# Restricting carbohydrates at breakfast is sufficient to reduce 24-hour exposure to postprandial hyperglycemia and improve glycemic variability

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**ABSTRACT**

**Background:** The breakfast meal often results in the largest postprandial hyperglycemic excursion in people with type 2 diabetes.

**Objective:** Our purpose was to investigate whether restricting carbohydrates at breakfast would be a simple and feasible strategy to reduce daily exposure to postprandial hyperglycemia.

**Design:** Adults with physician-diagnosed type 2 diabetes [$n = 23$; mean ± SD age: 59 ± 11 y; glycated hemoglobin: 6.7% ± 0.6%; body mass index (kg/m$^2$): 31 ± 7] completed two 24-h isocaloric intervention periods in a random order. Participants consumed one of the following breakfasts: *1*) a very-low-carbohydrate high-fat breakfast (LCBF; <10% of energy from carbohydrate, 85% of energy from fat, 15% of energy from protein) or *2*) a breakfast with dietary guidelines–recommended nutrient profile (GLBF; 55% of energy from carbohydrate, 30% of energy from fat, 15% of energy from protein), with the same lunch and dinner provided. Continuous glucose monitoring was used to assess postprandial glucose responses over 24 h, and visual analog scales were used to assess ratings of hunger and fullness.

**Results:** The LCBF significantly reduced postprandial hyperglycemia after breakfast ($P < 0.01$) and did not adversely affect glycemia after lunch or dinner. As such, overall postprandial hyperglycemia (24-h incremental area under the glucose curve) and glycemic variability (mean amplitude of glycemic excursions) were reduced with the LCBF (24-h incremental area under the glucose curve: −173 ± 361 mmol/L; $P = 0.03$; mean amplitude of glycemic excursions: −0.4 ± 0.8 mmol/L · 24 h; $P = 0.03$) compared with the GLBF. Premeal hunger was lower before dinner with the LCBF than with the GLBF ($P$-interaction = 0.03).

**Conclusions:** A very-low-carbohydrate high-fat breakfast lowers postbreakfast glucose excursions. The effects of this simple strategy appear to be sufficient to lower overall exposure to postprandial hyperglycemia and improve glycemic variability. Longer-term interventions are warranted. This trial was registered at clinicaltrials.gov as NCT02982330. *Am J Clin Nutr* 2019;109:1302–1309.

**Keywords:** continuous glucose monitoring; diabetes, glycemic control, LCHF; macronutrient

Postprandial hyperglycemia contributes to the cardiovascular complications of type 2 diabetes (T2D) (1, 2). Dietary carbohydrate intake is a primary determinant of postprandial hyperglycemia and thus remains a nutrient of concern for individuals with T2D (3). Low-carbohydrate diets are effective for improving glycemic control, in addition to reducing body mass and blood lipids (4–6). However, there is general apprehension surrounding the adoption of a low-carbohydrate diet given that carbohydrates are commonly substituted with increasing amounts of dietary fat (7). With this in mind, and considering the relatively poor long-term adherence to restrictive and intensive diets (8), there is a need for alternative strategies that might be effective in reducing exposure to overall postprandial hyperglycemia. In patients with T2D, hyperglycemia is most prevalent following breakfast, leading to the largest glucose excursion across the day (9–11). Targeting the meal that leads to the largest postprandial hyperglycemic response may be a simple, feasible strategy to improve glycemic control and reduce the burden of diabetes complications.

The pronounced hyperglycemia experienced following breakfast is likely due to the combination of impaired insulin sensitivity and elevated hepatic glucose production (10, 12, 13) and because typical Western breakfast foods are high in carbohydrates (e.g., cereal, oatmeal, toast, fruit). It is known that consuming fat and protein at breakfast lowers postprandial hyperglycemia and increases satiety (14). Pedersen et al. (15) showed that a low-carbohydrate breakfast significantly reduced mean and peak glucose levels for 5 h after a meal. However,

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Abbreviations used: CGM, continuous glucose monitoring; iAUC, incremental AUC; MAGE, mean amplitude of glycemic excursion; T2D, type 2 diabetes.

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the impact of carbohydrate restriction at breakfast on 24-h postprandial hyperglycemia and glycemic variability was not reported. Glycemic variability is emerging as an independent risk factor for diabetes complications, of which postprandial hyperglycemia is a major contributor (16). Furthermore, Pedersen et al. (15) excluded patients with glycated hemoglobin of 7–8%. Studies have shown that the contribution of postprandial hyperglycemia to overall glycemic control decreases as glycated hemoglobin increases (17). Therefore, controlling postprandial hyperglycemia may be most important to prevent diabetes complications in patients with T2D who are fairly well controlled [i.e., those close to achieving glycemic targets of 7% (17)] but who are still at significant risk of developing cardiovascular disease.

The aim of the present study was to examine the impact of carbohydrate restriction at breakfast on postprandial hyperglycemia in individuals with well-controlled T2D. We tested the hypothesis that carbohydrate restriction at 1 meal would reduce postprandial hyperglycemia at that meal and also improve overall 24-h glycemic profiles. Continuous glucose monitoring (CGM) was used to test this hypothesis under controlled-diet but otherwise free-living conditions. An exploratory aim was to determine if a very-low-carbohydrate breakfast (LCBF), compared with a standard macronutrient profile breakfast based on dietary guidelines (GLBF), affected feelings of hunger and satiety throughout the day.

## Methods

### Participants

Twenty-seven patients with T2D were recruited from the local medical laboratory via sign-up sheets and mailouts to perform two 24-h trials in a random order. This study was performed at the University of British Columbia, Okanagan, during the period June 2016–June 2017. All participants provided written informed consent, and the study protocols were approved by the University of British Columbia Clinical Research Committee. The trial was registered at clinicaltrials.gov as NCT02982330. Participants were included if they had physician-diagnosed T2D with stable medication and body mass for the preceding 3 mo. Participants were excluded if they were taking exogenous insulin, regularly skipped breakfast, were aged <30 or >90 y, or had diagnosed coronary artery disease. Nine participants were taking metformin only, 2 participants were taking metformin + sodium glucose co-transporter-2 (SGLT-2) inhibitor, 2 participants were taking metformin + dipeptidyl peptidase-IV (DPP-IV) inhibitor, 1 participant was taking metformin + glucagon-like peptide-1 (GLP-1) analog, 1 participant was taking metformin + sulfonylurea + DPP-IV inhibitor, and 8 participants were not taking any diabetes medications. The CONSORT (Consolidated Standards of Reporting Trials) study flow diagram is presented as **Figure 1**, and baseline characteristics are shown in **Table 1**.

### Experimental protocol

After an initial telephone consultation to assess eligibility, participants reported to the laboratory to complete medical history and Godin leisure-time physical activity (18) questionnaires, blood pressure measurements (mean of last 2 of 3 measures obtained manually following 5 min of quiet sitting), and anthropometric measures and to receive instructions for completing a 3-d food log. Approximately 1 wk later, participants completed two 24-h trials in a randomized crossover design separated by a 24- to 48-h washout period. For 1 trial, an LCBF was consumed, and for the other trial a breakfast providing dietary guidelines–recommended macronutrient distribution (GLBF) was consumed. The 2 conditions differed only in the macronutrient composition of breakfast, with identical lunch and dinner meals provided. Macronutrient profiles for each provided lunch, dinner, and GLBF were based on the Canadian Diabetes Association Clinical Practice Guidelines providing (as % of energy) ~55% carbohydrate (focusing on low glycemic index), ~30% fat, and ~15% protein, whereas the LCBF consisted of <10% carbohydrate, ~85% fat, and ~15% protein. Breakfast options are shown in **Tables 2** and **3** and were standardized as an oatmeal-based breakfast (GLBF) or an egg omelet breakfast (LCBF). The 3-d food log was used to generate individualized meal plans based on food preferences. This was deemed an important aspect of the free-living study design, so as to not drastically alter participants' current dietary habits (i.e., habitual caloric intake at meals or food types for lunch and dinner). Calories were matched between conditions for each meal and total 24-h period within participants. Energy requirements for the day were calculated with the Harris-Benedict formula and a physical activity level of 1.4 (19)—males: resting metabolic rate (kcal/d) = 66.5 + (13.75 × weight in kilograms) + (5.003 × height in centimeters) – (6.775 × age in years); females: resting metabolic rate (kcal/d) = 665.1 + (9.563 × weight) + (1.850 × height) – (4.676 × age). Baseline food logs and meal plans were analyzed and prepared with the use of Microsoft Excel and FoodWorks16 (The Nutrition Company) software. Participants were provided with all food items, as well as any meal preparation instructions for 6 meals (3 meals/d), with the timing of meals standardized between trials (meals were separated by ≥3 h). All food was provided; any meals requiring cooking (e.g., eggs) were prepared by participants from instructions with premeasured ingredients and consumed at home under free-living conditions. The evening meal prior to each condition was also standardized within participants, because it has been shown that this meal may affect morning and next-meal glycemic responses. Participants were instructed to consume a meal that could easily be replicated on the evening prior to the second study date. This was recorded with preparation instructions and confirmation of consumption prior to the second study date. A logbook was provided for participants, who were instructed to record the timing of their meals and medications, any changes made to their prescribed meal plan, daily physical activity, and capillary glucose measurements for CGM calibration. Participants were instructed not to perform any structured exercise and to maintain similar habitual physical activity for both conditions. Physical activity was recorded (amount, type, and intensity) by participants in a logbook each day during the intervention. Researchers used the logbooks to verify physical activity between conditions to ensure no protocol deviations (data not shown).

The primary outcome measure was 24-h incremental AUC (iAUC); the secondary outcome measure was 24-h mean blood glucose; other outcome measures included 24-h glycemic variability, postmeal glucose responses, and hunger/satiety. Glucose

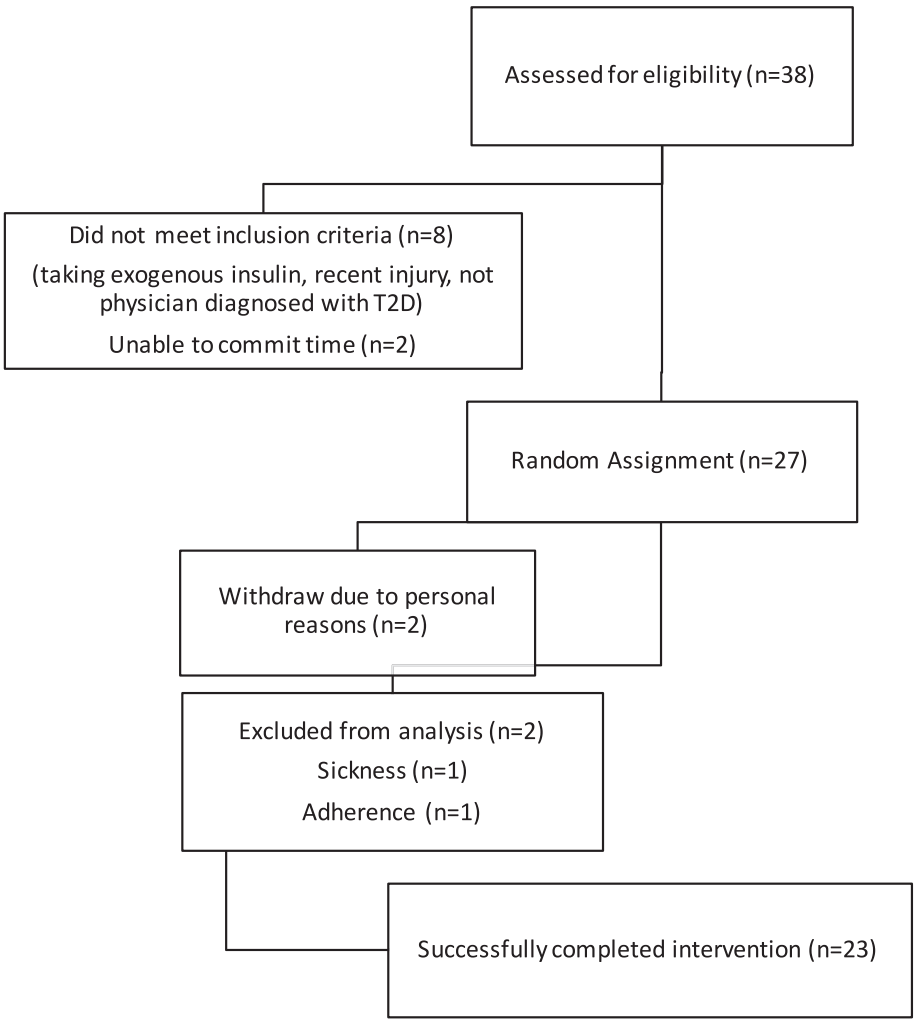


**FIGURE 1** CONSORT study flow diagram. CONSORT, Consolidated Standards of Reporting Trials; T2D, type 2 diabetes.

outcomes were assessed by CGM (iPro2 Professional CGM; Medtronic, Inc.). The CGM sensor (Enlite Sensor; Medtronic, Inc.) was inserted the day before the first condition and removed 24 h after the second condition. Participants were also instructed to take 4 capillary glucose measurements/d for CGM calibration (before breakfast, lunch, dinner, and bedtime).

### Self-reported appetite ratings

Visual analog scales were used to explore self-reported ratings of hunger, fullness, and desire to eat something sweet or savory. Before each meal, participants rated each of the following 4 questions by marking vertically on a horizontal line with descriptive anchors on either side ("not at all" to "extremely"): *1*) How hungry do you feel, *2*) How full do you feel, *3*) How strong is your desire to eat savory foods, and *4*) How strong is your desire to eat sweet foods? The visual analog scale scores were converted to a 0–100 scale, as previously described (20).

### Analyses

Data from the CGM were downloaded and integrated with 4 capillary glucose calibrations with the use of CareLink Pro software (Medtronic, Inc.) before being exported to Excel for analyses. Glycemic variability and mean glucose across each

**TABLE 1** Baseline characteristics of participants[1]

| Sex, F:M | Age, y | HbA1c, % | Body mass, kg | BMI, kg/m$^2$ | Energy intake, kcal | Blood pressure, mm Hg | Duration of T2D, y |
|---|---|---|---|---|---|---|---|
| 12:11 | 59 ± 11 | 6.7 ± 0.6 | 88 ± 20 | 31 ± 7 | 1921 ± 387 | 124/79 | 10 ± 6 |

[1] Values are means ± SDs; $n = 23$. HbA1c, glycated hemoglobin; T2D, type 2 diabetes.

**TABLE 2** Example breakfasts for the GLBF and LCBF[1]

| GLBF | LCBF |
|---|---|
| Breakfast parfait with: | Omelet with: |
| 0.5 cup oats | 2 eggs |
| 0.75 cup sliced banana | 3.5 tablespoons whipping cream |
| 0.5 cup blueberries | 0.5 cup shredded cheddar cheese |
| 100 g low-fat yogurt | 1 cup spinach |
| 100 g Greek yogurt | 1 tsp margarine (for frying) |
| 1 tablespoon + 2 teaspoons pumpkin seeds | 1 cup coffee with 1 tablespoon 10% cream |
| 1 cup coffee with 3 tablespoons 1% milk | |

[1]Amounts are based on the energy requirements for a 62-y-old inactive women, BMI (kg/m$^2$) = 27. Conversion factors for cups, teaspoons, and tablespoons were converted to metric units in FoodWorks through the use of the USDA Food Composition Database for Standard Reference (SR29). GLBF, guidelines breakfast; LCBF, very-low-carbohydrate breakfast.

24-h period (starting immediately before breakfast) were analyzed with the use of the online EasyGV platform. Postprandial hyperglycemia as 24-h and meal (3-h) total AUC and iAUC was assessed by the trapezoid method. Total AUC describes glycemic control incorporating basal blood glucose concentrations, whereas iAUC largely represents the glycemic excursions following meals.

### Statistical analyses

Sample size was calculated a priori in order to detect a 20% reduction (calculated effect size, Cohen's $d = 0.72$) in 24-h iAUC based on means ± SDs from previous CGM studies conducted in T2D participants in our laboratory (21, 22). It was estimated that 23 paired observations would be needed to detect a 20% difference in iAUC with 90% power and an effect size of 0.72 assuming a conservative correlation between repeated measures of $r = 0.5$ (calculated with G∗Power version 3). A 20% reduction was considered clinically relevant based on previous studies showing that commonly prescribed glucose-lowering medications lead to a ∼20% reduction in postprandial glucose (21–23).

Statistical analyses were performed with SPSS version 24.0 (SPSS, Inc.). Data were assessed for normality through the use of histograms and Q-Q plots and transformed with natural log or square root transformation prior to analyses if necessary. For all summary CGM variables, a paired *t* test was used to compare the LCBF day with the GLBF day. The primary outcome was overall postprandial hyperglycemia, which we defined as the 24-h iAUC. Data are reported as means ± SDs as well as differences between the LCBF and GLBF with 95% CIs. Additionally, repeated-measures ANOVA (2 conditions, 3 time points; breakfast, lunch, and dinner) examined the postprandial responses to each meal and hunger/satiety scores before meals. Significant interactions were followed up with paired-sample *t* tests between conditions. To infer whether the outcomes had a clinically meaningful implication, magnitude-based inference analyses were performed (24) with the use of the spreadsheet available from http://www.sportsci.org. The threshold for a clinically meaningful change in postprandial hyperglycemia (AUC measures) was a 20% reduction in postprandial glucose (23), and for the mean amplitude of glycemic excursions (MAGEs), a 34% decrease was used based on reducing the development of diabetes complications (16).

## Results

### Participants and compliance

Of the 27 participants randomly assigned to the meals, 23 participants completed the 2 conditions and were included in the analyses (Figure 1). All participants adhered to the LCBF and GLBF as verified by food records. Two participants withdrew prior to beginning the intervention conditions for personal reasons, 1 participant's data were excluded due to sickness during 1 of the conditions, and 1 participant was excluded from analyses due to noncompliance with the standardized meals.

**TABLE 3** Energy content and macronutrient composition for an example GLBF and LCBF[1]

| | GLBF | | LCBF | |
|---|---|---|---|---|
| | Breakfast meal | Total day | Breakfast meal | Total day |
| Energy, kcal | 628 | 2081 | 633 | 2086 |
| Carbohydrate | | | | |
| g | 82 | 270 | 5 | 188 |
| % of energy | 52 | 52 | 3 | 36 |
| Fat | | | | |
| g | 20 | 67 | 55 | 83 |
| % of energy | 29 | 29 | 78 | 46 |
| Protein | | | | |
| g | 29 | 99 | 29 | 99 |
| % of energy | 18 | 19 | 18 | 19 |

[1]Amounts are based on the energy requirements for a 62-y-old inactive woman, BMI (kg/m$^2$) = 27. Conversion factors for cups, teaspoons, and tablespoons were converted to metric units in FoodWorks through the use of the USDA Food Composition Database for Standard Reference (SR29). GLBF, guidelines breakfast; LCBF, very-low-carbohydrate breakfast.

### Postprandial blood glucose

**Figure 2** shows the CGM data (average of all 23 participants) over 24 h in the LCBF and GLBF conditions. The 24-h iAUC was lower by 32% ± 30% with the LCBF compared with the GLBF (95% CI: −61%, −3%; $P = 0.03$). The 3-h iAUC sum of breakfast, lunch, and dinner was lower with the LCBF than with the GLBF (3-h iAUC: −100 ± 116 mmol/L · 9 h; 95% CI: −150, −48 mmol/L · 9 h; $P < 0.01$). The probability that the change in postprandial glucose was clinically meaningful based on a 20% reduction threshold was 80%/20%/0% (beneficial/negligible/harmful). The 3-h postprandial iAUC (Figure 2B), and the mean and peak (**Table 4**) glucose responses to breakfast, lunch, and dinner showed significant condition × time interactions (all $P \leq 0.01$) with post hoc pairwise comparison testing between conditions showing lower glycemic responses to breakfast in the LCBF than in the GLBF condition, with no significant differences in any glycemic response variables to lunch or dinner. Compared with the GLBF, the LCBF reduced the 3-h mean glucose following breakfast (by −1.4 ± 1.3 mmol/L; 95% CI: −1.9, −0.8 mmol/L; $P < 0.01$), but there were no differences between LCBF and GLBF glycemic responses to lunch (0.1 ± 1.3 mmol/L; 95% CI: −0.5, 0.7 mmol/L; $P = 0.65$) or dinner (0.0 ± 1.1 mmol/L; 95% CI: −0.4, 0.5 mmol/L; $P = 0.91$).

### Glycemic variability

The 24-h MAGEs for the LCBF condition were significantly lower (by 0.4 ± 0.8 mmol/L; 95% CI: −0.7, −0.04 mmol/L; $P = 0.03$) compared with the GLBF. The probability that this was a clinically meaningful reduction based on a 34% change was 0%/100%/0% (beneficial/negligible/harmful). The SD of blood glucose across 24 h with the LCBF was also significantly lower (by 0.2 ± 0.4 mmol/L; 95% CI: −0.35, −0.05 mmol/L; $P = 0.01$; Table 4) than with the GLBF.

### Twenty-four-hour average and peak blood glucose

Mean 24-h blood glucose was not significantly different between the LCBF (7.2 ± 1.1 mmol/L) and GLBF (7.5 ± 1.5 mmol/L) conditions (Cohen's *d*: 0.3; 95% CI: 0.6, −0.05; $P = 0.09$). However, peak blood glucose was significantly reduced by 1.0 mmol/L (95% CI: −1.8, −0.17 mmol/L; $P = 0.02$; Table 4).

### Appetite ratings

Hunger, satiety, desire for sweets, and desire for savory foods assessed before each meal are presented in Table 4. Full data were only available for $n = 14$ participants due to the failure of 9 participants to complete these measures at all time points in their logbooks. Premeal hunger showed a significant condition × time interaction ($P = 0.03$), with post hoc pairwise comparison testing between conditions showing lower hunger before dinner in the LCBF than in the GLBF condition ($P = 0.02$; Table 4). The desire to eat sweet foods tended to be lower in the LCBF condition than in the GLBF condition (main effect: $P = 0.06$; Table 4). Premeal fullness and desire to eat savory foods did not differ between conditions (both $P > 0.17$; Table 4).

## Discussion

The present study provides evidence that consuming an LCBF lowers the glucose excursion at breakfast to an extent that overall exposure to postprandial hyperglycemia and glycemic variability are improved over a 24-h period. In addition, ratings of premeal hunger and desire to eat sweet foods later in the day tended to be lower in the LCBF condition. These potential benefits of an LCBF were realized when it was compared with an isocaloric mixed-macronutrient breakfast that was low in fat and moderate in carbohydrate as is typically recommended (25, 26). Previous studies have shown that an overall low-carbohydrate, high-fat diet lowers hyperglycemia and blood lipids and improves body composition over several weeks or months (4–6); however, long-term compliance to restrictive dietary interventions are poor (8). Here, we provide evidence that a very-low-carbohydrate, high-fat breakfast may be a simple and effective strategy that is sufficient to reduce overall exposure to postprandial hyperglycemia and improve glycemic variability in individuals with T2D. However, longer-term intervention studies will be needed to determine the potential impact on glycemic control measures, cardiovascular risk factors, and other health outcomes.

The postprandial glucose response to breakfast was reduced by 74% when carbohydrates were restricted to <10% of breakfast caloric intake. This is in agreement with previous studies (15, 27, 28) and highlights how effective carbohydrate restriction is at limiting postprandial hyperglycemia in T2D. The present findings, and those of others (15, 29), show that there are no carryover effects of an LCBF on the postprandial responses to lunch or dinner. Pedersen et al. (15) previously proposed that restricting carbohydrates at breakfast might lead to a subsequent worsening of the lunch and dinner responses, because this has been seen with breakfast omission (30). However, this does not appear to be the case because there were no differences for lunch and dinner between the LCBF and GLBF conditions. Therefore, much of the effect for reducing overall postprandial hyperglycemia in our study (i.e., 24-h iAUC and sum of meal iAUC) can be attributed to reducing the immediate postprandial glycemic response to breakfast, with no evidence of an LCBF worsening glucose responses to lunch or dinner. Because the postprandial glucose increase following breakfast is typically the largest of the day (see Figure 2), the large reduction in breakfast glucose seen in the LCBF condition appeared to be sufficient to improve overall postprandial hyperglycemia and glycemic variability.

Glycemic variability (frequency and magnitude of 24-h glucose oscillations) as assessed by MAGEs and 24-h SD was significantly reduced when an LCBF, rather than a GLBF, was consumed. The reduction in MAGEs with an LCBF in the present study is of similar magnitude to that found in a previous study that used the drug acarbose (31). Reducing glycemic variability may be cardioprotective because hyperglycemic excursions are known to be proatherogenic by stimulating reactive oxygen species and inflammatory cytokine production, which contribute to the development of cardiovascular disease (1). For example, in individuals with T2D, a meal high in carbohydrates (one that promotes hyperglycemia) increases the susceptibility of LDL to oxidation (27) and has been shown to impair vascular endothelial function (32). Further to this, a meal that combines carbohydrate and fat impairs endothelial function to a greater extent, whereas a low-carbohydrate meal alone does not (33).

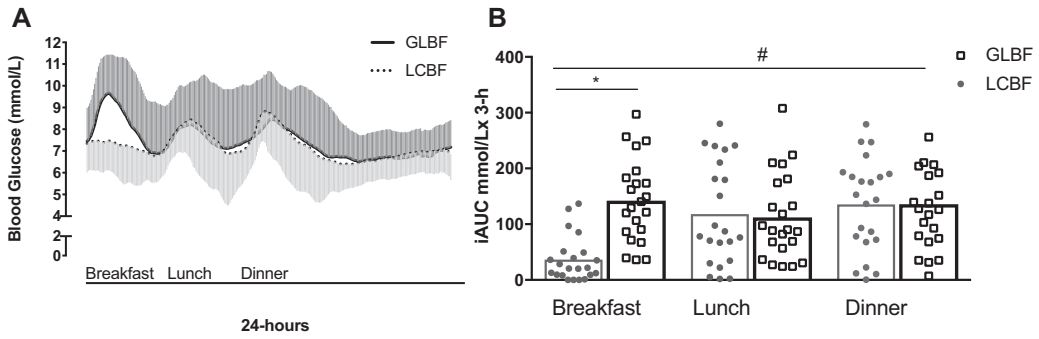


**FIGURE 2** Results from continuous glucose monitoring. (A) Continuous blood glucose data (mean ± SD values for $n = 23$) for the 24-h intervention period with an LCBF (dashed line) compared with a GLBF (black line); (B) sum of the postprandial iAUC for the 3 h following breakfast, lunch, and dinner when participants ($n = 23$) consumed an LCBF or a GLBF. Lunch and dinner were identical on both days and consisted of a low-fat dietary guidelines macronutrient composition. $^{\#}P$-interaction $< 0.05$ (ANOVA); $*P < 0.05$ (paired $t$ test between conditions). GLBF, dietary guidelines breakfast; iAUC, incremental AUC; LCBF, very-low-carbohydrate breakfast.

Oscillating blood glucose is more deleterious for oxidative stress (32) and predicting future cardiovascular risk than is constant hyperglycemia (2). Taken together, these data highlight the importance of reducing postprandial hyperglycemia and glycemic variability in individuals with T2D. The current study expands on previous work by using CGM analyses to show that postprandial hyperglycemia and glycemic variability are reduced over a 24-h period when an LCBF is consumed compared with a GLBF.

Generally, dietary guidelines recommend an even distribution of macronutrients across the day (25, 26, 34). However, it is currently unclear whether this recommendation is optimal for patients with T2D. The hyperglycemic response to breakfast is the largest and most prevalent in individuals with T2D (11). Indeed, the present study showed that by reducing hyperglycemia at breakfast, the 24-h peak glucose was reduced. Therefore, restricting carbohydrates at breakfast appears to be a simple and effective strategy that is sufficient to reduce overall exposure

**TABLE 4** Continuous glucose–derived measures of postprandial hyperglycemia and glycemic variability for the GLBF and LCBF conditions[1]

| | GLBF | LCBF | *P* |
|---|---|---|---|
| iAUC, mmol/L ·24 h | 540 ± 477 | 366 ± 289 | 0.03 |
| Total AUC, mmol/L · 24 h | 10,580 ± 2271 | 10,194 ± 1168 | 0.08 |
| 24-h SD, mmol/L | 1.3 ± 0.5 | 1.0 ± 0.3 | 0.01 |
| 24-h MAGEs, mmol/L | 3.3 ± 1.2 | 2.9 ± 0.8 | 0.03 |
| 3-h Peak blood glucose, mmol/L | | | Interaction: <0.01 |
| Breakfast | 10.6 ± 2.3 | 8.1 ± 1.5 | <0.01 |
| Lunch | 9.3 ± 2.6 | 9.3 ± 1.7 | 0.86 |
| Dinner | 10.0 ± 3.3 | 9.5 ± 1.8 | 0.44 |
| Total 24 h | 11.0 ± 2.6 | 10.1 ± 1.6 | 0.02 |
| Self-reported ratings of satiety | | | |
| Premeal hunger | | | Interaction: 0.03 |
| Breakfast | 47 ± 15.6 | 51.1 ± 18.3 | 0.51 |
| Lunch | 50 ± 24.6 | 44.8 ± 24.7 | 0.11 |
| Dinner | 51.9 ± 28.4 | 37.6 ± 21.8 | 0.02 |
| Premeal fullness | | | Interaction: 0.16 |
| Breakfast | 21.7 ± 15.3 | 23.1 ± 23.3 | |
| Lunch | 15.4 ± 12.9 | 24.2 ± 23.7 | |
| Dinner | 23.4 ± 18.3 | 36.3 ± 22.5 | |
| Premeal desire for savory | | | Interaction: 0.17 |
| Breakfast | 26.4 ± 25.1 | 27.5 ± 21 | |
| Lunch | 34.3 ± 20.3 | 31.6 ± 20.7 | |
| Dinner | 39.6 ± 28.6 | 30.2 ± 20.2 | |
| Premeal desire for sweets | | | Interaction: 0.06 |
| Breakfast | 15.1 ± 15.8 | 13.7 ± 14.3 | |
| Lunch | 10.4 ± 14.6 | 13.5 ± 17.6 | |
| Dinner | 22.3 ± 21.3 | 8.8 ± 14 | |

[1]Values are means ± SDs; $n = 23$. Interactions are shown for the repeated-measures ANOVA, with main effects between conditions shown for significant ($P < 0.05$) interactions. iAUC, incremental AUC; GLBF, guidelines breakfast; LCBF, very-low-carbohydrate breakfast; MAGE, mean amplitude of glycemic excursion.

to postprandial hyperglycemia across the day. However, it is important to note that the same may not be true for individuals without T2D. In healthy adults, markedly higher responses to carbohydrates are seen in the evening (35, 36), which is likely related to the opposite diurnal variation in glucose tolerance and insulin sensitivity seen in healthy adults compared with individuals with T2D (reviewed in references 12 and 37). Therefore, the optimal timing of carbohydrates may depend on the individual's degree of glycemic control.

Research on the satiating effects of carbohydrate compared with fat is conflicting (38–40); however, most studies have only looked at the immediate response and not the effect on subsequent meals. Our design allowed us to determine how changing only breakfast might impact hunger and satiety later in the day when identical lunch and dinner meals were consumed. Our findings of lower hunger at dinner, after consuming an LCBF, could be interpreted to indicate that such a strategy could lead to lower energy intakes in individuals with T2D, but longer interventions with larger samples will clearly be needed. Interestingly, cravings for sweet foods followed the same trend as hunger, showing evidence of reduced cravings for sweets in the LCBF condition (condition main effect: $P = 0.06$). These findings of lower hunger, and potentially lower cravings for sweets, may help inform additional ad libitum studies to determine whether consuming an LCBF can curb hunger and therefore help promote weight loss in T2D. Unfortunately, the current study lacks any mechanistic insight into the subjective ratings, but our findings provide interesting insight for future investigations. In this regard, it would be beneficial to measure appetite-regulating hormones throughout the day, in association with feelings of hunger and satiety, following a low-carbohydrate, high-fat breakfast in future studies.

Pearce et al. (11) previously showed that an even distribution of carbohydrates across the day does not provide the most favorable 24-h glucose profile. The purpose of the present study was to examine the impact of an LCBF on postprandial hyperglycemia across the day. To isolate whether restricting carbohydrates at breakfast leads to improved glycemic responses, the LCBF was compared with a control GLBF, and the following lunch and dinner meals were matched between conditions. We acknowledge that the total amount of carbohydrates was not matched between groups and thus may contribute to the lower 24-h glycemic variability observed with the LCBF. However, the purpose of this study was to explore the effect of restricting carbohydrates at breakfast on the glycemic and appetite responses to the following meals over a 24-h period. Therefore, it was deemed to be more important to match the lunch and dinner meals between conditions.

In conclusion, a breakfast low in carbohydrate significantly reduces the largest glucose increase of the day, which appears sufficient to lower overall exposure to postprandial hyperglycemia and improve glycemic variability in individuals with T2D. The inclusion of a very-low-carbohydrate, high-fat breakfast meal in patients with T2D may be a practical and easy way to target the large morning glucose increase and reduce associated complications. The results of our study suggest potential benefits of altering macronutrient distribution throughout the day, such that consumption of carbohydrates is restricted at breakfast with a balanced lunch and dinner rather than consuming an even distribution and moderate amount of carbohydrates throughout the day. Further research is needed to determine if, over the long term, this meal pattern lowers cardiovascular risk markers and diabetes complications. The encouraging preliminary findings showing lower hunger later in the day following an LCBF also indicates that this approach could have wider implications for weight loss, but this will require further research.

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The authors' responsibilities were as follows—MEF, CRC, and JPL: designed the study, analyzed the data, and wrote the initial draft of the manuscript; MEF and CRC: conducted the research; JPL: is the guarantor and takes responsibility for this work as a whole; and all authors: edited the manuscript and read and approved the final manuscript. MEF and CRC had no conflicts of interest. JPL is a Chief Scientific Officer for the Institute for Personalized Therapeutic Nutrition, a not-for-profit organization that supports a food-first approach to treating and preventing chronic disease; he holds shares in Metabolic Insights, Inc., a for-profit company that is developing techniques for noninvasive metabolic monitoring.

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