Received: 8 September 2021 | Revised: 3 December 2021 | Accepted: 18 December 2021

DOI: 10.1111/dom.14630

ORIGINAL ARTICLE

WILEY

Where can you wear your Libre? Using the FreeStyle Libre continuous glucose monitor on alternative sites

Rosemary M. Hall Phd[1,2] | Sophie Dyhrberg MBChB[3] | Arthur McTavish[3] | Lindsay McTavish, Diabetes CNS[1] | Brian Corley PhD[1] | Jeremy D. Krebs MD[1,2]

[1]Endocrine, Diabetes and Research Centre, Wellington Regional Hospital, Wellington, New Zealand

[2]Department of Medicine, University of Otago, Wellington, New Zealand

[3]University of Otago Medical School, Dunedin, New Zealand

Correspondence
Rosemary M. Hall, Phd, Endocrine, Diabetes and Research Centre, Wellington Regional Hospital, Wellington, New Zealand.
Email: rosemary.hall@otago.ac.nz

Funding information
Diabetes Wellington; Wellington Endocrine Foundation

Abstract

Aim: To investigate the accuracy and acceptability of the FreeStyle Libre Flash continuous glucose monitoring system (FSL-CGM) at alternative sites during free living and under experimental conditions.

Materials and Methods: Participants with type 1 diabetes were provided with three FSL-CGM sensors applied to the upper arm, the lower back, and the anterior chest. On day 2 or 3, FSL-CGM sensor glucose was compared with venous glucose following a standard meal, during and after an exercise test, and after skin cooling. Participants completed 14-day use of the sensors with concomitant sensor scanning at all sites and capillary glucose tests. The primary outcome was accuracy between sensor sites of 14-day mean glucose. Clarke's error grids, precision absolute relative deviation, and mean absolute relative deviation were calculated.

Results: In the 20 participants, compared with the arm sensor, the accuracy of the back sensor and the chest sensor was 97.9% and 98%, respectively. Under experimental conditions, the arm sensor was more accurate than that of the back and chest. All the sensors recorded higher glucose concentration than venous samples during exercise. The arm and chest sites were most preferred, with the greatest sensor failures from the back.

Conclusions: The FSL-CGM is clinically accurate when the sensors are applied to alternate chest or back sites. Greater variability occurs during rapid changes in glucose concentration with all sensor sites compared with venous glucose. Understanding these variabilities allows appropriate use of an economically viable continuous glucose monitor.

KEYWORDS
continuous glucose monitoring, dietary intervention, exercise intervention, glycaemic control, insulin therapy, type 1 diabetes

1 | INTRODUCTION

Subcutaneous continuous glucose monitoring (CGMS) has revolutionized the management of type 1 diabetes (T1D). People with T1D require multiple measurements of blood glucose daily to guide insulin dosing for optimal glycaemic control. Capillary blood glucose monitoring, which can be painful and is often inconvenient, has been the main method of day-to-day blood glucose measurements over the last 40 years. The FreeStyle Libre Flash continuous glucose monitoring system (FSL-CGM; Abbott Diabetes Care, Alameda, CA) is a factory-calibrated subcutaneous interstitial continuous glucose monitor that does not require concomitant capillary glucose tests. The ease

of obtaining blood glucose levels with the FSL-CGM, and a sensor that is not prohibitive in cost, has led to an increase in the use of this technology, even in countries where it is not funded.[1]

The manufacturer recommends that the FSL-CGM is used on the back of the upper arm to ensure the reliability of the sensor device.[1] However, there are many reasons why an alternative site may be more preferable for patients, for aesthetic or practical reasons. From the limited research available, it appears that the upper thigh may be a suitable alternative site for the FGL-CGM, whereas the sensor placed on the abdomen performs poorly.[2,3] This appears to differ from other CGM sensors, where the abdomen is the recommended site.

Measured glucose concentrations are lower and increase more slowly after an oral glucose load when measured on the FSL-CGM compared with a laboratory-measured plasma glucose.[3] Variation in tissue glucose dispersal and blood flow may in part explain variations in blood glucose recordings when sensors are placed in different locations. In addition, rapid changes in glucose concentration may occur during exercise or with temperature changes, leading to a differential impact on FSL-CGM sensors at different sites. Cold-induced vasoconstriction may reduce blood flow to the skin, while lowered whole-body temperature increases cold-induced thermogenesis, which leads to increased glucose uptake and carbohydrate oxidation. By contrast, increased blood flow to the skin with heat exposure, from ambient temperature or during exercise, reduces glucose delivery to skeletal muscle and decreases insulin sensitivity.[4]

The accuracy of the sensor site is important, as people with T1D must be able to trust the performance of any method of glucose measurement for optimal diabetes management. Glucose monitoring via CGMS reduces HbA1c compared with capillary glucose monitoring,[5] but for widespread use it is essential that patients are able to use this technology to complement their individual lifestyles. We aimed to investigate the accuracy and acceptability of the FSL-CGM when a sensor is applied to alternative sites that may be preferred by people with T1D. We compared the recommended upper arm site with the upper chest and lower back during free living and under experimental conditions when blood glucose levels are expected to be changing more rapidly, that is, during a meal, in response to exercise, and with changing skin temperature.

2 | MATERIALS AND METHODS

This prospective experimental study was conducted at the Centre for Endocrine, Diabetes and Obesity Research (CEDOR), Wellington Hospital, New Zealand. Patients with T1D who attended diabetes outpatients' clinics were invited to participate in the study. Participants were included if they had T1D, were aged 18 years or older, and were using either a basal bolus regimen of insulin or a subcutaneous continuous insulin pump. Potential participants were not eligible to be included if they were regularly taking aspirin or had an allergy to medical adhesive tape.

The study was approved by the New Zealand Health and Disability Northern Regional Ethics committee (18/NTA/171) and is registered at ANZCTR.org.au (number 12618001516279).

2.1 | Study procedures

Participants attended the CEDOR on three occasions. At the first visit, after providing informed consent to participate, information was collected on the type and duration of diabetes, medications, usual glucose monitoring device and pattern, usual frequency of hypoglycaemia, and medical history, including complications of diabetes, dietary intolerances, and habitual exercise pattern. Measurements were made of weight in kg, height in metres, and blood pressure (BP) in mmHg in the seated position using a manual sphygmomanometer. Three BP measurements were taken and the mean of the last two was used. The most recent HbA1c within the previous 3 months was extracted from laboratory data. If no value was available then the HbA1c was measured using a Cobas c501 point of care device (Roche, Switzerland).

FSL-CGM sensors were applied to three sites, as shown in Figure 1, at: (A) the back of the upper arm; (B) the back, posteriorly at the level of L4/5 halfway between the iliac crest and the vertebrae; and (C) the third intercostal space in the midclavicular line on the anterior chest. The sensors were secured with additional adhesive tape. Participants were educated in the use of the sensors and advised to avoid vitamin C supplements and aspirin, as recommended in the manufacturer's instructions, to avoid interference in the measurement

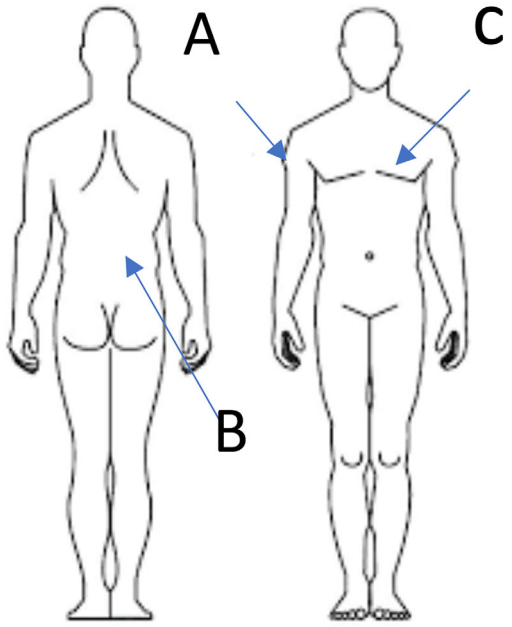

FIGURE 1 Location of the FreeStyle Libre Flash continuous glucose monitoring system (FSL-CGM) sensors: A, The back of the upper arm; B, The back, posteriorly at the level of L4/5 halfway between the iliac crest and the vertebrae; and C, The third intercostal space in the midclavicular line on the anterior chest

of interstitial glucose. Participants completed a 14-day food and exercise diary while using the FSL-CGM sensors, and continued with usual capillary finger-prick glucose testing before and 3 hours after each meal using CareSens blood glucose meters and strips (i-SENS, South Korea). Three colour-coded FSL-CGM readers were supplied to each participant to match the colour placed on each sensor. The readers can only gather data from one sensor at a time, thus the glucose levels obtained could only have come from the matched sensor. Participants were asked to record sensor glucose levels at each site at the same time as the capillary blood glucose levels.

Participants returned within 3 days of the first visit, when sensor accuracy was optimal, to undertake three physiological tests designed to assess the performance of the sensors under different conditions: (a) following a standardized mixed meal, (b) during moderate exercise, and (c) at a low skin temperature. Participants were required to consume their usual meal the night before and refrain from unaccustomed exercise. Participants arrived in the morning after a 10-hour overnight fast. They were instructed to take their usual long-acting insulin and withhold their rapid-acting insulin. Those on an insulin pump continued with their usual basal rates. Upon arrival, an intravenous (IV) cannula was inserted into the antecubital fossa.

2.1.1. Meal test

Baseline venous samples and capillary glucose measurements were taken and FSL-CGM glucose was recorded. A test meal of porridge with milk, almonds, and raisins, consisting of 61 g of carbohydrate (of which 36 g were sugar), 22 g fat, and 16 g protein, was provided and consumed within 10 minutes. Participants used their individual insulin: carbohydrate ratio for their premeal insulin dose. Insulin was administered at time 0 and the meal was consumed within 10 minutes. Venous glucose samples were taken via the IV cannula at −5, 0, 10, 20, 30, 40, 50, and 60 minutes.

2.1.2. Exercise test

An Astrand-Ryhming submaximal Wattbike exercise test was performed.[6] The exercise consisted of a 5-minute warm-up at low intensity, a 10-minute interval at moderate intensity, and a 5-minute warm-down at low intensity. The participants wore a wrist pulse oximeter to measure their heart rate. Moderate intensity exercise was defined as 75% of maximum heart rate, which was calculated with the equation 220 − the participant's age. Venous glucose samples were taken at baseline, at 5-minute intervals for the duration of the exercise, followed by 10-minute intervals for 30 minutes upon completion of the exercise at −5, 0, 5, 10, 15, 20, 30, 40, and 50 minutes. Each sensor was scanned when blood was sampled.

2.1.3. Temperature test

The skin was cooled for 10 minutes by applying long thin balloons filled with water, tied into a doughnut shape and frozen, then placed around the sensor. The skin temperature was taken before and after cooling by infrared laser thermometer. Blood samples were taken at the beginning and end of the cooling process, and then at 10-minute intervals for 30 minutes: 0, 10, 20, 30, and 40 minutes. Each sensor was scanned when blood was sampled.

Blood glucose samples were collected in fluoride tubes and analysed using a Yellow Springs Instrument (YSI; Yellow Springs, OH) glucose analyser. Each sample was analysed in duplicate. If the coefficient of variation (CV) of the first two tests was more than 5.0% then a third analysis was performed. The mean of the two closest measurements was used.

At the end of the 14-day period, participants returned for their final visit, when the sensors were removed and the data were downloaded. Participants completed a questionnaire about the use and acceptability of the FSL-CGM, which included questions on ease of use, discomfort experienced, visibility of the sensors, preference of location, and perceived positive and negatives aspects of the FSL-CGM.

2.2 | Outcomes

The primary outcome was the accuracy of the FSL-CGM sensors at the back and chest relative to at the arm site, as measured by mean glucose over the 14-day period of free living.

The secondary outcomes included:

- The sensor accuracy relative to venous blood glucose measurements, during a standard test meal, during a standard exercise test, and during cold exposure.
- The proportion of time above (>8.0 mmol/L) and below (<4.0 mmol/L) the target glucose range.
- The 14-day time-normalized area under the curve (AUC).
- Preferred sensor site.
- Sensor failure: the failure of a sensor was defined as the sensor becoming unscannable by the reader, or removal of the sensor because of discomfort or an adverse skin reaction before 14 days.

2.3 | Statistical analysis

A sample size of 20 individuals was determined to be sufficient for stability of estimates of variance. This sample size was based on a previous analysis of data available at the clinical study site (unpublished). Our database of Libre sensor uploads from free-living adults with T1D and type 2 diabetes includes average glucose. Twenty repeated random samples using sample sizes of 15, 20, 25, and 50 patients were obtained. For each sample size, the mean and SD of the randomly sampled glucose metrics were calculated (R studio, Vienna). The mean (SD) of the average glucose metric was 10.3 (0.6) mmol/L for a sample size of 15, 10.2 (0.5) mmol/L for a sample size of 20, 10.3 (0.4) mmol/L for a sample size of 25, and 10.4 (0.3) mmol/L for a sample size of 50. Similar results were recorded for the CV metric.

For the main analysis, the variables of 14-day mean blood interstitial-derived plasma glucose, 14-day time-normalized AUC glucose, and proportion of time spent in the range of 4 to 8 mmol/L, were used for a Bland–Altman limits of agreement plot with estimation of the mean bias between the licensed site (A) and the other two sites and the limits of agreement (95% CI for an individual prediction).

For ambulatory CGM data, Clarke's error grids and descriptive statistics, including the proportion of time in hyperglycaemia,

euglycaemia, and hypoglycaemia, and the precision absolute relative deviation (PARD), were calculated.[7-9] The PARD is the average difference in measurements from two different CGMs expressed as a proportion of the average of the CGM values. Time matching between sensors at different sites was achieved by linear interpolation of each sensor's samples. If a sensor was missing more than two consecutive CGM samples (e.g. because of sensor loss), this was left as missing data and linear interpolation was not performed. To ensure that there was a high degree of accuracy of the CGM data, those data from the first 24 hours were not used in the analysis, and visual inspection and correlation of all interpolated and CGM samples were performed.

For sensor accuracy during the standardized tests, the mean absolute relative deviation (MARD) was calculated. The MARD is the individual average difference between two methods of glucose measurement: glucose measurements using the YSI glucose analyser and the CGM sensor, expressed as a proportion of the average values of both methods.

As Clarke's error grids, MARD, PARD, and descriptive variables are more illustrative of the outcomes of interest, they are presented in the paper, and the Bland–Altman plots are presented as Figure S1 and Table S1.[10]

3 | RESULTS

Twenty participants completed the study, and their characteristics are presented in Table 1. All participants wore the FSL-CGM sensors for 14 days. Sensors were replaced if sensor loss was reported within the first week. In the circumstance of an unsuccessful initial sensor placement, then the recordings from the sensor replacement were used. There was sensor loss within the first 3 days of wear for one arm sensor, one back sensor, and one chest sensor, and there was at least 7 days of wear for 19/20 arm sensors, 18/20 chest sensors, and 15/20 back sensors. Reported causes for sensor failure included physical trauma, the sensor dropping off, or removal because of discomfort or a skin reaction.

TABLE 1 Baseline characteristics of participants

	N	Mean (SD)
Participants	20	
Male	11	
Female	9	
Ethnicity		
NZ European	15	
NZ Maori	2	
Other	3	
Age (y)		36 (15.3)
Duration of diabetes (y)		14.7 (9.8)
Weight (kg)		78.4 (17.3)
BMI (kg/m^2)		26.8 (5.0)
HbA1c (mmol/mol)		63.2 (11.4)
(%)		7.9 (1.0)
Smoking (vape)	3 (1)	
Insulin therapy		
Continuous SC insulin infusion	9	
Multiple daily injections	11	

Abbreviations: BMI, body mass index; NZ, New Zealand; SC, subcutaneous.

3.1 | Accuracy of ambulatory 14-day FSL-CGM

The total number of FSL-CGM glucose samples from all participants available for analysis was 21 136 from sensor A (arm), 15 833 from sensor B (back), and 19 964 from sensor C (chest) (Table 2). Mean (SD) glucose concentration deviated from reference sensor A by 0.53 (SD 1.73) mmol/L for sensor B, and 0.47 (1.39) mmol/L for sensor C. Figure 2 presents the Clarke's error grid analyses of the paired readings from sensors A and B (Figure 2A) and sensors A and C (Figure 2B). The percentage of results in zones A and B for the paired sensor A and B readings was 97.9%, and for the paired sensor A and C readings it was 98%. The overall results indicated a lower correlation between results from sensor B and those from sensor A in the

TABLE 2 Continuous glucose monitoring ambulatory data descriptive statistics and deviation from sensor A

	Sensor A	Sensor B	Sensor C
Number of patients	20	20	19[a]
Total hours recording	5284	3958	4991
Total no. of days	220	165	208
Total samples	21 136	15 833	19 964
Missing values	2377	1700	2194
Interpolated samples	55 208	44 812	53 006
All categories (mmol/L)	NA	0.53 (1.73) n = 42 933	0.47 (1.39) n = 50 762
Mean ARD	NA	10%	9%
Median ARD	NA	8%	7%
Mean PARD	NA	13%	12%
Median PARD	NA	8%	7%
Hyperglycaemic range	NA	0.83 (1.89)	0.59 (1.45)
>8.0 (mmol/L)		n = 27 067	n = 31 295
Euglycaemic range	NA	0.06 (1.22)	0.33 (1.23)
4.0-8.0 (mmol/L)		n = 13 214	n = 15 965
Hypoglycaemic range	NA	−0.20 (1.35)	−0.08 (1.28)
<4.0 (mmol/L)		n = 2652	n = 3086

Note: Descriptive statistics for ambulatory glucose recordings of sensors B and C with mean and median absolute relative deviation (ARD), mean and median precision ARD (PARD) from reference sensor A, and mean absolute deviation (SD) from reference sensor A, are presented by category of glycaemia. Deviation is calculated from interpolated samples at matched time points only.

[a]One sensor dislodged early and was unable to be replaced.

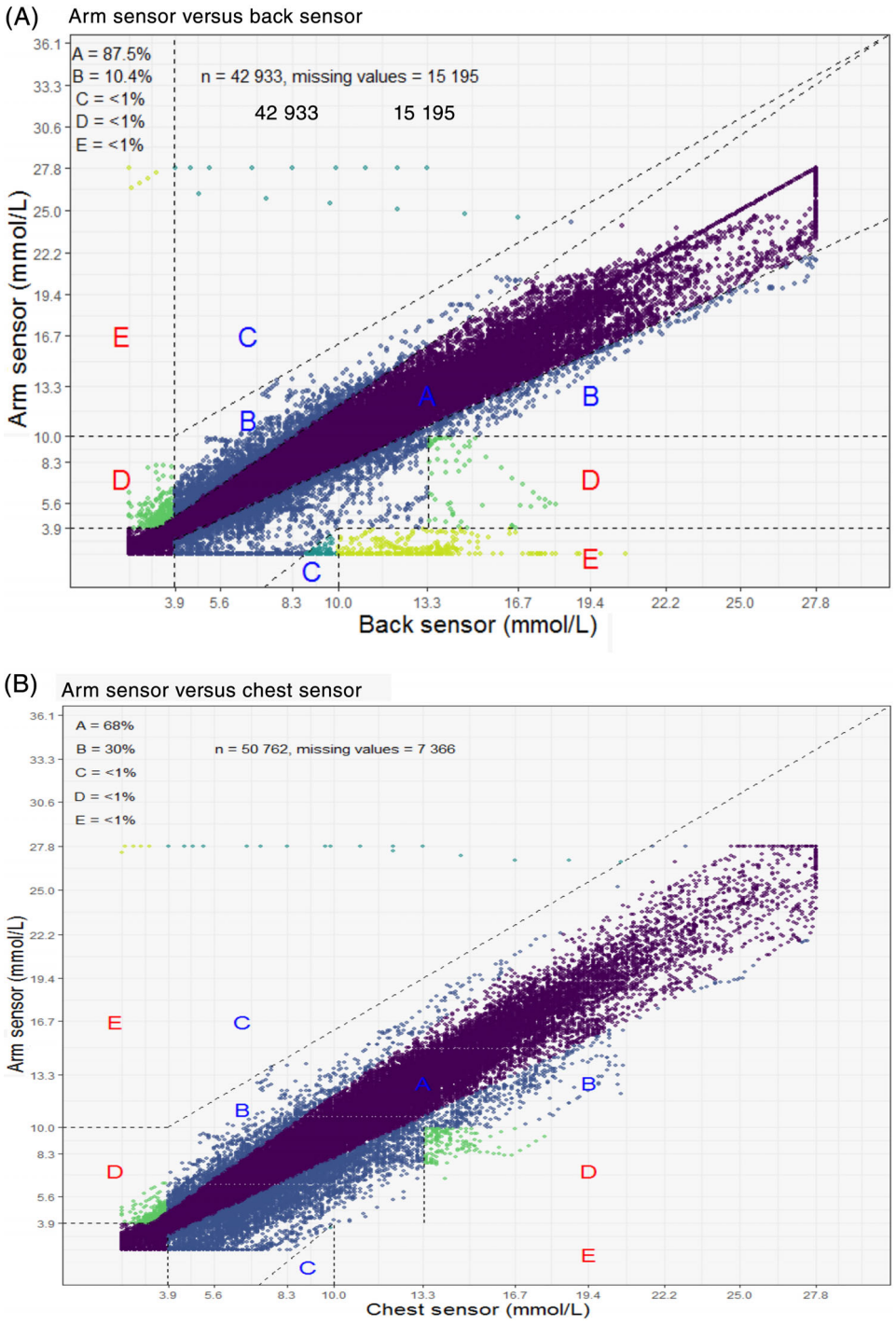

FIGURE 2 Accuracy of alternative sensor sites. Clarke error grids of paired glucose concentrations measured by the FreeStyle Libre Flash continuous glucose monitoring system (FSL-CGM) at A, Sensor A (upper arm) and sensor B (lower back/flank), and B, Sensor A and sensor C (anterior chest). Percentages of paired readings within the error grid zones A, B, C, D, and E are presented. Clarke error grid definitions[11]: zone A, clinically accurate; zone B, benign; zone C, overcorrection results; zone D, failure of the CGM to detect a high glucose level; zone E erroneous

higher glucose ranges, leading to fewer results in zone A in these paired sensors.

3.2 | Accuracy of the FSL-CGM under experimental test conditions

Glucose concentrations during the three test conditions are presented in Figure 3. Glucose concentrations at the three FSL-CGM sensor sites (arm, back, and chest) were compared with venous glucose samples obtained at the same time points. After a standard meal, the arm sensor performed better than the sensors placed on the back or chest (mean ARD arm, 8.2% [SD 6.8%], back 11% [11.1%], and chest 11.3% [10.4%]; Figure 3A). There was a greater deviation in glucose concentrations taken from the FSL-CGM compared with venous samples during exercise (Figure 3B). All sensors recorded higher glucose concentrations than the venous samples during exercise (0 to 20 minutes), with less deviation between sensor and venous glucose concentrations postexercise (20-50 minutes). During skin cooling, the arm sensor performed better than the back and chest sensors (mean

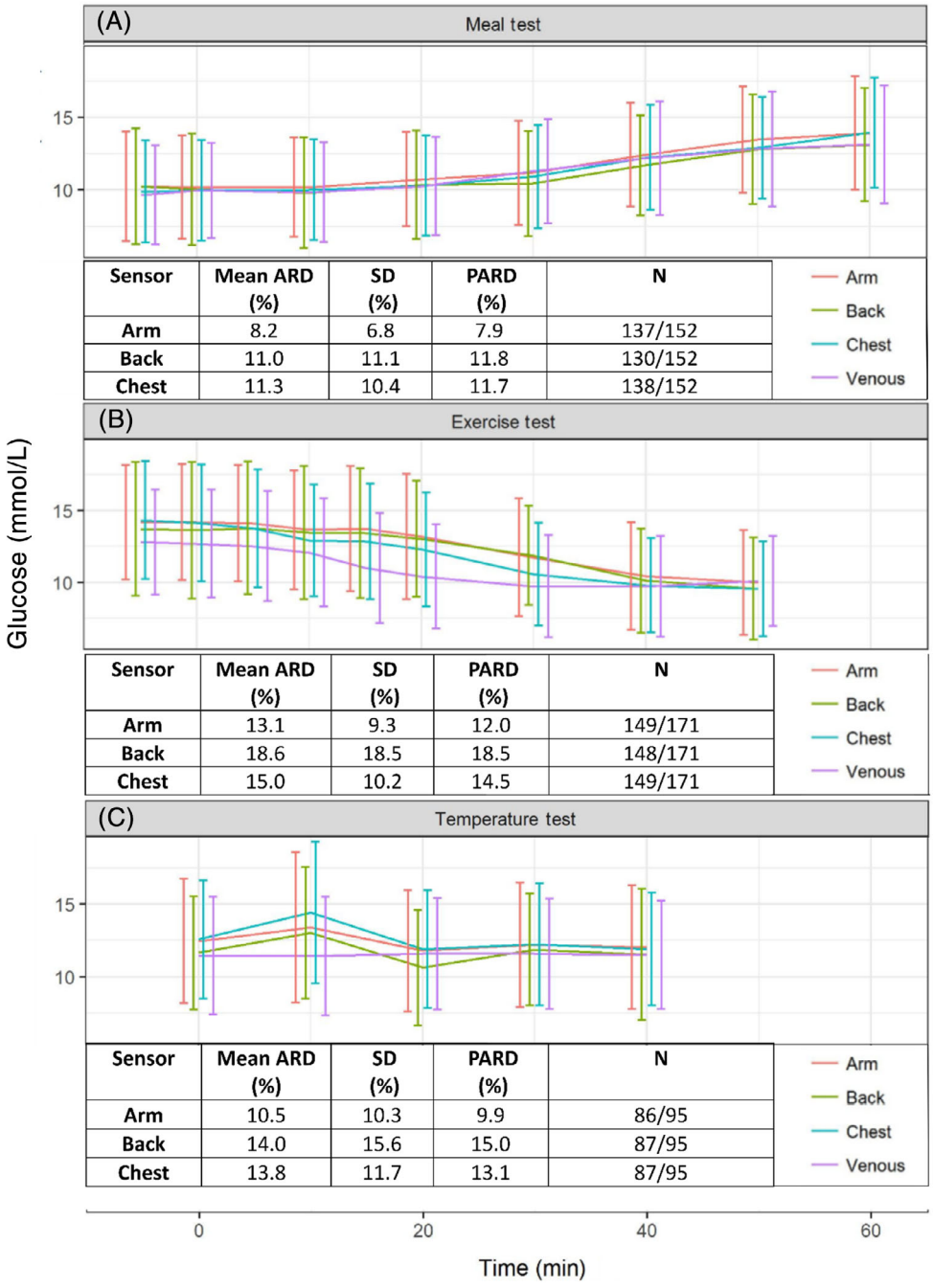

FIGURE 3 Mean (SD) venous glucose concentration compared with the FreeStyle Libre Flash continuous glucose monitoring system (FSL-CGM) from three sensor sites, arm, chest, and back, A, After a standard meal, B, During exercise, and C, With skin temperature cooling. Mean absolute relative difference (ARD)% of the three FSL-CGM sensors relative to venous glucose is presented, and precision absolute relative difference (PARD) is the difference between venous glucose and sensor-derived glucose as a proportion of their average

ARD arm 10.5% [SD 10.3%], back 14.0% [15.6%], and chest 13.8% [11.7%]; Figure 3C). The mean (SD) skin temperatures recorded at each sensor site at the start and end of cooling were: arm 29.9 (1.05) and 23.9 (2.29)°C; back 31 (0.83) and 25.3 (2.88)°C; and chest 31.5 (1.08) and 25.5 (2.19)°C, respectively.

3.3 | Preferred site of the FSL-CGM

The chest site was ranked as the preferred site by nine participants (45%), with eight (40%) preferring the arm, and three (15%) the back. Ten participants (50%) ranked the back as the least preferred site.

4 | DISCUSSION

This study investigated the accuracy and acceptability of the FSL-CGM during a free-living period, when sensors were applied to the upper chest and lower back compared with the recommended site on the back of the upper arm. It is the first study to compare FGL-CGM to plasma glucose concentration under experimental conditions, when blood glucose concentrations are expected to be changing more rapidly: during a meal, during exercise, and with a change of temperature.

During the 14-day free-living period, glucose readings from the FSL-CGM sensors on the arm showed acceptable agreement with the back (mean ARD 10%) and chest sensors (mean ARD 9%). Paired

FSL-CGM absolute deviation between sensor sites varied, depending on the level of glycaemia, with higher readings on the chest and back sensors for euglycaemic and hyperglycaemic recordings. Fewer than ideal glucose readings fell within the clinically accurate zone A: 65% for the back compared with the arm sensor, and 74% for the chest compared with the arm sensor; however, more than 97% of the results in each comparison fell within the clinically acceptable zones A and B.[11] There was wide variation in glucose concentrations between individuals throughout the day, which reflects the real-life experience of people living with T1D and enhances the robustness of the generalizability of these results. Even with this variation, sensors had a sufficient clinically acceptable level of accuracy, such that those who choose to apply their sensor at one of these alternative sites can be reassured.

The preferred sites were the arm and chest, while only 15% of participants rated the lower back as their most preferred site. The sensors commonly failed or fell off the back because of interference with clothes, contributing to their unpopularity. We had selected the lower back as a possible alternative site for the sensor as many patients are familiar with using this site, either to inject insulin or insert insulin pumps. However, the use of the sensors here was limited by their accuracy and longevity. By contrast, the chest site showed the lowest rate of loss and, combined with acceptable accuracy, may prove an acceptable alternative site.

People with diabetes report use of the sensors in locations that suit their habits and lifestyle, and it is therefore important to investigate their accuracy. Charleer et al.[2] showed that sensors placed on the upper thigh produced similar glucose measurements to those from the arm, with lower levels of accuracy from sensors placed on the abdomen, during free-living conditions. Fokkert et al.[3] investigated the performance of sensors placed on the arm and abdomen during 14-day free living, and compared capillary blood glucose after an oral glucose load. FSL-CGM measurements were acceptable for the arm sensor during daily life and after an oral glucose load, but were not accurate when placed on the abdomen. However, glucose readings from the arm sensor were lower in the hypoglycaemic range and higher in the hyperglycaemic range, with an underestimation of the effect of a glucose load on glucose response calling into question the overall accuracy of the FGL-CGM under dynamic conditions.[12]

Our study is the first to evaluate sensors placed in these three FSL-CGM sites compared with venous blood glucose during dynamic physiological tests. We showed that, after a meal, sensors at all three sites recorded accurate glucose concentrations compared with venous blood, with a mean ARD of between less than 8% and 11% across all sensors (Figure 3). These results are limited by wide variability in glucose levels throughout the testing day. Participants were asked to use an insulin dose for the meal test based on their own insulin: carbohydrate ratio. Despite this, some participants experienced hyperglycaemia, while others were nearing hypoglycaemia. However, intra-individual comparisons ensured that individual accuracy between the sensor sites and venous blood was identified in an environment mimicking real life, where glucose concentrations vary widely.

During exercise, venous glucose was lower than glucose concentrations recorded at any of the FSL-CGM sensor sites and only approached acceptable accuracy 40 minutes from the start of exercise, 20 minutes after its completion (Figure 3B). These data are in keeping with studies performed during exercise in people using Dexcom CGM. Inaccuracies in CGM glucose levels have been explained, in part, in one study, by CGM lagging behind capillary glucose by an average of 12 minutes, with higher blood glucose levels recorded by CGM throughout the exercise and recovery period.[13] Sensor bias may occur rapidly during exercise. Larose et al. found that median ARD increased from 8.4% before exercise to 16.8% during exercise, peaking within the first 15 minutes of exercise.[14] Similarly, Li et al. reported that sensor accuracy worsened during exercise, with CGM values lagging behind venous blood.[15] Our data support findings that, during exercise in a clinical research facility[16,17] or a real-life setting,[18,19] interstitial glucose measurements are often inaccurate compared with capillary glucose measurements, and suggest that inaccuracies are the results of significant physiological change rather than a specific feature of the sensor. During exercise, volume and fluid distribution within the interstitial fluid and vasculature changes rapidly, alongside increased non-insulin–mediated and insulin-mediated glucose uptake[20] and endogenous glucose production. Understanding these inaccuracies are important as the use of CGM becomes more widespread, with many specifically using these devices during exercise, when measuring capillary glucose is inconvenient. It is important that people understand their individual variability and respond appropriately to avoid unexpected episodes of hypoglycaemia or inappropriate treatment in response to sensor glucose levels.

Our study is the first to report the effect of skin temperature on the accuracy of the FSL-CGM. With application of ice to the skin, the FSL-CGM sensor recorded higher glucose levels than venous samples, returning to normal once the ice was removed. These findings are contrary to the expected effect of vasoconstriction from cold exposure and suggest that reported increased glucose oxidation only occurs when the whole-body temperature is lowered, rather than at individual sites.[4] A limitation to these findings is that we lack information on the rate of change of skin temperature around the sensor sites, which may have occurred at different rates in the different locations. As with the use of CGM during exercise, sensors are ideally suited for use in cold environments, where capillary glucose measurements may be inconvenient, but accuracy remains essential to prevent inappropriate glucose management. It is possible that one of the reasons for variations in sensor glucose levels during exercise is an increase in skin temperature. To our knowledge, the effect of heating the skin on the FSL-CGM has not been evaluated, but may be relevant to exercise or in hot environments.[21,22]

CGM has been shown to improve diabetes control[23,24] while reducing hypoglycaemia and, if available and comfortable, is preferentially used rather than capillary finger-prick measurements. CGM allows people with T1D to have more confidence in managing their diabetes in unpredictable environments. However, the accuracy of CGM is essential for safe and effective self-management. In this study, we have shown that using an alternative chest or back site for FSL-CGM sensor placement is clinically acceptable, if people choose to do so. Appropriate education that sensors may read lower in the hypoglycaemic range and

higher in the hyperglycaemic range, requiring capillary glucose measurement for confirmation of results at these levels, is important. After our standard meal, the FSL-CGM results were acceptable, even with participants calculating their own insulin doses. It would be important to evaluate the sensors with meals varying in macronutrients and total energy to ensure that this effect was reproducible. The FSL-CGM performed less accurately during exercise and with changes in temperature. Further investigations during prolonged or more extreme physiological change would help to inform these decisions. One limitation of the accuracy of the FSL-CGM during physiological change was that participants were investigated on day 2 or 3 after application of the sensor. Information at the time of designing the study suggested that concerns with accuracy existed for 24 hours after sensor application; however, it may be that the sensor is more stable and accurate on day 3.

The FSL-CGM provides a more economically viable CGM for participants or governments to fund, therefore it is essential that ongoing understanding of the appropriate use of these sensors empowers people with diabetes to make meaningful decisions to improve their control while liberating their lifestyle.

ACKNOWLEDGEMENTS

The authors would like to thank the participants for their involvement in the study, and the assistance of staff at the Centre for Endocrine, Diabetes and Obesity Research, Wellington, New Zealand. The study was funded by Diabetes Wellington and the Wellington Endocrine Foundation.

CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

AUTHOR CONTRIBUTIONS

RMH, LM, BC and JDK designed the study. SD and AM ran the study. All authors were involved in analysis and interpretation of data. RMH drafted the manuscript. All authors were involved in revising the manuscript and gave final approval of the version to be published.

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1111/dom.14630.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

ORCID

Rosemary M. Hall https://orcid.org/0000-0002-4718-5917
Jeremy D. Krebs https://orcid.org/0000-0002-7850-3447

REFERENCES

1. Bailey T, Bode BW, Christiansen MP, Klaff LJ, Alva S. The performance and usability of a factory-calibrated flash glucose monitoring system. *Diabetes Technol Ther*. 2015;17(11):787-794.
2. Charleer S, Mathieu C, Nobels F, Gillard P. Accuracy and precision of flash glucose monitoring sensors inserted into the abdomen and upper thigh compared with the upper arm. *Diabetes Obes Metab*. 2018;20(6):1503-1507.
3. Fokkert MJ, van Dijk PR, Edens MA, et al. Performance of the FreeStyle Libre Flash glucose monitoring system in patients with type 1 and 2 diabetes mellitus. *BMJ Open Diabetes Res Care*. 2017;5(1):e000320.
4. Dumke CL, Slivka DR, Cuddy JS, Hailes WS, Rose SM, Ruby BC. The effect of environmental temperature on glucose and insulin after an oral glucose tolerance test in healthy young men. *Wilderness Environ Med*. 2015;26:335-342.
5. Pickup JC, Freeman SC, Sutton AJ. Glycaemic control in type 1 diabetes during real time continuous glucose monitoring compared with self monitoring of blood glucose: meta-analysis of randomised controlled trials using individual patient data. *BMJ*. 2011;343:d3805.
6. Astrand PO, Ryhming I. A nomogram for calculation of aerobic capacity (physical fitness) from pulse rate during submaximal work. *J Appl Physiol*. 1954;7(2):218-221.
7. Clarke WL. The original Clarke error grid analysis (EGA). *Diabetes Technol Ther*. 2005;7(5):776-779.
8. Clarke WL, Cox D, Gonder-Frederick LA, Carter W, Pohl SL. Evaluating clinical accuracy of systems for self-monitoring of blood glucose. *Diabetes Care*. 1987;10(5):622-628.
9. Clarke WL, Anderson S, Farhy L, et al. Evaluating the clinical accuracy of two continuous glucose sensors using continuous glucose-error grid analysis. *Diabetes Care*. 2005;28(10):2412-2417.
10. Schnell O, Barnard K, Bergenstal R, et al. Role of continuous glucose monitoring in clinical trials: recommendations on reporting. *Diabetes Technol Ther*. 2017;19(7):391-399.
11. Jendrike N, Baumstark A, Kamecke U, Haug C, Freckmann G. ISO 15197: 2013 evaluation of a blood glucose monitoring system's measurement accuracy. *J Diabetes Sci Technol*. 2017;11(6):1275-1276.
12. Steineck IIK, Mahmoudi Z, Ranjan A, Schmidt S, Jorgensen JB, Norgaard K. Comparison of continuous glucose monitoring accuracy between abdominal and upper arm insertion sites. *Diabetes Technology and Therapeutics*. 2019;21(5):295-302.
13. Zaharieva DP, Turksoy K, McGaugh SM, et al. Lag time remains with newer real-time continuous glucose monitoring technology during aerobic exercise in adults living with type 1 diabetes. *Diabetes Technol Ther*. 2019;21(6):313-321.
14. Larose S, Rabasa-Lhoret R, Roy-Fleming A, et al. Changes in accuracy of continuous glucose monitoring using Dexcom G4 platinum over the course of moderate intensity aerobic exercise in type 1 diabetes. *Diabetes Technol Ther*. 2019;21(6):364-369.
15. Li A, Riddell MC, Potashner D, Brown RE, Aronson R. Time lag and accuracy of continuous glucose monitoring during high intensity interval training in adults with type 1 diabetes. *Diabetes Technol Ther*. 2019;21(5):286-294.
16. Moser O, Eckstein ML, Mueller A, et al. Impact of physical exercise on sensor performance of the FreeStyle Libre intermittently viewed continuous glucose monitoring system in people with Type 1 diabetes: a randomized crossover trial. *Diabet Med*. 2019;36(5):606-611.
17. Moser O, Eckstein ML, McCarthy O, 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):2505-2512.
18. Fokkert MJ, van Dijk PR, Edens MA, et al. Performance of continuous glucose monitoring devices during intensive exercise conditions in people with diabetes: the Mont Blanc experience. *Diabet Med*. 2020;37(7):1204-1205.

19. Fokkert M, van Dijk PR, Edens MA, et al. Performance of the Eversense versus the Free Style Libre Flash glucose monitor during exercise and normal daily activities in subjects with type 1 diabetes mellitus. *BMJ Open Diabetes Res Care*. 2020;8(1):e001193.
20. Castle JR, Rodbard D. How well do continuous glucose monitoring systems perform during exercise? *Diabetes Technol Ther*. 2019;21(6):305-309.
21. Breton MD, Cherñavvsky DR, Forlenza GP, DeBoer MD, Robic J, Wadwa RP, Messer LH, Kovatchev BP, Maahs DM. Closed-loop control during intense prolonged outdoor exercise in adolescents with type 1 diabetes: the artificial pancreas ski study. *Diabetes Care*. 2017;40(12):1644–1650. http://dx.doi.org/10.2337/dc17-0883
22. Englert K, Ruedy K, Coffey J, et al. Skin and adhesive issues with continuous glucose monitors: a sticky situation. *J Diabetes Sci Technol*. 2014;8(4):745-751.
23. Beck RW, Riddlesworth T, Ruedy K, et al. Effect of continuous glucose monitoring on glycemic control in adults with type 1 diabetes using insulin injections: the DIAMOND randomized clinical trial. *JAMA*. 2017;317(4):371-378.
24. Ólafsdóttir AF, Polonsky W, Bolinder J, et al. A randomized clinical trial of the effect of continuous glucose monitoring on nocturnal hypoglycemia, daytime hypoglycemia, glycemic variability, and hypoglycemia confidence in persons with type 1 diabetes treated with multiple daily insulin injections (GOLD-3). *Diabetes Technol Ther*. 2018;20(4):274-284.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

How to cite this article: Hall RM, Dyhrberg S, McTavish A, McTavish L, Corley B, Krebs JD. Where can you wear your Libre? Using the FreeStyle Libre continuous glucose monitor on alternative sites. *Diabetes Obes Metab*. 2022;1-9. doi:10.1111/dom.14630