol L^{-1}, $p < 0.001$). Of a possible 832 sample draws, there were 66 (8%) confirmed vBG hypoglycemic events during the entire experimental period (**FF** = 21 events in 14 people, **FR** = 16 events in 14 people, **RF** = 15 events in 9 people, **RR** = 14 events in 10 people, $p = 0.593$). During their study involvement, every participant experienced at least 1 hypoglycemic event, whilst 15/16 people experienced recurrent hypoglycemia (>1 event). There was no difference between trials in the probability of experiencing recurrent hypoglycemia ($\chi^2 = 1.834$, $DF = 3$, $p = 0.608$). The average depth of hypoglycemia during the experimental period was similar between trials ($p = 0.302$, Table 4), with a mean concentration of 3.3 ± 0.4 mmol L^{-1} (range 2.2–3.9 mmol L^{-1}).

Hypoglycemia during exercise

Baseline (**FF** 7.1 ± 1.9, **FR** 6.7 ± 1.3, **RF** 6.1 ± 1.5, **RR** 6.3 ± 2.0 mmol L^{-1}, $p = 0.670$) and immediate pre-exercise (Table 2, $p = 0.448$) vBG concentrations were identical between experimental arms. In all trials, vBG decreased during exercise ($p \leq 0.001$). However, both the magnitude of the drop (**FF** Δ −3.45 ± 2.94, **FR** Δ −4.41 ± 2.29, **RF** Δ −3.37 ± 1.4, **RR** Δ −3.59 ± 2.13 mmol L^{-1}, $p = 0.444$) and the rate of change in vBG were similar between trials (**FF** -0.10 ± 0.08, **FR** -0.13 ± 0.06, **RF** -0.09 ± 0.04, **RR** -0.08 ± 0.05 mmol L^{-1}.min^{-1}, $p = 0.278$). Of 64 exercise sessions, 39 (61%) were terminated prematurely due to hypoglycemia (**FF** 11, **FR** 14, **RF** 8, **RR** 6 events, $p = 0.021$ [Table 3]) with proportionality more hypoglycemia observed in the **FR** vs **RR** dosing arm ($p = 0.023$). The risk of hypoglycemia during cycling was 2-fold higher in trials that incorporated a full dose of IAsp with the pre-exercise meal (ERR 2.00 [95% CI 1.234–3.259], $p = 0.005$). The mean hypoglycemic value at the end of exercise was 3.3 ± 0.4 mmol L^{-1} (ranging from 2.2 to 3.9 mmol L^{-1}) and reached severe hypoglycemia (<3.00 mmol L^{-1}) in all except the **FR** dose-trial, in which the lowest vBG measurement was 3.0 mmol L^{-1} (Table 4). There was no difference between trials in the end hypoglycemic ($p = 0.659$ [Table 4]) or overall ($p = 0.711$ [Table 2]) vBG concentrations. Exercise duration did not differ between trials (**FF** 37.0 ± 10.2, **FR** 36.1 ± 6.2, **RF** 39.3 ± 8.7, **RR** 42.0 ± 6.3 min, $p = 0.175$). As a result of a greater incidence of hypoglycemia, more rescue CHO were needed in the pre-exercise unaltered insulin dosing trials (**FF** 6.9 ± 4.8, **FR** 8.8 ± 3.4, **RF** 5.0 ± 5.2, **RR** 4.4 ± 5.1 g, $p = 0.048$).

Table 2 Metabolic, physiologic, and counter-regulatory hormonal responses to exercise.

Parameter	Physiologic, metabolic, and respiratory responses				
	FF	FR	RF	RR	*p* value
a) Cardiorespiratory responses					
HR_{mean} (bpm)	133 ± 11†	135 ± 12†	134 ± 11†	133 ± 12†	0.904
$\dot{V}O_{2mean}$ (l min^{-1})	1.9 ± 0.3†	1.9 ± 0.4†	1.9 ± 0.3†	1.9 ± 0.3†	0.632
$\dot{V}CO_{2mean}$ (l min^{-1})	1.8 ± 0.3†	1.8 ± 0.4†	1.8 ± 0.3†	1.8 ± 0.3†	0.723
CHO $oxidation_{mean}$ (g min^{-1})	1.9 ± 0.5†	1.9 ± 0.5†	1.9 ± 0.4†	1.9 ± 0.4†	0.915
Lipid $oxidation_{mean}$ (g min^{-1})	0.2 ± 0.1†	0.2 ± 0.1†	0.2 ± 0.2†	0.2 ± 0.1†	0.455
TEE_{mean} (kcals min^{-1})	9.3 ± 1.6†	9.1 ± 1.8†	9.2 ± 1.7†	9.3 ± 1.5†	0.668
b) Metabolic responses					
$vBG_{pre\text{-}ex}$ (mmol L^{-1})	8.04 ± 3.29	8.26 ± 2.02	7.87 ± 2.49	9.40 ± 2.60	0.448
vBG_{end} (mmol L^{-1})	4.59 ± 3.09†	3.69 ± 1.19†	4.69 ± 1.86†	4.98 ± 2.18†	0.711
$vBLa_{pre\text{-}ex}$ (mmol L^{-1})	0.97 ± 0.28	0.98 ± 0.25	0.96 ± 0.23	0.95 ± 0.24	0.975
$vBLa_{end}$ (mmol L^{-1})	2.71 ± 1.48	2.63 ± 0.98†	2.61 ± 1.23†	2.74 ± 1.57	0.980
$v\beta\text{-}OHB_{pre\text{-}ex}$ (mmol L^{-1})	0.04 ± 0.01	0.04 ± 0.00	0.04 ± 0.00	0.04 ± 0.01	0.185
$v\beta\text{-}OHB_{end}$ (mmol L^{-1})	0.05 ± 0.01	0.05 ± 0.01	0.05 ± 0.02	0.04 ± 0.01	0.408
c) Counter-regulatory hormonal responses					
$EPI_{pre\text{-}ex}$ (nmol L^{-1})	0.03 ± 0.03	0.06 ± 0.10	0.06 ± 0.12	0.05 ± 0.05	0.773
EPI_{end} (nmol L^{-1})	0.09 ± 0.11	0.09 ± 0.12	0.05 ± 0.78	0.08 ± 0.11	0.887
$NE_{pre\text{-}ex}$ (nmol L^{-1})	0.65 ± 0.85	0.63 ± 1.01	0.79 ± 0.90	1.01 ± 1.09	0.605
NE_{end} (nmol L^{-1})	1.08 ± 1.04	1.36 ± 1.29	1.62 ± 1.38	1.21 ± 1.00	0.367
$Glucagon_{pre\text{-}ex}$ (pg mL^{-1})	14.9 ± 34.8	21.1 ± 33.5	50.5 ± 83.4	15.6 ± 26.8	0.191
$Glucagon_{end}$ (pg mL^{-1})	16.4 ± 24.8	18.6 ± 21.7	45.5 ± 76.9	21.0 ± 54.7	0.361

Data are reported as mean ± SD (metabolic and counter-regulatory hormonal data $n = 16$. Cardiorespiratory data $n = 14$).
HR, heart rate; bpm, beats per minute; VO_2, volume of inhaled oxygen; VCO_2, volume of inhaled carbon dioxide; l min^{-1}, liters per minute; g min^{-1}, grams per min; TEE, Total energy expenditure; kcals, kilocalories; vBLa, venous blood lactate; vβ-OHB, venous beta-hydroxybutyrate; End, end of exercise; Pre-exe, pre-exercise.
†$p \leq 0.05$ compared with the corresponding pre-exercise value.

Post-exercise and nocturnal hypoglycemia

The second largest incidence of trial-related hypoglycemia (13 of 66 events = 20% of trial total) occurred in the immediate post-exercise period (17:46–23:59). The 13 events happened in 12/16 people across all 4 trials (**FF**; 6 events in 6 people [38%], **FR**; 2 events in 2 people [13%], **RF**; 2 events in 2 people [13%], **RR**; 3 events in 2 people [13%]). During the post-exercise period, there were no differences between trials in either the occurrence ($p = 0.348$, Table 3), nor depth ($p = 0.527$, Table 4), of hypoglycemia, neither was there any difference in the risk of recurrent hypoglycemia ($\chi^2 = 3.048$, $DF = 3$, $p = 0.384$). Overall post-exercise (17:45–23:59) vBG concentrations were highest in the **RR** trial (**FF** 7.49 ± 3.76, **FR** 7.35 ± 2.76, **RF** 7.45 ± 2.78, **RR** 8.67 ± 3.52, $p = 0.034$). There was a greater need for post-exercise treatment CHO in the **FF** trial (**FF** 9.7 ± 8.7, **FR** 2.5 ± 7.7, **RF** 5.6 ± 9.6, **RR** 1.9 ± 5.4 g, $p = 0.030$).

Mean nocturnal (00:00–05:59) vBG concentrations were highest during the **RR** trial (**FF** 9.5 ± 3.2, **FR** 10.1 ± 3.2, **RF** 9.2 ± 3.7, **RR** 11.5 ± 3.6 mmol L^{-1}, $p = 0.001$), which differed from the two opposing unaltered post-exercise dosing other arms. Nocturnal hypoglycemia occurred on 7 occasions (11% of trial total) with a mean hypoglycemic vBG value of 3.03 ± 0.36 mmol L^{-1}. The occurrence of nocturnal hypoglycemia was proportionately low between conditions (**FF** 3, **FR** 0, **RF** 3, **RR** 1 events, $p = 0.558$, Table 3) as was the likelihood of experiencing recurrent nocturnal hypoglycemia ($\chi^2 = 3.048$, $DF = 3$, $p = 0.384$). The extent of hypoglycemia was also equivalent ($p = 0.238$, Table 4) Of the 7 incidences of nocturnal hypoglycemia, 6 (86%) occurred in the trials that included a full dose of IAsp in the post-exercise period, which was associated with a near 4-fold increase in the risk of hypoglycemia during the night (ERR 3.81 [95% CI 0.611–23.734], $p = 0.045$).

Physiologic, metabolic, and counter-regulatory hormonal responses to exercise

The cardiorespiratory, metabolic, and counter-regulatory hormonal responses to exercise are presented in Table 2. There were no differences between trials in any parameter at immediately prior to exercise, as an exercising mean, or at the end of exercise. The exercising energy expenditure from CHO (**FF** 83.8 ± 10.7, **FR** 84.6 ± 9.8, **RF** 79.4 ± 13.1, **RR** 81.6 ± 7.4%, $p = 0.752$) and lipids (**FF** 16.2 ± 10.7, **FR** 15.4 ± 9.8, **RF** 20.6 ± 13.1, **RR** 18.5 ± 7.4%, $p = 0.752$) was similar between trials. Cycling induced a significant increase in all cardio-respiratory variables (Table 2†). Catecholamines and glucagon remained unchanged by exercise in all conditions. There were no differences between trials in the magnitude of change ($_{delta}$) in response to exercise in any counter-regulatory hormonal or metabolic biomarkers (EPI_{delta}, $p = 0.142$, NE_{delta}, $p = 0.443$, $Glucagon_{delta}$, $p = 0.842$, $v\beta\text{-}OHB_{delta}$, $p = 0.758$, $vBLa_{delta}$, $p = 0.919$). There were no recorded incidences of any trial related hyperketonemia or lactic acidosis at any timepoint throughout the entire experimental period.

Table 3 Prevalence of trial-day hypoglycemia.

Prevalence of trial-day hypoglycaemia					
Time	FF	FR	RF	RR	# hypos as % total (n = 66)
Pre-exercise (16:00–16:59)	1/1 (6%)	0/0 (0%)	1/1 (6%)	4/3 (19%)	6/5 (9% of total hypos) p = 0.197
Exercise (17:00–17:45)	11/11 (69%)	14/14 (88%)*	8/8 (50%)	6/6 (38%)*	39/16 (59% of total hypos) p = 0.021*
Post-exercise (17:46–23:59)	6/6 (38%)	2/2 (13%)	2/2 (13%)	3/2 (13%)	13/12 (20% of total hypos) p = 0.348
Nocturnal (00:00–05:59)	3/1 (6%)	0/0 (0%)	3/3 (19%)	1/1 (6%)	7/5 (11% of total hypos) p = 0.558
Fasted a.m. (06:00–07:00)	0/0 (0%)	0/0 (0%)	1/1 (6%)	0/0 (0%)	1/1 (2% of total hypos) p = 0.406
Overall (16:00–07:00)	21/14 (88%)	16/14 (88%)	15/9 (56%)	14/10 (63%)	Total = 66 in 16 people p = 0.593

Data are reported as X/Y (Z%), where X = number of hypoglycemic episodes, Y = number of people in which hypoglycemia occurred and Z = number of people in which hypoglycemia occurred as a percentage of total number of participants (n = 16). *$p \leq 0.05$ between the FR and RR trial (p = 0.009) trial.

Discussion

This study is the first to detail the extent and prevalence of post-exercise and nocturnal hypoglycemia, following peri-evening exercise bolus insulin dose alterations using specific multiple daily injections of insulins aspart (IAsp) and degludec (IDeg) in individuals with T1D over a 23-hour in-patient monitoring period. Our findings demonstrated that a 50% dose reduction in IAsp prior to evening exercise reduced the occurrence of wihtin-exercise hypoglycemia, and mimicking this strategy in the post-exercise period decreased the risk of nocturnal hypoglycemia. Combining this approach by reducing IAsp either side of exercise resulted in higher glucose concentrations in acute post-exercise, nocturnal and overall periods.

The significant reduction in IAsp units injected before exercise (PreEx50% 2.6 ± 1.2 vs PreEx100% 5.1 ± 2.4 IU, $p < 0.001$), resulted in a greater meal-induced rise in glucose compared to the unaltered dose (PreEx50% Δ +2.1 ± 2.1 vs PreEx100% Δ +1.2 ± 2.0 mmol L^{-1}, p = 0.031). However, despite the small amount of insulin taken before exercise and the consequent increase in post-prandial blood glucose, this acute relative reduction represented only ~6% of injected insulin up to this point. Hence, similar to previous studies [12,24,30,32], participants were likely supra-hyperinsulinemic ahead of exercise commencement, which potentially evoked an inhibitory effect on endogenous glucose production by inactivating phosphorylase, whilst simultaneously accentuating peripheral glucose uptake [12]. Furthermore, exercise induced increases in skeletal muscle blood flow, capillary perfusion and membrane permeability enhance the rate of delivery and absorption of blood borne substrates and hormones to working muscles during exercise [42,43]. In the context of T1D, these physiological adaptations may result in an increased mobilisation of exogenous insulin from the subcutaneous depot into the bloodstream, further exacerbating the problem. The macronutrient composition of a pre-exercise meal also considerably influences patterns of fuel metabolism and utilisation during exercise, with shifts towards higher muscle glycogenolysis and carbohydrate oxidation observed following ingestion of a glucose load [44], particularly when superimposed with hyperinsulinemia [12]. Thus, that participants not only exercised within the peak effect of IAsp (time until peak onset of action = ~31–70 min [45]), but were also acutely post-prandial, having just consumed a high carbohydrate meal (~65% carbohydrate content), likely primed tissues to use glucose as the predominate energy source during exercise [46,47]. Indeed, irrespective of the pre-exercise insulin dose used, exercising rates of carbohydrate oxidation were high compared to lipid combustion (contribution of carbohydrates ~83 ± 9%), and probably

Table 4 Extent of trial-day hypoglycemia (≤3.9 mmol L^{-1}) with reference to the range in values in distinct time phases.

Extent of trial-day hypoglycaemia							
Time	Value	FF	FR	RF	RR	Overall	p value
Pre-exercise (16:00–16:59)	Mean	3.2 ± 0.0	–	3.9 ± 0.0	3.1 ± 0.4	3.2 ± 0.5	0.511
	Range	*3.2–3.2*		*3.9–3.9*	*2.6–3.5*	*2.6–3.9*	
Exercise (17:00–17:45)	Mean	3.3 ± 0.4	3.3 ± 0.3	3.4 ± 0.3	3.2 ± 0.6	3.3 ± 0.4	0.659
	Range	*2.5–3.9*	*3.0–3.8*	*2.9–3.8*	*2.2–3.8*	*2.2–3.9*	
Post-exercise (17:46–23:59)	Mean	3.4 ± 0.3	3.5 ± 0.1	3.0 ± 1.1	3.3 ± 0.3	3.3 ± 0.4	0.527
	Range	*3.2–3.9*	*3.4–3.6*	*2.2–3.8*	*2.9–3.4*	*2.2–3.9*	
Nocturnal (00:00–05:59)	Mean	3.2 ± 0.2	–	3.3 ± 0.5	2.6 ± 0.0	3.2 ± 0.4	0.238
	Range	*2.9–3.3*		*2.8–3.7*	*2.6–2.6*	*2.6–3.7*	
Fasted a.m. (06:00–07:00)	Mean	–	–	2.7 ± 0.0	–	2.7 ± 0.0	–
	Range			*2.7–2.7*		*2.7–2.7*	
Overall (16:00–07:00)	Mean	3.3 ± 0.4	3.4 ± 0.3	3.3 ± 0.5	3.1 ± 0.5	3.3 ± 0.4	0.302
	Range	*2.5–3.9*	*3.0–3.8*	*2.2–3.9*	*2.2–3.8*	*2.2–3.9*	

Data are reported as mean ± SD (n = 16).

accounted for the significant drop in blood glucose concentrations during exercise (~Δ vBG 3.7 ± 2.2 mmol L^{-1}). Notably, 61% of all exercise tests were terminated prematurely due to hypoglycemia. As such, as an independent time phase, the 45-min exercise period accounted for 59% of all hypoglycemic events recorded over 23 h. This was most obvious when exercising with an unaltered dose of IAsp, which led to a two-fold increase in the risk of hypoglycemia relative to when a 50% dose reduction was incorporated.

Hypoglycemia defence mechanisms were challenged by our model of cycling, with pronounced drops in arterial blood glucose concentrations observed across all trial arms. However, glucagon and catecholamine concentrations remained unchanged from pre-exercise values in all conditions. Both glucagon and the catecholamines positivity regulate net hepatic endogenous glucose production via stimulating glycogenolysis and gluconeogenesis [48,49]. However, in addition to abnormalities in hepatic glucose production during exercise [50], individuals with T1D demonstrate attenuated counter-regulatory responses to hypoglycemia [51], a situation worsened by hyperinsulinemia [52]. Thus, the small, and possibly blunted, counter-regulatory hormonal responses observed in our data, may be an additional factor owing to the high prevalence of within-exercise hypoglycemia.

The effects of exercise on enhancing tissue sensitivity to insulin and peripheral glucose uptake persist for several hours following exercise cessation, a situation intensified in the presence of hyperinsulinemia [15–18,53]. Our data reveal that overall acute post-exercise (~6 h) glycemia was most supported in the peri-exercise dose reduction arm, whilst in direct contrast, the incorporation of an unaltered dosing strategy either side of exercise independently accounted for ~50% of all acute post-exercise hypoglycemic events. These data support and advance research work by Campbell et al. [54], who also demonstrated the glycemic preservation benefits associated with a 50% dose reduction to the post-exercise bolus insulin (IAsp or lispro used with background insulins glargineU100 and detemir) dose in the acute (~4 h) but not extended (~8 h) period after exercise [54]. The authors hypothesised that the observed similarity in the prevalence of hypoglycemia in the extended post-exercise window may have been due to the administration of additional, and indeed unaltered, bolus insulin doses in the post-laboratory home-phase. In heed of these discoveries, later work highlighted the protective effect of consuming a small carbohydrate based snack (0.4 g CHO kg bm^{-1}) ahead of the night-time period in minimising rates of nocturnal hypoglycemia subsequent to evening exercise in patients treated with insulins aspart and glargineU100 [25]. However, due to relatively short post-exercise in-patient monitoring phases (~3 h), hypoglycemia was determined via interstitial glucose monitoring in both of these studies, and given the inherent flaws in device accuracy during hypoglycemia [38], may have misidentified events. Thus, using venous derived glucose values collated in laboratory-controlled conditions, our data confirm the effectiveness of these strategies in people with T1D using MDI consisting of insulins aspart and degludec.

A 50% dose reduction to mealtime insulin in the post-exercise period provided a near 4-fold decrease in the risk of nocturnal hypoglycemia compared to a full bolus insulin dose. Interestingly, in addition to the provision of a small carbohydrate based snack with bolus insulin omission 2 h ahead of the night time hours, the nocturnal period in this study commenced ~5 h following the last bolus insulin injection, hence, given its pharmacokinetic characteristics (time of duration of action; 3–5 h [45]), it was unlikely that IAsp represented much of the total pool within the circulation. The enhanced sensitivity to insulin following exercise has been shown to follow a biphasic trend, during which in addition to an initial increase immediately after exercise, a second peak occurs 7–11 h later [21].Thus, in addition to the direct effects of acute hyperinsulinemia in accelerating risk of in-exercise hypoglycemia, these data affirm the long-standing metabolic effects of antecedent exercise in increasing the risk of delayed onset of hypoglycemia in people with T1D [24]. Irrespective of hypoglycemia *per se*, employing 50% dose reductions either side of exercise led to the highest preservation in glucose throughout the night-time hours, thus reinforces the glycemic safety of prudent dose alterations alongside carbohydrate rich meals before and after exercise for this cohort. Though considerably higher following the administration of an unaltered insulin dose post-exercise, rates of nocturnal hypoglycemia in this study were minimal, and align with previous reports of a low prevalence of severe ($\leq$3.1 mmol L^{-1}) nocturnal hypoglycemia following moderate intensity cycle exercise (~60% $\dot{V}O_{2max}$ for 30 min) in participants with T1D treated with insulins aspart and degludec [55]. However, in this study the pre-exercise mealtime bolus insulin manipulation was taken well in advance of exercise commencement (~3 h), with an equivalent reduction in the carbohydrate amount. Critically this meant that the individualised carbohydrate:insulin ratio remained unaltered, which may explain the complete avoidance of hypoglycemia during exercise. Interestingly, when we re-examined our data against the threshold for severe hypoglycemia, the occurrence dropped to 3 events which happened similarly across trials (**FF**, 1 **FR** 0, **RF** 1, **RR** 1 events, $\chi^2 = 1.049$, $DF = 3$, $p = 0.789$) and provide some assurance for glycemic stability whilst using IDeg. In light of the potential obesogenic implications associated with an over reliance on additional carbohydrate intake and exogenous insulin administration [56], the increase in energy expenditure as a result of longer duration exercise, combined with a lesser need for treatment carbohydrates with insulin dose reductions, has important clinical undertones that stretch beyond those relating to dysglycemia. Finally, trial day β-OHB concentrations were below levels deemed hyper-ketonemic (>1.0 mmol L^{-1})

[57], thus support previous work in displaying no adverse metabolic implications associated with bolus insulin reduction (or omission) concomitant with high carbohydrate intakes in individuals with T1D [36]. Therefore, from a clinical viewpoint, the integration of peri-exercise IAsp dose reductions with IDeg can be implemented safely with no risk of ketone body formation.

Study strengths, limitations, and future recommendations

The study design enabled intensive 23-h monitoring including an overnight stay in a medically-supervised clinical research facility with frequent venous sample draws, standardised mealtime feedings and monitored insulin dose administrations. Collectively, these factors helped overcome the identified limitations of previous research whilst providing up-to-date information on the extent and prevalence of exercise-related hypoglycemia, using specific modern insulin analogue combinations in people with T1D. With mixed gender design of the study and a wide age range for trial inclusion, our participant cohort findings are applicable to the wider population and advance out understanding of insulin dose adjustments in T1D individuals treated with MDI.

Conclusion

These findings demonstrate improved glycemia with peri-exercise bolus dose reduction strategies which reduce the prevalence of acute and nocturnal hypoglycemia following evening exercise. Incorporation of newer background insulins with current bolus insulins demonstrates efficacy and advances current recommendations for safe performance of exercise in people with T1D using MDI.

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Author contributions

OM, OM, MLE, RD, JP and RMB were responsible for data collection, interpretation and analysis. JH, DMW and SCB provided to medical oversight. RC, GJD and CJ performed laboratory-based data analysis. OM[c] and RMB wrote the manuscript. SCB and RMB are the chief and principle investigators of the study. RMB wrote and secured funding for the study. All co-authors contributed to feedback and revisions for the final manuscript.

Declaration of Competing Interest

All authors declare no conflict of interest.

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References

[1] Gregory JM, Smith TJ, Slaughter JC, Mason HR, Hughey CC, Smith MS, et al. Iatrogenic hyperinsulinemia, not hyperglycemia, drives insulin resistance in type 1 diabetes as revealed by comparison with GCK-MODY (MODY2). Diabetes 2019;68(8):1565–76. https://doi.org/10.2337/db19-0324.

[2] Wang M-Y, Yu X, Lee Y, Kay McCorkle S, Clark GO, Strowig S, et al. Iatrogenic hyperinsulinemia in type 1 diabetes: its effect on atherogenic risk markers. J Diabetes Complicat 2013;27(1):70–4. https://doi.org/10.1016/j.jdiacomp.2012.08.008.

[3] Nathan DM, DCCT/EDIC Research Group for the DR. The diabetes control and complications trial/epidemiology of diabetes interventions and complications study at 30 years: overview. Diabetes Care 2014;37(1):9–16. https://doi.org/10.2337/dc13-2112.

[4] Cryer PE. The barrier of hypoglycemia in diabetes. Diabetes 2008; 57(12):3169–76. https://doi.org/10.2337/db08-1084.

[5] Douen AG, Ramlal T, Rastogill II S, Bilan PJ, Cartee GD, Vranicq M, et al. Exercise induces recruitment of the "insulin-responsive glucose transporter". Evidence for distinct intracellular insulin- and exercise-recruitable transporter pools in skeletal muscle. J Biol Chem 1990;265(23):13427–30.

[6] Holloszy JO, Narahara HT. Enhanced permeability to sugar associated with muscle contraction. Studies of the role of Ca++. J Gen Physiol 1967;50(3):551–62.

[7] Lund S, Holman GD, Schmitz O, Pedersen O. Contraction stimulates translocation of glucose transporter GLUT4 in skeletal muscle through a mechanism distinct from that of insulin. Proc Natl Acad Sci USA 1995;92(13):5817–21. https://doi.org/10.1073/pnas.92.13.5817.

[8] Richter EA, Hargreaves M. Exercise, GLUT4, and skeletal muscle glucose uptake. Physiol Rev 2013;93(3):993–1017. https://doi.org/10.1152/physrev.00038.2012.

[9] Etgen GJ, Fryburg DA, Gibbs EM. Nitric oxide stimulates skeletal muscle glucose transport through a calcium/contraction- and

phosphatidylinositol-3-kinase-independent pathway. Diabetes 1997;46(11):1915–9. https://doi.org/10.2337/diab.46.11.1915.
[10] Ploug T, Galbo H, Richter EA. Increased muscle glucose uptake during contractions: No need for insulin. Am J Physiol Endocrinol Metab 1984;10(6). https://doi.org/10.1152/ajpendo.1984.247.6.e726.
[11] DeFronzo RA, Ferrannini E, Sato Y, Felig P, Wahren J. Synergistic interaction between exercise and insulin on peripheral glucose uptake. J Clin Invest 1981;68(6):1468–74. https://doi.org/10.1172/jci110399.
[12] Chokkalingam K, Tsintzas K, Norton L, Jewell K, Macdonald IA, Mansell PI. Exercise under hyperinsulinaemic conditions increases whole-body glucose disposal without affecting muscle glycogen utilisation in type 1 diabetes. Diabetologia 2007;50(2):414–21. https://doi.org/10.1007/s00125-006-0520-0.
[13] Sjøberg KA, Frøsig C, Kjøbsted R, Sylow L, Kleinert M, Betik AC, et al. Exercise increases human skeletal muscle insulin sensitivity via coordinated increases in microvascular perfusion and molecular signaling. Diabetes 2017;66(6):1501–10. https://doi.org/10.2337/db16-1327.
[14] Gao J, Ren J, Gulve EA, Holloszy JO. Additive effect of contractions and insulin on GLUT-4 translocation into the sarcolemma. J Appl Physiol 1994;77(4):1597–601. https://doi.org/10.1152/jappl.1994.77.4.1597.
[15] Ren JM, Semenkovich CF, Gulve EA, Gao J, Holloszy JO. Exercise induces rapid increases in GLUT4 expression, glucose transport capacity, and insulin-stimulated glycogen storage in muscle. J Biol Chem 1994;269(20):14396–401.
[16] Ren JM, Semenkovich CF, Gulve EA, Gao J, Holloszy JO. Insulin signaling and insulin sensitivity after exercise in human skeletal muscle. Diabetes 2000;49(3):325–31. https://doi.org/10.2337/diabetes.49.3.325.
[17] Hansen PA, Nolte LA, Chen MM, Holloszy JO. Increased GLUT-4 translocation mediates enhanced insulin sensitivity of muscle glucose transport after exercise. J Appl Physiol 1998;85(4):1218–22. https://doi.org/10.1152/jappl.1998.85.4.1218.
[18] Cartee GD, Young DA, Sleeper MD, Zierath J, Wallberg-Henriksson H, Holloszy JO. Prolonged increase in insulin-stimulated glucose transport in muscle after exercise. Am J Physiol Endocrinol Metab 1989;256(4). https://doi.org/10.1152/ajpendo.1989.256.4.e494.
[19] Arias EB, Kim J, Funai K, Cartee GD. Prior exercise increases phosphorylation of Akt substrate of 160 kDa (AS160) in rat skeletal muscle. Am J Physiol Metab 2007;292(4):E1191–200. https://doi.org/10.1152/ajpendo.00602.2006.
[20] Treebak JT, Frøsig C, Pehmøller C, Chen S, Maarbjerg SJ, Brandt N, et al. Potential role of TBC1D4 in enhanced post-exercise insulin action in human skeletal muscle. Diabetologia 2009;52(5):891–900. https://doi.org/10.1007/s00125-009-1294-y.
[21] McMahon SK, Ferreira LD, Ratnam N, Davey RJ, Youngs LM, Davis EA, et al. Glucose requirements to maintain euglycemia after moderate-intensity afternoon exercise in adolescents with type 1 diabetes are increased in a biphasic manner. J Clin Endocrinol Metab 2007;92(3):963–8. https://doi.org/10.1210/jc.2006-2263.
[22] Tsalikian E, Mauras N, Beck RW, Tamborlane WV, Janz KF, Peter Chase H, et al., Diabetes Research In Children Network Direcnet Study Group. Impact of exercise on overnight glycemic control in children with type 1 diabetes mellitus. J Pediatr 2005;147(4):528–34. https://doi.org/10.1016/j.jpeds.2005.04.065.
[23] Maran A, Pavan P, Bonsembiante B, Brugin E, Ermolao A, Avagaro A, et al. Continuous glucose monitoring reveals delayed nocturnal hypoglycemia after intermittent high-intensity exercise in nontrained patients with type 1 diabetes. Diabetes Technol Ther 2010;12(10):763–8. https://doi.org/10.1089/dia.2010.0038.
[24] Campbell MD, Walker M, Trenell MI, Stevenson EJ, Turner D, Bracken RM, et al. A low-glycemic index meal and bedtime snack prevents postprandial hyperglycemia and associated rises in inflammatory markers, providing protection from early but not late nocturnal hypoglycemia following evening exercise in type 1 diabetes. Diabetes Care 2014;37(7):1845–53. https://doi.org/10.2337/dc14-0186.
[25] Juvenile Diabetes Research Foundation Continuous Glucose Monitoring Study Group. Prolonged nocturnal hypoglycemia is common during 12 Months of continuous glucose monitoring in children and adults with type 1 diabetes. Diabetes Care 2010;33(5):1004–8. https://doi.org/10.2337/DC09-2081.
[26] Adolfsson P, Riddell MC, Taplin CE, Davis EA, Fournier PA, Annan F, et al. ISPAD Clinical Practice Consensus Guidelines 2018: exercise in children and adolescents with diabetes. 2018. https://doi.org/10.1111/pedi.12755. Published online.
[27] Colberg SR, Sigal RJ, Yardley JE, Riddell MC, Dunstan DW, Dempsey PC, et al. Physical activity/exercise and diabetes: a position statement of the American diabetes association. Diabetes Care 2016;39(11):2065–79. https://doi.org/10.2337/dc16-1728.
[28] Riddell MC, Gallen IW, Smart CE, Taplin CE, Adolfsson P, Lumb AN, et al. Exercise management in type 1 diabetes: a consensus statement. Lancet Diabetes Endocrinol 2017;5(5):377–90. https://doi.org/10.1016/S2213-8587(17)30014-1.
[29] Riddell MC, Zaharieva DP, Tansey M, Tsalikian E, Admon G, Li Z, et al. Individual glucose responses to prolonged moderate intensity aerobic exercise in adolescents with type 1 diabetes: the higher they start, the harder they fall. Pediatr Diabetes 2018;20(1):12799. https://doi.org/10.1111/pedi.12799.
[30] West DJ, Stephens JW, Bain SC, Kilduff LP, Luzio S, Still R, et al. A combined insulin reduction and carbohydrate feeding strategy 30 min before running best preserves blood glucose concentration after exercise through improved fuel oxidation in type 1 diabetes mellitus. J Sports Sci 2011;29(3):279–89. https://doi.org/10.1080/02640414.2010.531753.
[31] Bracken RM, West DJ, Stephens JW, Kilduff LP, Luzio S, Bain SC. Impact of pre-exercise rapid-acting insulin reductions on ketogenesis following running in type 1 diabetes. Diabet Med 2011;28(2):218–22. https://doi.org/10.1111/j.1464-5491.2010.03162.x.
[32] Campbell MD, Walker M, Bracken RM, Turner D, Stevenson EJ, Gonzalez JT, et al. Insulin therapy and dietary adjustments to normalize glycemia and prevent nocturnal hypoglycemia after evening exercise in type 1 diabetes: a randomized controlled trial. BMJ Open Diabetes Res Care 2015;3(1):1–10. https://doi.org/10.1136/bmjdrc-2015-000085.
[33] Moser O, Yardley JE, Bracken RM. Interstitial glucose and physical exercise in type 1 diabetes: integrative physiology, technology, and the gap in-between. Nutrients 2018;10(1):93. https://doi.org/10.3390/nu10010093.
[34] Mauvais-Jarvis F, Sobngwi E, Porcher R, Garnier JP, Vexiau P, Duvallet A, et al. Glucose response to intense aerobic exercise in type 1 diabetes: maintenance of near euglycemia despite a drastic decrease in insulin dose. Diabetes Care 2003;26(4):1316–7. http://www.ncbi.nlm.nih.gov/pubmed/12663620. [Accessed 4 October 2018].
[35] West DJ, Morton RD, Bain SC, Stephens JW, Bracken RM. Blood glucose responses to reductions in pre-exercise rapid-acting insulin for 24 h after running in individuals with type 1 diabetes. J Sports Sci 2010;28(7):781–8. https://doi.org/10.1080/02640411003734093.
[36] Campbell MD, Walker M, Trenell MI, Luzio S, Dunseath G, Tuner D, et al. Metabolic implications when employing heavy pre- and post-exercise rapid-acting insulin reductions to prevent hypoglycaemia in type 1 diabetes patients: a randomised clinical trial. PLoS One 2014;9(5):e97143. https://doi.org/10.1371/journal.pone.0097143.
[37] Rabasa-Lhoret R, Bourque J, Ducros F, Chiasson JL. Guidelines for premeal insulin dose reduction for postprandial exercise of different intensities and durations in type 1 diabetic subjects treated intensively with a basal-bolus insulin regimen (ultralente-lispro). Diabetes Care 2001;24(4):625–30. https://doi.org/10.2337/diacare.24.4.625.
[38] Moser O, Eckstein ML, McCarthy O, Deere R, Pitt J, Williams DM, et al. Performance of the Freestyle Libre flash glucose monitoring (flash GM) system in individuals with type 1 diabetes: a secondary outcome analysis of a randomized crossover trial. Diabetes Obes Metab. 2019;21(11):2505–12. https://doi.org/10.1111/dom.13835.
[39] Hofmann P, Tschakert G. Special needs to prescribe exercise intensity for scientific studies. Cardiol Res Pract 2011:209302. https://doi.org/10.4061/2011/209302. Published online.
[40] Walsh J, Roberts R, Bailey T. Guidelines for optimal bolus calculator settings in adults. J Diabetes Sci Technol 2011;5(1):129–35. https://doi.org/10.1177/193229681100500118.
[41] Jeukendrup AE, Wallis GA. Measurement of substrate oxidation during exercise by means of gas exchange measurements. Int J Sport Med Suppl 2005;26(1). https://doi.org/10.1055/s-2004-830512.

[42] Clark MG, Wallis MG, Barrett EJ, Vincent MA, Richards SM, Clerk LH, et al. Blood flow and muscle metabolism: a focus on insulin action. Am J Physiol Endocrinol Metab 2003;284(2 47–2). https://doi.org/10.1152/ajpendo.00408.2002.
[43] Hawley JA, Burke LM, Phillips SM, Spriet LL. Nutritional modulation of training-induced skeletal muscle adaptations. J Appl Physiol 2011;110(3):834–45. https://doi.org/10.1152/japplphysiol.00949.2010.
[44] Costill DL, Coyle E, Dalsky G, Evans W, Fink W, Hoopes D. Effects of elevated plasma FFA and insulin on muscle glycogen usage during exercise. J Appl Physiol 1977;43(4):695–9. https://doi.org/10.1152/jappl.1977.43.4.695.
[45] Lindholm A, Jacobsen LV. Clinical pharmacokinetics and pharmacodynamics of insulin aspart. Clin Pharmacokinet 2001;40(9):641–59. https://doi.org/10.2165/00003088-199937020-00002.
[46] Jenni S, Oetliker C, Allemann S, Ith M, Tappy L, Wuerth S, et al. Fuel metabolism during exercise in euglycaemia and hyperglycaemia in patients with type 1 diabetes mellitus—a prospective single-blinded randomised crossover trial. Diabetologia 2008;51(8):1457–65. https://doi.org/10.1007/s00125-008-1045-5.
[47] Vieira AF, Costa RR, Macedo RCO, Coconcelli L, Kruel LFM. Effects of aerobic exercise performed in fasted v. fed state on fat and carbohydrate metabolism in adults: a systematic review and meta-analysis. Br J Nutr 2016;116(7):1153–64. https://doi.org/10.1017/S0007114516003160.
[48] Röder PV, Wu B, Liu Y, Han W. Pancreatic regulation of glucose homeostasis. Exp Mol Med 2016;48(3):e219. https://doi.org/10.1038/emm.2016.6.
[49] Barth E, Albuszies G, Baumgart K, Matejovic M, Wachter U, Vogt J, et al. Glucose metabolism and catecholamines. Critical Care Med 2007;35. https://doi.org/10.1097/01.CCM.0000278047.06965.20.
[50] Petersen KF, Price TB, Bergeron R. Regulation of net hepatic glycogenolysis and gluconeogenesis during exercise: impact of type 1 diabetes. J Clin Endocrinol Metab 2004;89(9):4656–64. https://doi.org/10.1210/jc.2004-0408.
[51] Kishore P, Gabriely I, Cui MH, Di Vito J, Gajavelli S, Hwang J-W, et al. Role of hepatic glycogen breakdown in defective counterregulation of hypoglycemia in intensively treated type 1 diabetes. Diabetes 2006;55(3):659–66. https://doi.org/10.2337/diabetes.55.03.06.db05-0849.
[52] Banarer S, McGregor VP, Cryer PE. Intraislet hyperinsulinemia prevents the glucagon response to hypoglycemia despite an intact autonomic response. Diabetes 2002;51(4):958–65. https://doi.org/10.2337/DIABETES.51.4.958.
[53] Cartee GD, Wojtaszewski JFP. Role of Akt substrate of 160 kDa in insulin-stimulated and contraction-stimulated glucose transport. Appl Physiol Nutr Metab 2007;32:557–66. https://doi.org/10.1139/H07-026.
[54] Campbell MD, Walker M, Trenell MI, Jakovljevic DG, Stevenson EJ, Bracken RM, et al. Large pre- and postexercise rapid-acting insulin reductions preserve glycemia and prevent early—but not late-onset hypoglycemia in patients with type 1 diabetes. Diabetes Care 2013;36(8):2217–24. https://doi.org/10.2337/dc12-2467.
[55] Heise T, Bain SC, Bracken RM, Zijlstra E, Nosek L, Stender-Petersen K, et al. Similar risk of exercise-related hypoglycaemia for insulin degludec to that for insulin glargine in patients with type 1 diabetes: a randomized cross-over trial. Diabetes Obes Metab 2016;18(2):196–9. https://doi.org/10.1111/dom.12588.
[56] Purnell JQ, John EH, Cleary PA. The effect of excess weight gain with intensive diabetes mellitus treatment on cardiovascular disease risk factors and atherosclerosis in type 1 diabetes mellitus: results from the Diabetes Control and Complications Trial/Epidemiology of Diabetes Interventions and Complications Study (DCCT/EDIC) study. Circulation 2013;127(2):180–7. https://doi.org/10.1161/CIRCULATIONAHA.111.077487.
[57] Laffel L. Ketone bodies: a review of physiology, pathophysiology and application of monitoring to diabetes. Diabetes Metab Res Rev 1999;15(6):412–26. http://www.ncbi.nlm.nih.gov/pubmed/10634967. [Accessed 28 September 2019].