

Management of Type 1 Diabetes With a Very Low–Carbohydrate Diet

Belinda S. Lennerz, MD, PhD,^{a,b} Anna Barton, MD,^c Richard K. Bernstein, MD,^d R. David Dikeman, PhD,^e Carrie Diulus, MD,^f Sarah Hallberg, DO,^g Erinn T. Rhodes, MD, MPH,^a Cara B. Ebbeling, PhD,^{a,b} Eric C. Westman, MD,^h William S. Yancy Jr, MD,^h David S. Ludwig, MD, PhD^{a,b}

abstract

OBJECTIVES: To evaluate glycemic control among children and adults with type 1 diabetes mellitus (T1DM) who consume a very low–carbohydrate diet (VLCD).

METHODS: We conducted an online survey of an international social media group for people with T1DM who follow a VLCD. Respondents included adults and parents of children with T1DM. We assessed current hemoglobin A1c (HbA1c) (primary measure), change in HbA1c after the self-reported beginning of the VLCD, total daily insulin dose, and adverse events. We obtained confirmatory data from diabetes care providers and medical records.

RESULTS: Of 316 respondents, 131 (42%) were parents of children with T1DM, and 57% were of female sex. Suggestive evidence of T1DM (based on a 3-tier scoring system in which researchers took into consideration age and weight at diagnosis, pancreatic autoimmunity, insulin requirement, and clinical presentation) was obtained for 273 (86%) respondents. The mean age at diagnosis was 16 ± 14 years, the duration of diabetes was 11 ± 13 years, and the time following a VLCD was 2.2 ± 3.9 years. Participants had a mean daily carbohydrate intake of 36 ± 15 g. Reported mean HbA1c was $5.67\% \pm 0.66\%$. Only 7 (2%) respondents reported diabetes-related hospitalizations in the past year, including 4 (1%) for ketoacidosis and 2 (1%) for hypoglycemia.

CONCLUSIONS: Exceptional glycemic control of T1DM with low rates of adverse events was reported by a community of children and adults who consume a VLCD. The generalizability of these findings requires further studies, including high-quality randomized controlled trials.



^aDivision of Endocrinology, and ^bNew Balance Foundation Obesity Prevention Center, Boston Children's Hospital and Harvard Medical School, Harvard University, Boston, Massachusetts; ^cRichmond Diabetes and Endocrinology, Bon Secours Medical Group, Richmond, Virginia; ^dNew York Diabetes Center, Mamaroneck, New York; ^eLockheed Martin, Honolulu, Hawaii; ^fCrystal Clinic Orthopaedic Center, Akron, Ohio; ^gVirta Health and Indiana University Health, School of Medicine, Indiana University, Indianapolis, Indiana; and ^hDuke University Medical Center, Durham, North Carolina

Dr Lennerz conceptualized and designed the study, created the data collection instruments, collected the data, reviewed the medical records, conducted the statistical analyses, drafted the initial manuscript, and maintained full control over the database and all statistical analysis; Drs Barton and Diulus conceptualized the study, participated in the design of the data collection instruments, and revised the manuscript; Drs Bernstein, Dikeman, Hallberg, Rhodes, and Ebbeling participated in the design of the data collection instruments and revised the manuscript; Drs Westman and Yancy participated in the scientific design and revised the manuscript; Dr Ludwig conceptualized and designed the study, drafted the initial manuscript, and maintained full control over the database and all statistical analysis; and all authors approved the final manuscript as submitted and agree to be accountable for all aspects of the work.

DOI: <https://doi.org/10.1542/peds.2017-3349>

Accepted for publication Mar 8, 2018

WHAT'S KNOWN ON THIS SUBJECT: Despite pharmacological and technological advances, optimal glycemic control of type 1 diabetes remains elusive, putting millions of people worldwide at increased risk of micro- and macrovascular complications. One conceptually promising but poorly studied approach is dietary carbohydrate restriction.

WHAT THIS STUDY ADDS: Exceptional glycemic control of type 1 diabetes without high rates of acute complications may be achievable among children and adults with a very low–carbohydrate diet. However, the generalizability of these findings and long-term safety of carbohydrate restriction remain unknown.

To cite: Lennerz BS, Barton A, Bernstein RK, et al. Management of Type 1 Diabetes With a Very Low–Carbohydrate Diet. *Pediatrics*. 2018;141(6):e20173349

Before the discovery of insulin, the lives of children with type 1 diabetes mellitus (T1DM) were extended, sometimes for years, by severe carbohydrate restriction.¹ After the advent of insulin treatment, the recommended carbohydrate intake was increased without clinical trial proof of superiority. By the 1980s, a low-fat diet containing up to 60% of energy from carbohydrates became the standard of care.² More recently, the American Diabetes Association (ADA) has emphasized the individualization of diet rather than focusing on macronutrients.³

Despite major medical and technological advances, the management of T1DM remains suboptimal. With an average overall hemoglobin A1c (HbA1c) of 8.2%, only 20% of children and 30% of adults achieve the glycemic targets of HbA1c <7% for adults and <7.5% for children as set forth by the ADA to reduce long-term complications.⁴ The greatest challenge in this regard involves difficulty controlling postprandial glycemia, which is a major determinant of HbA1c.⁵ Even with modern insulin analogs and technical advances, a mismatch between carbohydrate absorption and insulin action typically exists after meals. Beyond a point, measures to lower postprandial hyperglycemia inevitably increase risk for hypoglycemia, with potentially life-threatening consequences.^{6–9}

The source and amount of carbohydrates consumed affect postprandial hyperglycemia and glycemic variability more than any other dietary factor,^{3,10–12} providing a conceptual basis for interest in carbohydrate-modified diets for T1DM. Regarding carbohydrate source, a diet with a low versus high glycemic index can be used to reduce HbA1c moderately (by ~0.5%).¹³ Case series and pilot studies reveal more substantial improvements in HbA1c and other benefits (less hypoglycemia and reduced

glycemic variability) with a very low-carbohydrate diet (VLCD).^{14–21} Although varying to some degree among studies, a VLCD is typically defined as ≤20 to 50 g per day of carbohydrates or ≤5% to 10% carbohydrates as a proportion of calories.^{22–24} In T1DM, small sample sizes and methodological issues limit the significance of VLCD benefits, and little is known about prevalence, practice, and sustainability. In the absence of larger studies in pragmatic settings, a VLCD is generally discouraged out of concern for potential diabetic ketoacidosis (DKA), hypoglycemia, dyslipidemia, nutrient deficiency, growth failure in children, and sustainability.^{25,26} Our aim in this study was to characterize glycemic control and acute adverse events among children and adults who have adopted this approach for the long-term self-management of T1DM.

METHODS

Design

Using an online survey, we collected primary data from respondents and confirmatory medical information from a secondary survey of health care providers or a review of medical records. Our goals were to (1) establish that adult respondents and children for whom an adult respondent completed the survey (both henceforth referred to as participants) were formally and accurately diagnosed with T1DM, (2) characterize glycemic control (ie, HbA1c, total daily insulin dose, average blood glucose concentrations and SD as measured by a continuous glucose monitor [CGM] or glucose meter), (3) determine adverse event rates (eg, DKA, hypoglycemia, diabetes-related hospitalizations and emergency department visits), (4) assess anthropometrics (eg, weight, height, and BMI) and metabolic health parameters (eg, serum lipids), (5) compare longitudinal changes in

glycemic control (pre- to post-VLCD), and (6) characterize participants' satisfaction with their diabetes management and relationship with the health care system. The study was approved by the Boston Children's Hospital Institutional Review Board and is registered at www.clinicaltrials.gov (identifier NCT02839174). Electronic consent was obtained from the respondents.

Participants and Enrollment

A volunteer sample was recruited from TypeOneGrit, an online Facebook community for people with T1DM who follow a VLCD and diabetes management method as recommended in the book *Dr Bernstein's Diabetes Solution*.^{20,27} This method comprises a VLCD with weight-based carbohydrate prescription of up to 30 g per day derived from fibrous vegetables and nuts with a low glycemic index. High-protein foods with associated fat are substituted for carbohydrates and adjusted on the basis of outcomes, including glycemic control and weight. Participants adhere to a structured meal plan and adjust bolus insulin empirically according to postprandial glycemia. Basal insulin is adjusted according to fasting glycemia. The group was established in April 2014, with ~1900 members at the time of the survey.

We used an eligibility survey of community members between September 2016 and November 2016. Members aged ≥18 years were eligible if they or a child in their care satisfied these 3 self-reported criteria: having T1DM, receiving insulin therapy, and consuming a carbohydrate-restricted diet for at least 3 months. Women who were pregnant or breastfeeding were excluded. Of 493 eligibility survey responses, 414 (84%) individuals were eligible to participate and 316 (76%) provided sufficient information to be included in the study (Fig 1). With respondent

permission, we contacted 182 providers; 97 (53%) completed the full or short provider survey. Of 238 participants who agreed to provide medical records, 101 records were received. Primary data acquisition continued until January 2017. Confirmatory medical information was collected until March 2017.

Data Collection and Categorization

When possible, survey questions were modified from the T1D Exchange Clinic Registry (<https://t1dexchange.org/pages/resources/our-data/studies-with-data>)²⁸ and covered several domains: (1) diabetes diagnosis and treatment, (2) diet, (3) insulin regimen, (4) other diabetes-related care, (5) glycemic control, (6) diabetes complications, (7) general health and health care, (8) interactions between the patient and the diabetes care provider, and (9) sociodemographic data. Survey instruments are available at <https://osf.io/d6wrj/>. Respondents were asked to provide consent so that their or their children's primary diabetes care providers could be contacted or to provide confirmatory medical records themselves. Data were collected and managed by using research electronic data capture (version 7.3.5; Vanderbilt University, Nashville, TN) tools hosted at Boston Children's Hospital.²⁹

Ascertainment of T1DM Diagnosis

We created a 3-tiered scoring system to ascertain T1DM diagnosis with varying levels of confidence using participant-reported and confirmatory medical information. Participants were classified as having diagnostic evidence of T1DM if they had a diabetes diagnosis at age <20 years, a nonobese body weight (BMI <30 in adults or BMI standard deviation score [SDS] <1.645 [~95th percentile] in children), and positive diabetes antibody test results. A classification of strong evidence was assigned to participants with

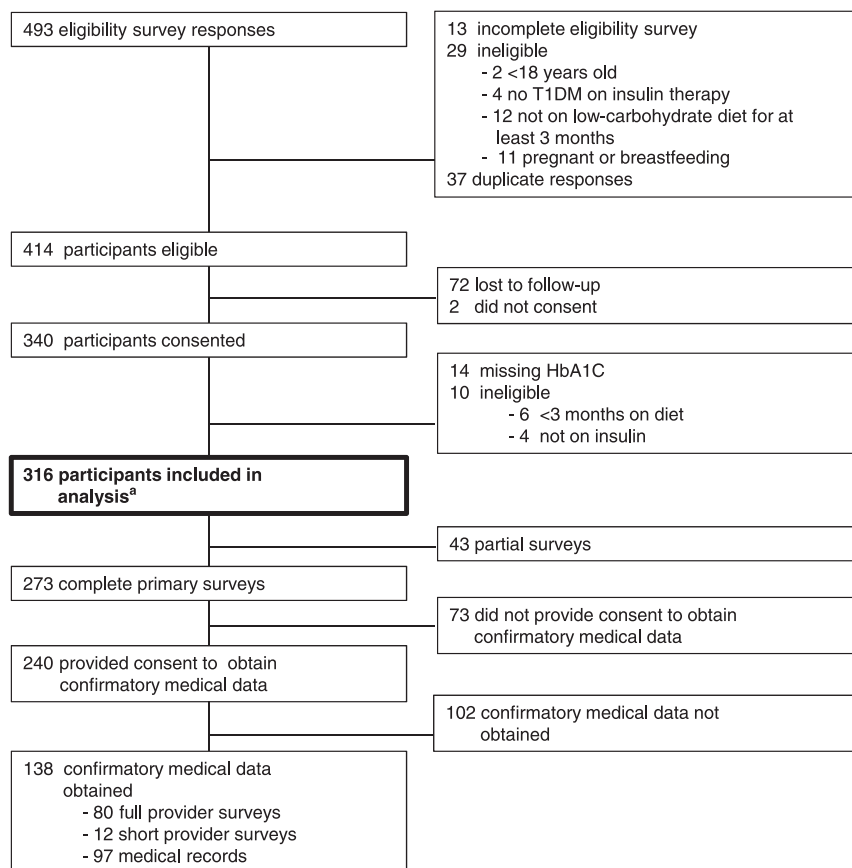


FIGURE 1

Enrollment. ^a The primary end point, current HbA1c, was available in the appropriate time frame (at least 3 months after starting the VLCD) for 300 participants. Data from all 316 eligible participants are included in the other analyses.

a diabetes diagnosis at age <10 years; a diagnosis between ages ≥10 and <20 years, immediate insulin requirement, and a nonobese body weight; or a diagnosis between ages ≥20 and <40 years, immediate insulin requirement, positive diabetes antibody test results, and a nonobese body weight. A classification of suggestive evidence was assigned to participants with a diagnosis at ages ≥20 and <40 years, immediate insulin requirement, a nonobese body weight, and 1 additional factor (including low C-peptide level at diagnosis, physician-specified diagnosis of T1DM, or other evidence [abrupt onset with consistent symptoms, history of DKA, or negative genetic test results for maturity onset diabetes of the young (MODY)]);

or diagnosis at age >40 years, immediate insulin requirement, a nonobese body weight, and positive diabetes antibody test results or 1 of the aforementioned additional factors.

Statistical Analysis

Analyses were performed by using SAS version 9.3 (SAS Institute, Inc, Cary, NC). Statistical significance was defined as $P < .01$, which is a conservative threshold chosen to take into account multiple secondary outcomes. Exact P values are reported. To assess agreement among data sources, we performed Lin's concordance correlation between patient-provider pairs of each clinical measurement. The following statistical comparisons were made according to an a

priori analysis plan. Comparisons between participants were made by independent sample *t* test or χ^2 test for participants with versus without confirmatory medical information and adults versus children. A within-subject, paired, 2-tailed *t* test was used for pre- and postdiet data and height SDS comparison. Multiple comparisons for diagnostic evidence groups were made by analysis of variance. We performed a linear regression of current, self-reported HbA1c on age, years with diabetes, years on VLCD, carbohydrate intake goal, educational status, and income class.

Post hoc analyses were performed with Pearson's correlation between pediatric height SDS and carbohydrate intake and by Wilcoxon signed-rank test and McNemar's test to compare participant- and provider-satisfaction data.

RESULTS

Participants

Descriptive characteristics are listed in Table 1. Most participants were from the United States, Canada, Europe, or Australia; 57% were of female sex, 42% were children, 88% were white and non-Hispanic, and 84% of all respondents (adults or parents of children with T1DM) completed college or the equivalent. The mean age at diabetes diagnosis was 16 ± 14 years, the duration of diabetes was 11 ± 13 years, and the time following a VLCD was 2.2 ± 3.9 years.

Validation of Participant-Reported Data

Confirmatory medical information (from providers and/or medical records) was available for 148 (47%) participants (Fig 1, Supplemental Table 4). Participant- and provider-reported data revealed good agreement for relevant clinical variables. Participants with and without confirmatory medical information did not differ

TABLE 1 Participant-Reported Descriptive Characteristics

Characteristics	No. Responses	Finding, No. (%) or Mean \pm SD
Anthropometrics		
Female sex	281	161 (57)
Age, y	316	27 \pm 19
Pediatric	316	131 (42)
Height SDS	272	0.37 \pm 1.1
BMI (adult)	168	24 \pm 3
BMI SDS (pediatric)	106	0.44 (0.96)
Diabetes-related data		
Age at diagnosis, y	316	16 \pm 14
Years with T1DM	316	11 \pm 13
Diagnostic category		
Diagnostic evidence of T1DM	316	85 (27)
Strong evidence of T1DM	316	153 (48)
Suggestive evidence of T1DM	316	35 (11)
T1DM unascertained	316	43 (14)
HbA1c at diagnosis	173	11.20% \pm 2.72%
Diet		
Years on VLCD ^a	313	2.2 \pm 2.9
Use of a specific carbohydrate intake goal	313	223 (71)
Carbohydrate intake goal, g	223	36 \pm 15
Goal achieved, d per wk	216	6.4 \pm 1.0
Sociodemographic		
Country	284	
United States, Canada		193 (68)
Europe, United Kingdom		40 (14)
Australia		36 (13)
Other ^b		15 (5)
Race and/or ethnicity	284	
White, non-Hispanic		250 (88)
Hispanic or Latino		8 (3)
Black		0 (0)
Asian		2 (1)
Other		24 (8.5)
Education	283	
Primary or less		1 (0.4)
Secondary		13 (5)
Upper, postsecondary		31 (11)
Tertiary		238 (84)
Income	284	
Lower		22 (8)
Middle		200 (70)
Upper		62 (22)
Diabetes care provider subspecialty	288	
Endocrinology		234 (81)
Pediatrics, family medicine		38 (13)
Other		16 (6)

^a The median was 1.7 y; the range was 0.2–31.7 y.

^b New Zealand, South Africa, United Arab Emirates, Saudi Arabia, Singapore, Israel, India, and Aruba.

(Supplemental Table 5). Therefore, only participant-reported information is reported below.

Ascertainment of T1DM

At least suggestive evidence for T1DM was reported by participants or providers in 273 (86%) patients, at least strong evidence was reported in 238 (75%) patients, and diagnostic

evidence was reported in 85 (27%) patients. Evidence was unavailable for 36 (10%) patients, and 7 (2%) did not meet criteria only because of obesity (Table 1). Apart from expected differences related to the scoring system (eg, age, age at diagnosis, and obesity), participants with and without supportive evidence of T1DM did not differ

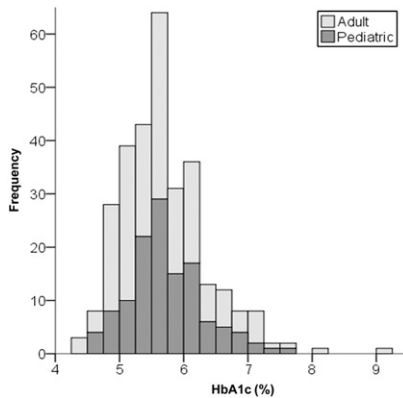


FIGURE 2
HbA1c distribution. The adult (light gray) and pediatric (dark gray) age groups are shown ($n = 300$).

(Supplemental Table 6). Therefore, data for all participants regardless of evidence category are presented together.

Clinical Outcomes

Participants reported a mean daily carbohydrate intake of 36 ± 15 g ($n = 223$). The mean participant-reported current HbA1c was $5.67\% \pm 0.66\%$ among the 300 participants who provided this information in the acceptable time frame (Table 2, Fig 2), and 97% of participants achieved the ADA glycemic targets. The participant-reported change in HbA1c from pre- to post-VLCD was $-1.45\% \pm 1.04\%$ ($n = 127$; $P < .001$). Of the 137 respondents who reported CGM mean blood glucose values and the 115 who reported CGM blood glucose SD, average blood glucose was 104 ± 16 mg/dL and SD was 28 ± 12 mg/dL. In the regression analysis, a priori covariates explained little of the variation in HbA1c ($r^2 = 0.06$). Carbohydrate intake goal was the only significant predictor ($F = 10.4$; $P = .001$), with an increase in HbA1c of 0.1% per 10 g of carbohydrate consumed (Supplemental Table 9). The mean daily insulin dose was 0.40 ± 0.19 U/kg per day.

Participant-reported rates of adverse events were low, and many declined after the initiation of a VLCD (Supplemental Table 7). Of

TABLE 2 Participant-Reported Clinical Variables

Clinical Variables	No. Responses	Finding, Mean \pm SD or No. (%)
Glycemic control		
HbA1c	300	$5.67\% \pm 0.66\%$
CGM average, mg/dL ^a	137	104 ± 16
CGM SD, mg/dL ^a	115	28 ± 12
Blood glucose meter average, mg/dL ^b	77	106 ± 21
Blood glucose meter SD, mg/dL ^b	36	36 ± 35
Insulin daily dose, U/kg per d	282	0.40 ± 0.19
Insulin % basal	198	$64\% \pm 21\%$
Adverse events		
Diabetes-related hospitalizations, persons per y ^c		
DKA	300	7 (2)
Hypoglycemia		4 (1)
Other		2 (1)
Diabetes-related emergency encounters, persons per y		
DKA	301	10 (3)
Hypoglycemia		3 (1)
Other		2 (1)
Hypoglycemia with seizure and/or coma, persons per y		
Hypoglycemia requiring help from others, adults per y	298	7 (2)
Hypoglycemia requiring glucagon, persons per y ^d	174	20 (12)
Symptomatic hypoglycemic episodes, persons per mo		
0	297	92 (31)
1–5		112 (38)
5–10		40 (13)
10–20		30 (10)
≥ 21		23 (8)
Monthly symptomatic hypoglycemic episodes	101	6.1 (8.5)
Lipids, fasting		
Total cholesterol, mg/dL		
Total cholesterol ≥ 200 mg/dL	79	234 ± 89
LDLc, mg/dL		47 (60)
>130 mg/dL	81	147 ± 83
HDLc, mg/dL		39 (48)
<35 mg/dL	80	74 ± 21
TG, mg/dL		0 (0)
>150 mg/dL	81	74 ± 37
Dyslipidemia (TG >130 mg/dL, LDLc >130, or HDLc <35 mg/dL)	82	5 (6)
		51 (62)

^a Obtained over 20 ± 18 d.

^b Obtained over 20 ± 18 d; 8 ± 3 measurements per day.

^c Data overlap because some participants reported events in different categories.

^d Only assessed in adults because help from others is always required in children.

300 participants, 7 (2%) reported hospitalizations in the past 12 months (14 separate occurrences; 0.05 hospitalizations per person per year), 4 (1%) had 4 (0.01 per person per year) hospitalizations for DKA, and 6 (2%) had 9 hospitalizations (0.03 per person per year) for other reasons. Symptomatic hypoglycemia within the past month was reported by 205 (69%) participants, with the majority (112; 55%) having few (1–5) episodes per month. Likewise, rates of severe hypoglycemia were low, with 7 (2%) reporting

hypoglycemia with seizure or coma and 11 (4%) requiring glucagon in the past year. Conventional chronic disease risk factors revealed a mixed profile, with low triglycerides (TG) and elevated high-density lipoprotein cholesterol (HDLc) but high total and low-density lipoprotein cholesterol (LDLc) (Table 2).

Pediatric Age Group and Growth

Children, compared with adults, had similar participant-reported HbA1c and other clinical parameters (Supplemental Table 8).

Participant- and provider-reported height SDSs were 0.26 ± 1.21 ($n = 107$; 82% of children) and 0.25 ± 1.00 ($n = 49$; 37%), respectively. There was no correlation of height SDS with carbohydrate intake goal ($r = 0.15$; $P = .20$) or diet duration ($r = 0.14$; $P = .16$). Provider-reported, current height SDS compared with height SDS at diagnosis was 0.20 ± 1.02 vs 0.41 ± 1.27 ($P = .05$) among the small subset of children for whom data were available ($n = 34$; 26%). Of the interval of 2.3 ± 2.0 years since diagnosis, these children had followed a VLCD for 1.2 ± 0.8 years.

Health and Health Care Satisfaction

Participants reported high levels of overall health and satisfaction with diabetes management but not with their professional diabetes care (Table 3), and 27% did not discuss their adherence to a VLCD with their diabetes care providers. Of those who did discuss their diet, only 49% agreed or strongly agreed that their diabetes care providers were supportive. Narrative explanations by participants for not discussing their diet included disagreement on treatment goals and approach, perceived provider disinterest or unfamiliarity with a VLCD, a desire to avoid conflicts with the provider, and (for parents) fear of being accused of child abuse. Participating providers corroborated the overall health ratings and reported even greater satisfaction with diabetes control compared with participants ($Z = -4.09$; $P < .001$). The therapeutic relationship was perceived as very good or excellent by 82% of providers. Interestingly, providers perceived themselves as more supportive of the VLCD compared with participant perception ($Z = -2.69$; $P = .007$).

DISCUSSION

In this survey of children and adults who follow a VLCD for the long-term treatment of T1DM, we observed measures of glycemic control in

TABLE 3 Participant- and Provider-Reported Health, Satisfaction With Diabetes Control and Care

Clinical Variables	All Participants	Participant With Provider Response	Provider	Z; P ^a
Health, overall rating				
No. responses	288	79	65	-1.87; .06
Excellent, <i>n</i> (%)	119 (41)	40 (51)	50 (77)	
Very good, <i>n</i> (%)	130 (45)	34 (43)	10 (15)	
Good, <i>n</i> (%)	32 (11)	5 (6)	4 (6)	
Fair, <i>n</i> (%)	5 (2)	0 (0)	0 (0)	
Poor, <i>n</i> (%)	2 (1)	0 (0)	1 (1.5)	
Diabetes control satisfaction				
No. responses	288	79	66	-4.09; <.001
Very satisfied, <i>n</i> (%)	104 (36)	25 (32)	51 (77)	
Satisfied, <i>n</i> (%)	147 (51)	39 (49)	11 (17)	
Neutral, <i>n</i> (%)	22 (8)	12 (15)	3 (4.5)	
Dissatisfied, <i>n</i> (%)	14 (5)	3 (4)	1 (1.5)	
Very dissatisfied, <i>n</i> (%)	1 (0)	0 (0)	0 (0)	
Satisfaction with professional diabetes care				
No. responses	287	78	64	—
Very satisfied, <i>n</i> (%)	53 (19)	16 (21)	—	—
Satisfied, <i>n</i> (%)	89 (31)	36 (46)	—	—
Neutral, <i>n</i> (%)	67 (23)	12 (15)	—	—
Dissatisfied, <i>n</i> (%)	50 (17)	8 (10)	—	—
Very dissatisfied, <i>n</i> (%)	28 (10)	6 (8)	—	—
Therapeutic relationship				
Excellent, <i>n</i> (%)	—	—	35 (55)	—
Very good, <i>n</i> (%)	—	—	17 (27)	—
Good, <i>n</i> (%)	—	—	10 (16)	—
Fair, <i>n</i> (%)	—	—	2 (3)	—
Poor, <i>n</i> (%)	—	—	0 (0)	—
Diet and/or lifestyle not discussed with diabetes care provider				
No. responses	287	79	65	.12
<i>n</i> (%)	77 (27)	15 (19)	4 (6)	
Diabetes care provider supportive of diet				
No. responses	210	64	61	-2.69; .007
Strongly agree, <i>n</i> (%)	34 (16)	12 (19)	22 (36)	
Agree, <i>n</i> (%)	70 (33)	22 (34)	21 (34)	
Neutral, <i>n</i> (%)	64 (30)	19 (30)	12 (20)	
Disagree, <i>n</i> (%)	27 (13)	8 (13)	5 (8)	
Strongly disagree, <i>n</i> (%)	14 (7)	3 (5)	1 (2)	

—, not applicable.

^a Wilcoxon signed-rank test for ordinal variables and McNemar's test for binomial variables.

the near-normal range, low rates of hypoglycemia and other adverse events, and generally high levels of satisfaction with health and diabetes control. These findings are without precedent among people with T1DM, revealing a novel approach to the prevention of long-term diabetes complications.

Researchers in the Diabetes Control and Complications Trial achieved an average HbA1c of 7.2% in the intensively treated group but with increased rates of hypoglycemia.^{6,7,30} In a recent survey of 3 international pediatric registries, an HbA1c <7% was not associated with higher rates of hypoglycemia.³¹

Nevertheless, targeting a near-normal HbA1c is generally not recommended because of concern for hypoglycemia. The participants in our survey had an average HbA1c in the normal range and low rates of hypoglycemia compared with those in other surveys.^{32,33} Likewise, hospitalizations for DKA or all diabetes-related causes compared favorably with prevailing rates.^{32–34}

The effect of a VLCD on cardiovascular disease risk has been subject to debate. Consistent with the known effects of low carbohydrate and (presumed) associated higher saturated fat intakes, participants had low TG and high HDLc and LDLc levels. The remarkably low ratio of TG to HDLc of 1:1, together with the low total daily insulin requirement, indicate high insulin sensitivity and good cardiometabolic health.³⁵ In contrast, total LDLc is considered a conventional cardiovascular risk factor. However, total LDLc elevation on a VLCD (associated with low TG) may reflect large, buoyant lipoprotein particles, which is a relatively low-risk subtype.³⁶ Furthermore, in the Diabetes Control and Complications Trial cohort of 1441 adolescents and young adults, HbA1c had the largest effects on cardiovascular risk, followed by TG and LDLc.³⁷ Postprandial hyperglycemia has been proposed as an independent cardiovascular disease risk factor³⁸ for which a VLCD would plausibly provide benefit. Another major cardiovascular risk factor, BMI, was significantly below population averages for study participants, possibly reflecting another benefit of a VLCD.³⁹

Children generally did as well as adults, which is a promising finding in view of the adverse effects of diabetes-related hyper- and hypoglycemia on brain

development^{40,41} and growth.^{42–46} The commonly reported growth deceleration in T1DM is generally ascribed to poor glycemic control.^{42–46} Concerns have also been raised that a VLCD or chronic ketosis may adversely affect growth and pubertal development.²⁵ Although pubertal development was not assessed in this survey, we obtained children's height data from parents and medical providers. Participant-reported, current mean height was modestly above average for age and sex (SDS 0.26). Provider-reported data were used to corroborate this finding and also revealed a marginal decrease in height SDS since diabetes diagnosis. This possible growth deceleration may have preceded or occurred during the diet and is comparable in magnitude to the previously described decreases in height SDS in T1DM. Taken together, these data do not reveal an adverse effect of a VLCD on growth, but additional research into this possibility is warranted.

Although participants reported high levels of satisfaction with health and diabetes control, relationships with diabetes care providers were often fraught. A minority of participants did not disclose their adherence to a VLCD to their providers, citing concerns for being criticized, pressured to change behavior, or accused of child abuse. This distrust may increase the risk for a catastrophic adverse event if patients feel unable to seek medical support at times of need (eg, impending DKA) and instead make diabetes management decisions beyond their competencies. Notably, most providers described the therapeutic relationship as very good or excellent and perceived themselves as more supportive of a VLCD than how they were described by the participants. This discrepancy warrants follow-up in qualitative research.

Strengths of this study include verification of self-reported information by independent sources (diabetes care providers and medical records), a rigorous approach to establish T1DM diagnosis, and the pragmatic setting. Our study has 3 main limitations. First, we cannot prove that all participants had T1DM. However, we found no important discrepancies between those who did and did not have diagnostic evidence (eg, childhood onset, diabetes antibodies, and nonobese body weight). Second, the generalizability of the findings is unknown. We cannot determine how many of the members of the online group are active, have T1DM (versus being health care providers, family members, or others with general interest), and would be eligible to participate in the study. In addition, children and adults adhering to a VLCD and remaining in this online community may represent a special subpopulation with high levels of motivation and other health-related behaviors (eg, physical activity), presenting another source of selection bias. Therefore, the study sample may not be representative of all people with T1DM in the social media group and may differ from the general T1DM population in ways that could influence the safety, effectiveness, and practicality of a VLCD. Third, we did not obtain detailed information on participants' diet and other components of this diabetes management approach, nor did we assess factors contributing to glycemic control before the self-reported start of the VLCD.

CONCLUSIONS

We suggest that a VLCD may allow for exceptional control of T1DM without increased risk of adverse events. This possibility is

mechanistically plausible because of the dominant effects of dietary carbohydrates on postprandial glycemia and the lower insulin doses required with a VLCD. The results, if confirmed in clinical trials, indicate that the chronic complications of T1DM might be prevented by diet. In light of study limitations, these findings by themselves should not be interpreted as sufficient to justify a change in diabetes management. Additional research is needed to determine the degree of carbohydrate restriction (and other dietary aspects) necessary to achieve these benefits, optimal insulin regimen to accompany a VLCD (specifically, with regard to

avoiding severe hypoglycemia), safety and efficacy (in randomized controlled trials). If this work is a success, trials to evaluate effectiveness in preventing long-term diabetes complications should be conducted.

ACKNOWLEDGMENTS

We thank the TypeOneGrit community for participating in this study, Paul Lakin for assistance with statistical analyses, Mallory Mandel for assistance with programming the surveys, Victoria Ravenelle for help with study management, and Tessa Graham for help with data management.

ABBREVIATIONS

ADA: American Diabetes Association
CGM: continuous glucose monitor
DKA: diabetic ketoacidosis
HbA1c: hemoglobin A1c
HDLc: high-density lipoprotein cholesterol
LDLc: low-density lipoprotein cholesterol
MODY: maturity onset diabetes of the young
SDS: standard deviation score
TG: triglycerides
T1DM: type 1 diabetes mellitus
VLCD: very low-carbohydrate diet

Address correspondence to David S. Ludwig, MD, PhD, Division of Endocrinology, Boston Children's Hospital, 300 Longwood Ave, Boston, MA 02115. E-mail: david.ludwig@childrens.harvard.edu

PEDIATRICS (ISSN Numbers: Print, 0031-4005; Online, 1098-4275).

Copyright © 2018 by the American Academy of Pediatrics

FINANCIAL DISCLOSURE: Dr Yancy received research grants from the National Institutes of Health and the US Department of Veterans Affairs for projects involving veterans' health related to a low-carbohydrate diet. Drs Ebbeling and Ludwig received research grants (to Boston Children's Hospital) from the National Institutes of Health, the Nutrition Science Initiative, the Laura and John Arnold Foundation, and other philanthropic organizations unaffiliated with the food industry; the other authors have indicated they have no financial relationships relevant to this article to disclose.

FUNDING: Supported by grants K24DK082730 (Dr Ludwig) and K12DK094721 (Dr Lennerz) from the National Institute of Diabetes and Digestive and Kidney Diseases. No other honorarium, grant, or other form of payment was given to anyone to produce the article. Funded by the National Institutes of Health (NIH).

POTENTIAL CONFLICT OF INTEREST: Dr Bernstein reported receiving royalties for books on the management of diabetes (which were used by members of the online social media group surveyed in this study). Dr Hallberg reported stock options and research support from Virta Health, a company that provides health care services for type 2 diabetes, and consulting fees from Atkins. Dr Rhodes is the site principal investigator in clinical trials for pediatric type 2 diabetes that are sponsored by Merck and AstraZeneca. Dr Westman has ownership interest in companies using low-carbohydrate principles, and he receives royalties for books related to low-carbohydrate diets. Dr Ludwig reported receiving royalties from books on nutrition and obesity; the other authors have indicated they have no potential conflicts of interest to disclose.

REFERENCES

1. Newburgh LH, Marsh PL. The use of a high fat diet in the treatment of diabetes mellitus. *Arch Intern Med (Chic)*. 1921;27(6):699–705
2. American Diabetes Association. Nutritional recommendations and principles for individuals with diabetes mellitus: 1986. American Diabetes Association. *Diabetes Care*. 1987;10(1):126–132
3. Armstrong C. ADA updates standards of medical care for patients with diabetes mellitus. *Am Fam Physician*. 2017;95(1):40–43
4. Miller KM, Foster NC, Beck RW, et al; T1D Exchange Clinic Network. Current state of type 1 diabetes treatment in the U.S.: updated data from the T1D exchange clinic registry. *Diabetes Care*. 2015;38(6):971–978
5. Rohlfing CL, Wiedmeyer HM, Little RR, England JD, Tennill A, Goldstein DE. Defining the relationship between plasma glucose and HbA(1c): analysis of glucose profiles and HbA(1c) in the Diabetes Control and Complications Trial. *Diabetes Care*. 2002;25(2):275–278
6. The Diabetes Control and Complications Trial Research Group. Hypoglycemia in the Diabetes Control and Complications Trial. *Diabetes Control and Complications Trial Research Group*. *Diabetes*. 1997;46(2):271–286
7. The DCCT Research Group. Epidemiology of severe hypoglycemia in the diabetes control and complications trial. The DCCT Research Group. *Am J Med*. 1991;90(4):450–459
8. Fullerton B, Jeitler K, Seitz M, Horvath K, Berghold A, Siebenhofer A. Intensive glucose control versus conventional glucose control for type 1 diabetes mellitus. *Cochrane Database Syst Rev*. 2014;(2):CD009122
9. Cryer PE. Glycemic goals in diabetes: trade-off between glycemic control

- and iatrogenic hypoglycemia. *Diabetes*. 2014;63(7):2188–2195
10. Sheard NF, Clark NG, Brand-Miller JC, et al. Dietary carbohydrate (amount and type) in the prevention and management of diabetes: a statement by the American diabetes association. *Diabetes Care*. 2004;27(9):2266–2271
 11. Bell KJ, King BR, Shafat A, Smart CE. The relationship between carbohydrate and the mealtime insulin dose in type 1 diabetes. *J Diabetes Complications*. 2015;29(8):1323–1329
 12. Emami A, Willinska ME, Thabit H, et al. Behavioral patterns and associations with glucose control during 12-week randomized free-living clinical trial of day and night hybrid closed-loop insulin delivery in adults with type 1 diabetes. *Diabetes Technol Ther*. 2017;19(7):433–437
 13. Brand-Miller J, Hayne S, Petocz P, Colagiuri S. Low-glycemic index diets in the management of diabetes: a meta-analysis of randomized controlled trials. *Diabetes Care*. 2003;26(8):2261–2267
 14. Dressler A, Reithofer E, Trimmel-Schwahofer P, et al. Type 1 diabetes and epilepsy: efficacy and safety of the ketogenic diet. *Epilepsia*. 2010;51(6):1086–1089
 15. Nielsen JV, Gando C, Joensson E, Paulsson C. Low carbohydrate diet in type 1 diabetes, long-term improvement and adherence: a clinical audit. *Diabetol Metab Syndr*. 2012;4(1):23
 16. Nielsen JV, Jönsson E, Ivarsson A. A low carbohydrate diet in type 1 diabetes: clinical experience—a brief report. *Ups J Med Sci*. 2005;110(3):267–273
 17. Ranjan A, Schmidt S, Damm-Frydenberg C, Holst JJ, Madsbad S, Nørgaard K. Short-term effects of a low carbohydrate diet on glycaemic variables and cardiovascular risk markers in patients with type 1 diabetes: a randomized open-label crossover trial. *Diabetes Obes Metab*. 2017;19(10):1479–1484
 18. Tóth C, Clemens Z. Type 1 diabetes mellitus successfully managed with the paleolithic ketogenic diet. *Int J Case Rep Images*. 2014;5(10):699–703
 19. Feinman RD, Pogozelski WK, Astrup A, et al. Dietary carbohydrate restriction as the first approach in diabetes management: critical review and evidence base. *Nutrition*. 2015;31(1):1–13
 20. O'Neill DF, Westman EC, Bernstein RK. The effects of a low-carbohydrate regimen on glycemic control and serum lipids in diabetes mellitus. *Metab Syndr Relat Disord*. 2003;1(4):291–298
 21. Westman EC, Feinman RD, Mavropoulos JC, et al. Low-carbohydrate nutrition and metabolism. *Am J Clin Nutr*. 2007;86(2):276–284
 22. Astrup A, Meinert Larsen T, Harper A. Atkins and other low-carbohydrate diets: hoax or an effective tool for weight loss? *Lancet*. 2004;364(9437):897–899
 23. Paoli A, Rubini A, Volek JS, Grimaldi KA. Beyond weight loss: a review of the therapeutic uses of very-low-carbohydrate (ketogenic) diets. *Eur J Clin Nutr*. 2013;67(8):789–796
 24. Westman EC, Mavropoulos J, Yancy WS, Volek JS. A review of low-carbohydrate ketogenic diets. *Curr Atheroscler Rep*. 2003;5(6):476–483
 25. de Bock M, Lobley K, Anderson D, et al. Endocrine and metabolic consequences due to restrictive carbohydrate diets in children with type 1 diabetes: an illustrative case series. *Pediatr Diabetes*. 2018;19(1):129–137
 26. Kanikarla-Marie P, Jain SK. Hyperketonemia and ketosis increase the risk of complications in type 1 diabetes. *Free Radic Biol Med*. 2016;95:268–277
 27. Bernstein RK. *Dr. Bernstein's Diabetes Solution: The Complete Guide to Achieving Normal Blood Sugars*. 4th ed. Boston, MA: Little, Brown & Company; 2011
 28. Beck RW, Tamborlane WV, Bergenstal RM, Miller KM, DuBose SN, Hall CA; T1D Exchange Clinic Network. The T1D Exchange clinic registry. *J Clin Endocrinol Metab*. 2012;97(12):4383–4389
 29. Harris PA, Taylor R, Thielke R, Payne J, Gonzalez N, Conde JG. Research electronic data capture (REDCap)—a metadata-driven methodology and workflow process for providing translational research informatics support. *J Biomed Inform*. 2009;42(2):377–381
 30. Diabetes Control and Complications Trial Research Group; Nathan DM, Genuth S, Lachin J, et al. The effect of intensive treatment of diabetes on the development and progression of long-term complications in insulin-dependent diabetes mellitus. *N Engl J Med*. 1993;329(14):977–986
 31. Haynes A, Hermann JM, Miller KM, et al; T1D Exchange, WACDD and DPV Registries. Severe hypoglycemia rates are not associated with HbA1c: a cross-sectional analysis of 3 contemporary pediatric diabetes registry databases. *Pediatr Diabetes*. 2017;18(7):643–650
 32. Weinstock RS, Xing D, Maahs DM, et al; T1D Exchange Clinic Network. Severe hypoglycemia and diabetic ketoacidosis in adults with type 1 diabetes: results from the T1D exchange clinic registry. *J Clin Endocrinol Metab*. 2013;98(8):3411–3419
 33. Cengiz E, Xing D, Wong JC, et al; T1D Exchange Clinic Network. Severe hypoglycemia and diabetic ketoacidosis among youth with type 1 diabetes in the T1D exchange clinic registry. *Pediatr Diabetes*. 2013;14(6):447–454
 34. Angus VC, Waugh N. Hospital admission patterns subsequent to diagnosis of type 1 diabetes in children: a systematic review. *BMC Health Serv Res*. 2007;7:199
 35. Quispe R, Manalac RJ, Faridi KF, et al. Relationship of the triglyceride to high-density lipoprotein cholesterol (TG/HDL-C) ratio to the remainder of the lipid profile: the Very Large Database of Lipids-4 (VLDL-4) study. *Atherosclerosis*. 2015;242(1):243–250
 36. Ahmadi SA, Boroumand MA, Gohari-Moghaddam K, Tajik P, Dibaj SM. The impact of low serum triglyceride on LDL-cholesterol estimation. *Arch Iran Med*. 2008;11(3):318–321
 37. Diabetes Control and Complications Trial, Epidemiology of Diabetes Interventions and Complications Research Group. Risk factors for cardiovascular disease in type 1 diabetes. *Diabetes*. 2016;65(5):1370–1379

38. Ceriello A, Hanefeld M, Leiter L, et al. Postprandial glucose regulation and diabetic complications. *Arch Intern Med.* 2004;164(19):2090–2095
39. Mansoor N, Vinknes KJ, Veierød MB, Retterstøl K. Effects of low-carbohydrate diets v. low-fat diets on body weight and cardiovascular risk factors: a meta-analysis of randomised controlled trials. *Br J Nutr.* 2016;115(3):466–479
40. Malone JL. Diabetic central neuropathy: CNS damage related to hyperglycemia. *Diabetes.* 2016;65(2):355–357
41. Mazaika PK, Weinzimer SA, Mauras N, et al; Diabetes Research in Children Network. Variations in brain volume and growth in young children with type 1 diabetes. *Diabetes.* 2016;65(2):476–485
42. Parthasarathy L, Khadilkar V, Chiplokhar S, Khadilkar A. Longitudinal growth in children and adolescents with type 1 diabetes. *Indian Pediatr.* 2016;53(11):990–992
43. Khadilkar VV, Parthasarathy LS, Mallade BB, Khadilkar AV, Chiplokhar SA, Borade AB. Growth status of children and adolescents with type 1 diabetes mellitus. *Indian J Endocrinol Metab.* 2013;17(6):1057–1060
44. Hannon TS, Rogol AD. Diabetes mellitus and growth in children and adolescents. *J Pediatr.* 2012;160(6):893–894
45. Bonfig W, Kapellen T, Dost A, et al; Diabetes Patienten Verlaufsdokumentationssystem Initiative of the German Working Group for Pediatric Diabetology; German Bundesministerium für Bildung und Forschung Competence Net for Diabetes Mellitus. Growth in children and adolescents with type 1 diabetes. *J Pediatr.* 2012;160(6):900–903.e2
46. Frohlich-Reiterer EE, Kaspers S, Hofer S, et al; Diabetes Patienten Verlaufsdokumentationssystem-Wiss Study Group. Anthropometry, metabolic control, and follow-up in children and adolescents with type 1 diabetes mellitus and biopsy-proven celiac disease. *J Pediatr.* 2011;158(4):589–593.e2

Management of Type 1 Diabetes With a Very Low–Carbohydrate Diet
Belinda S. Lennerz, Anna Barton, Richard K. Bernstein, R. David Dikeman, Carrie
Diulus, Sarah Hallberg, Erinn T. Rhodes, Cara B. Ebbeling, Eric C. Westman,
William S. Yancy Jr and David S. Ludwig

Pediatrics 2018;141;

DOI: 10.1542/peds.2017-3349 originally published online May 7, 2018;

Updated Information & Services

including high resolution figures, can be found at:
<http://pediatrics.aappublications.org/content/141/6/e20173349>

References

This article cites 45 articles, 11 of which you can access for free at:
<http://pediatrics.aappublications.org/content/141/6/e20173349#BIBL>

Subspecialty Collections

This article, along with others on similar topics, appears in the following collection(s):

Endocrinology

http://www.aappublications.org/cgi/collection/endocrinology_sub

Diabetes Mellitus

http://www.aappublications.org/cgi/collection/diabetes_mellitus_sub

Nutrition

http://www.aappublications.org/cgi/collection/nutrition_sub

Permissions & Licensing

Information about reproducing this article in parts (figures, tables) or in its entirety can be found online at:

<http://www.aappublications.org/site/misc/Permissions.xhtml>

Reprints

Information about ordering reprints can be found online:

<http://www.aappublications.org/site/misc/reprints.xhtml>

American Academy of Pediatrics

DEDICATED TO THE HEALTH OF ALL CHILDREN®



PEDIATRICS®

OFFICIAL JOURNAL OF THE AMERICAN ACADEMY OF PEDIATRICS

Management of Type 1 Diabetes With a Very Low–Carbohydrate Diet

Belinda S. Lennerz, Anna Barton, Richard K. Bernstein, R. David Dikeman, Carrie Diulus, Sarah Hallberg, Erinn T. Rhodes, Cara B. Ebbeling, Eric C. Westman, William S. Yancy Jr and David S. Ludwig

Pediatrics 2018;141;

DOI: 10.1542/peds.2017-3349 originally published online May 7, 2018;

The online version of this article, along with updated information and services, is located on the World Wide Web at:

<http://pediatrics.aappublications.org/content/141/6/e20173349>

Data Supplement at:

<http://pediatrics.aappublications.org/content/suppl/2018/05/03/peds.2017-3349.DCSupplemental>

Pediatrics is the official journal of the American Academy of Pediatrics. A monthly publication, it has been published continuously since 1948. Pediatrics is owned, published, and trademarked by the American Academy of Pediatrics, 345 Park Avenue, Itasca, Illinois, 60143. Copyright © 2018 by the American Academy of Pediatrics. All rights reserved. Print ISSN: 1073-0397.

American Academy of Pediatrics

DEDICATED TO THE HEALTH OF ALL CHILDREN®

