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Accuracy and performance of continuous glucose monitors in athletes

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ABSTRACT

Continuous glucose monitoring (CGM) devices, with their 1–5 min measurement interval, allow blood glucose dynamics to be captured more frequently and less invasively than traditional measures of blood glucose concentration (BG). These devices are primarily designed for the use in type 1 and type 2 diabetic patients to aid BG regulation. However, because of their increased measurement frequency and reduced invasiveness CGM devices have been recently applied to other subject cohorts, such as intensive care patients and neonates. One unexamined cohort is athletes. Continuous monitoring of an athlete's BG has the potential to increase race performance, speed recovery, and aid training. However, before these benefits can be realised the accuracy and performance of CGM devices in active athletes must be evaluated.

Two Ipro2 and one Guardian Real-time CGM devices (Medtronic Minimed, Northridge, CA, USA) were inserted into 10 subjects (resting HR < 60 beats per minute (bpm), training 6–15 h per week). For each participant a fasting continuous exercise test was carried out until failure, ~90 min, and glucoses boluses were given at 30 min (0.5 g/kg) and failure (1 g/kg). Reference BG measurements were taken every 10 min for the first 60 min, every 5 min until failure + 30 min and every 10 min until failure + 60 min with an Abbott Optimum Xceed glucometer. Pre-glucose bolus, all sensors perform better compared to results seen in diabetic cohorts with median mean absolute relative difference (MARD) of 9.7%, 9.6% and 11.1% for the two Ipro2's and the Real-time, respectively. However, there is increased error post-bolus likely due to the gradient of BG change being higher, so the delay in transport to interstitial fluid and sensor results in a larger discrepancy from reference values. CGM devices agree very well with each other during rigorous exercise with median cross-correlation coefficients between 0.88 and 0.97 for the different sensor pairings. This good correlation between all three signals suggests the error between glucose measured by CGM and from blood is not random, but likely due to transport/uptake effects. As the interstitial fluid is the medium from which glucose enters muscle cells, this CGM value might be more useful than BG in determining glucose availability for athletes.

1. Introduction

Continuous glucose monitoring (CGM) devices, with their 1–5 min measurement interval, allow blood glucose concentration (BG) dynamics to be captured more frequently and less invasively than traditional measures of BG. CGM devices typically consist of a small pager-like monitoring device that receives a signal from a sensor inserted into the subcutaneous layer. The sensor creates a signal using the glucose oxidase reaction and produces a current proportional to the glucose concentration in the surrounding interstitial fluid. Calibration algorithms convert the signal into a BG value by comparing it to calibration BG measurements, which are entered into the monitor by the user every ~6–8 h.

These devices are primarily designed for the use in type 1 and type 2 diabetic individuals to aid BG regulation and are well studied in this cohort [1,2]. However, because of the increased measurement frequency and reduced invasiveness they have recently been applied to other cohorts, such as intensive care patients, to manage stress-induced hyperglycaemia, and neonates, to prevent hypogly-

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Table 1
Cohort demographics of the participants. Data are presented as median [interquartile range] where appropriate.

Number	10
Age (yr)	28 [23 37]
Gender (M/F)	7/3
BMI (kg/m^2)	22 [21 24]
Resting HR (bpm)	55 [53 56]
VO2max (mL/kg/min)	46 [39 59]
Trained Cyclist (Y/N)	7/3
Length of CGM data (h)	140 [105 141]

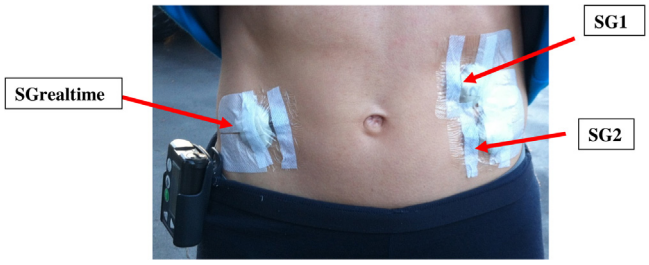

Fig. 1. Photo showing the locations of each CGM devices.

caemia, with varying success [3–10]. Another cohort where CGM may be beneficial is athletes. This cohort is yet to be thoroughly investigated but optimisation of an athlete's BG has the potential to increase race performance, speed recovery, and aid training [11–15]. In particular, there is ongoing research to improve carbohydrate delivery and oxidation, resulting in less accumulation of carbohydrate in the gastrointestinal track to decrease gastrointestinal problems during prolonged exercise [11]. CGM data could aid optimal carbohydrate delivery by allowing an athlete to know the best time and the amount of carbohydrate to consume. Additionally, optimal timing and amount of carbohydrate delivery has the potential to increase glycogen storage, speeding athlete recovery and providing additional energy for racing and training [16–18].

However, before these benefits can be realised, the accuracy and performance of CGM devices in active, trained athletes must be evaluated, which has not been done before. This evaluation is especially important as in populations with type 1 diabetes CGM has shown suboptimal accuracy during exercise [19] while other studies have shown improved accuracy [20]. Hence, the aim of this paper is to characterise the accuracy and performance of CGM in athletes while exercising in a manner representative of an endurance event or sport.

2. Subjects & methods

2.1. Subjects and experiments

Ten fit, healthy sub-elite athletes (resting HR < 60 bpm) were recruited under informed written consent for a study into optimal athlete nutrition (henceforth referred to as *athletes*). Table 1 summarizes the cohort demographics. Seven out of the ten participants cycled regularly and all subjects trained >6 h per week in a range of endurance based sports, predominantly running and cycling. The research procedures and use of data were approved by the University of Canterbury Ethics Committee.

Two Ipro2 and one Guardian Real-time CGM devices (Medtronic Minimed, Northridge, CA, USA) [21,22] were inserted into the abdomen of each athlete ~24 h prior to the first 'fasted exercise test'. The CGM device remained in each subject for 4–6 days. For all athletes, the Ipro CGM devices were both inserted in to the left side of the abdomen and the Guardian in the right side. These devices are referred to as sensor 1 (SG1), the lower left abdomen sensor, sensor 2 (SG2), the upper left abdomen sensor and real-time sensor, the right abdomen sensor (SGrealtime) (Fig. 1).

During the 6 days of CGM:

- Blood glucose was measured 4 times per day prior to meals and sleeping. These measurements were used to calibrate the device (calibration BG).
- All meals and snacks were recorded and carbohydrate intake calculated.
- Any additional exercise was also recorded and energy expenditure estimated.

Fasting exercise tests were carried out as shown in Fig. 2. Subjects were required not to exercise the day before the test. On the day of testing, the exercise protocol typically began at 8 a.m. and is defined:

- 0–60 min: Cycling on a stationary trainer (Cyclus 2, RBM elektronik-automation GmbH, Lepzig, Germany) after overnight fast. Cycling was carried out in the submaximal endurance HR zone <70% VO2max resulting in a resistance set to 2 W/kg for female and untrained cyclists or 2.5 W/kg, replicating the earlier stages of an endurance event where the athlete is likely to remain in the submaximal zone conserving energy and glucose stores.
- 30 min: Consume a 0.5 g/kg of body weight (30–45 g) glucose drink as per recommended practice of 30–60 g/h during endurance exercise lasting > 1.h [23].
- 60–Exhaustion (~90 min): Steadily increase effort until volitional exhaustion by increasing required power by 20 W every 5 min mimicking the later stages of an endurance event where the effort required is likely to increase until the finish.
- Exhaustion: Consume a 1 g/kg of body weight (60–90 g) glucose drink as per recommended practice to consume 1–1.5 g/kg of glucose for recovery of muscle glycogen post strenuous exercise lasting > 1 h [23].

Reference BG measurements:

- 0–60 min: every 10 min.

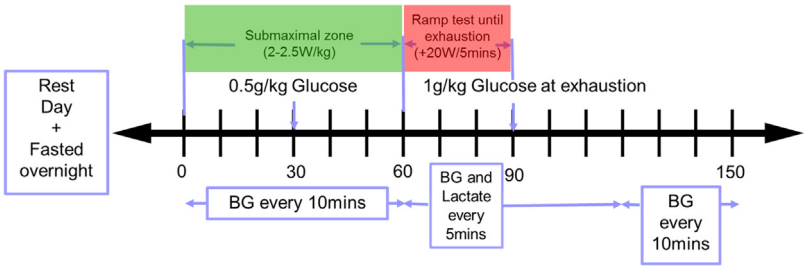

Fig. 2. Schematic of exercise trial protocol.