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REVIEW

Into the deep blue sea: A review of the safety of recreational diving in people with diabetes mellitus

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Abstract
People with diabetes, particularly those being insulin treated, have been for many years considered ineligible for diving, because of the high risk of adverse events. Blood glucose levels tend to decline during diving, probably because of changes in insulin requirements and resistance, due to increased physical activity and effects of hyperbaric environment on glucose tolerance. Strict adherence to safety protocols, in conjunction with optimal physical status, lack of diabetic complications (especially impaired awareness of hypoglycaemia) and satisfactory baseline glycaemic control, seem to minimise the risk of complications during diving. The integration of modern technology into diabetes management, providing potential for underwater continuous glucose monitoring, can be useful in optimising metabolic control before, during and after diving. Despite the significant progress been made on safety issues, there is still a need to implement the relevant recommendations into divers' everyday practice. Existing evidence is mainly derived from small studies and there is a wide heterogeneity in terms of study designs and explored outcomes, rendering the extraction of definitive conclusions challenging. The aim of this review is to present and critically evaluate available evidence, use of technology, and gaps in existing knowledge that deserve further evaluation by future studies.

Keywords: *Diving, diabetes, insulin, hypoglycaemia, continuous glucose monitoring*

Highlights

- Blood glucose levels tend to decline during diving, due to increased physical activity and effects of hyperbaric environment on glucose tolerance.
- Safety factors to consider when assessing people with diabetes who want to dive: presence of diabetes complications, diabetes duration, physical status, quality of glycaemic control, and degree of adherence to safety procedures.
- Continuous glucose monitoring system has been used during diving and demonstrated good credibility. No studies to date have evaluated flash glucose monitoring.
- Relevant studies have mostly included people with T1D or insulin-treated diabetes, whereas data on T2D or non-insulin treated diabetes are scarce.

Introduction

Recreational self-contained underwater breathing apparatus (SCUBA) diving is increasingly gaining popularity worldwide, as a sport and leisure activity. It is estimated that there are more than four million people actively involved in diving in the United States alone (Buzzacott, 2012).

Diving may be related to a series of health issues, with their severity ranging from mild or moderate (barotrauma of the ear, sea sickness) to potentially life-threatening [arterial gas embolism, decompression illness (DCI), and pulmonary barotraumas] (Sheeba & Sultan, 2014; Wohl, 2011). The underwater environment is characterised by an increased ambient pressure and low temperatures which pose a challenge to adaptive mechanisms of human physiology, particularly regarding the respiratory, cardiovascular and metabolic systems (Madsen, Hink, &

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Hyldegaard, 1994). For those reasons, safe diving requires optimal status of both mental and physical performance for divers to effectively adapt in a setting of continuously changing circumstances, requiring rapid decision making, especially in the case of emergencies (DeGorordo, Vallejo-Manzur, Chanin, & Varon, 2003).

Diabetes Mellitus (DM) is a common metabolic disorder, which can affect the quality of life and life expectancy. Specific diabetes-related conditions (hypoglycaemia, visual impairment due to diabetic retinopathy, diabetic autonomic neuropathy and coexisting cardiovascular disease) may be significant barriers for people with diabetes in undertaking demanding physical challenges (Colberg, 2017; Gawrecki et al., 2018). As a result, patients with DM, particularly those being insulin treated, have for many years been considered ineligible for diving, because of the high risk of adverse events. In light of new evidence, various scientific societies are nowadays defining a framework of rules and procedures to ensure safe diving for people with diabetes, even for those who are insulin treated.

The aim of this review is to evaluate available evidence about the safety of recreational diving in people with diabetes as well as gaps in existing knowledge that require further evaluation by future studies.

Defining the "divers with diabetes" population

In a voluntary survey among Divers Alert Network (DAN) members, divers with DM were asked to provide information with respect to their diving practices and history (Dear G de, Dovenbarger, Corson, Stolp, & Moon, 1994). Among 110 responders, 79 were using insulin to manage their diabetes. In a total of 48,663 dives, there was only one reported incident of DCI, suggesting a lower DCI prevalence between divers with DM, as compared to the general diving population (2.28/10.000 dives) (Bove, 1998; Taylor & Mitchell, 2001). Fifteen percent of responders had experienced hypoglycaemia at least once during diving, however, all episodes had been managed without any major issues.

Edge, St Leger Dowse, and Bryson (2005) aimed to evaluate the clinical and demographic features, outcomes and practices of divers with DM. Data were collected using questionnaires from 323 (269 males and 54 females) individuals, between 1991 and 2001 (8760 dives in total during this period). Among them, 254 (75%) had insulin-requiring diabetes (mean age 34 years), while only 69 (25%) had non-insulin managed diabetes (mean age 47 years). The sample consisted of 211 (65%) active divers, whereas 55 individuals (11%) had ceased diving and 11 more subjects (4%) reported to have stopped diving because of their refusal to undertake medical certification.

Only two diving-related fatalities were reported during the study period. The first death was attributed to acute myocardial infarction, while the cause of the second incident was not clarified. Both deceased patients had non-insulin-dependent DM. In the only incident of underwater hypoglycaemia, an insulin-treated patient was involved, who was safely treated with oral carbohydrates consumption when submerged.

The results of the aforementioned studies provided some direct indications that people with DM can dive safely. Still, their findings should be interpreted with caution, given that the studies conducted using self-reported questionnaires may be prone to bias, including a tendency for participants to under-report problems (Lippmann, Taylor, Stevenson, & Williams, 2018; Taylor & Mitchell, 2001; Van den Bergh & Walentynowicz, 2016). In addition, they can be criticised for focusing exclusively on a specific population of survivors. This issue has been previously described in the occupational epidemiology literature as the "healthy worker survivor effect", defining a continuing selection process during which those who remain employed tend to be healthier than those who leave employment (Arrighi & Hertz-Picciotto, 1994). The phenomenon may be attributed to the fact that workers (i.e. active divers in our case) usually exhibit lower overall death rates compared to the general population, because the severely ill and chronically disabled individuals are normally excluded from employment (i.e. recreational diving) (Shah, 2009).

A recent work by Ranapurwala, Kucera, and Denoble (2018) assessed the prevalence of common, chronic diseases among DAN members and this was subsequently compared to the respective prevalence of the general US population. Mean age of participants for the DAN and general populations were 50.2 and 46.4 years, and male representation in the sample was 73.5% and 48.7%, respectively. The general US population was found to have a significantly higher percentage of diabetes as compared to the DAN cohort (9.8% vs. 4% respectively, $p < .01$). The results of this study reflect a more effective utilisation of healthcare services for preventive purposes (routine check-up) among divers in comparison to the general population (Ranapurwala et al., 2018), possibly resulting from their need to optimise their health prior to undertaking diving.

However, an inverse interpretation of these outcomes could lead to the hypothesis that people with diabetes are discouraged from active involvement in diving, probably as a result of increased concern for adverse events during the activity. Another plausible explanation might be that only a minority of people with DM are capable of passing through the strict medical qualification process, being – in other words – healthy enough to qualify for diving. Additionally, medical approvals may be financially prohibitive for a proportion of people with diabetes, considering the fact that SCUBA diving is an expensive leisure activity, by itself.

Of interest, in a study (conducted in 2000 and published in 2002) (Taylor, O'Toole, & Ryan, 2002) where 346 experienced Australian divers were included, only one (0.2%) reported having diabetes (type not specified). This likely suggests an increasing trend in the number of divers with diabetes in the last years.

The impact of hyperbaric environment on glucose homeostasis

Until recently, little is known about the effects of hyperbaric environment on human glucose homeostasis. In studies where people with type 2 diabetes (T2D) were exposed to simulated hyperbaric conditions [hyperbaric oxygen therapy (HBOT)], improvements in both blood glucose (BG) concentrations and peripheral insulin sensitivity were observed (Chateau-Degat & Belley, 2012; Vera-Cruz, Guerreiro, Ribeiro, Guarino, & Conde, 2015; Wilkinson, Chapman, & Heilbronn, 2012). In particular, 20 HBOT sessions decreased fasting glucose by 21% and ameliorated glucose tolerance by 34%, suggesting that hyperbaric environment influences glucose metabolism, either by improving glucose uptake or glucose oxidation in the postprandial state (Vera-Cruz et al., 2015). In type 1 diabetes (T1D), a study demonstrated enhanced residual insulin secretion as a result of hyperbaric oxygenation (Dedov, Lukich, Bol'shakova, Gitel, & Dreval, 1987).

The exact mechanisms mediating these optimal effects remain obscure. In a model of diabetic mice, HBOT was shown to reduce autoimmune diabetes incidence, via increased resting T cells and reduced activation of dendritic cells, with preservation of beta-cell mass related to decreased apoptosis and increased proliferation (Faleo et al., 2012). HBOT has been shown to increase brain glucose utilisation (Contreras, Kadekaro, & Eisenberg, 1988), as well as central nervous system's sensitivity to responding in variations of BG concentrations, in a rat model (Torbati, 1985). Increased activity of carotid bodies (peripheral chemoreceptors that respond to hypoxia) has been demonstrated in T2D animal models (Ribeiro et al., 2013). Carotid bodies are a powerful glucose and insulin sensor and surgical ablation of its nerve inhibits the development of diet-induced metabolic diseases (Ribeiro et al., 2013). Deactivation of carotid body chemoreceptors reduces sympathetic hyperactivity, which contributes to the pathogenesis of T2D, possibly by negatively affecting insulin resistance (Esler et al., 2001). Therefore, functional inhibition of carotid bodies activity by hyperoxia may partially explain the HBOT optimal effects on glycemia (Vera-Cruz et al., 2015).

Amelioration of glucose and lipid oxidative metabolism in skeletal muscle has been postulated as an additional explanation (Fujita et al., 2012). Increased insulin receptor activity leading to improved insulin sensitivity, as a result of increased PPAR-γ (peroxisome proliferator-activated receptor-γ) regulation, has been reported (Zeng et al., 2012). Finally, as demonstrated in a diabetic rat model (Lee, Niu, Lin, & Niu, 2013), HBOT appears to ameliorate oxidative stress, a major pathophysiological pathway in the development of diabetic complications, by inhibiting the formation of toxic oxidising radicals, such as Nitric Oxide and 2,3-dihydroxybenzoic acid. In the same model, HBOT enhanced the release of the anti-inflammatory cytokine interleukin-10 in the hypothalamus, thus resulting in a decreased multiple organ dysfunction and an increased survival in diabetic rats with heatstroke.

It is still unclear whether the observed reductions in BG concentrations should be attributed to the hyperbaric environment *per se*, given that food deprivation during HBOT may be a confounder (Peleg et al., 2013). Furthermore, it is questionable to what extent the conditions during a simulated exposure to increased atmospheric pressure, actually simulate the real environmental conditions during scuba diving and whether the results of animal research can be directly applied to humans, considering the significant species differences in terms of physiology and glucose metabolism.

Glucose control during a simulated dive

Edge, Grieve, Gibbons, O'Sullivan, and Bryson (1997) designed an open, controlled, crossover study to evaluate the ability of people with T1D to control their BG levels during diving. Eight individuals with T1D and eight age- and sex-matched normoglycemic controls were included. Participants with T1D had no diabetes complications, glycated haemoglobin ($HbA1_C$) levels <75 mmol/mol (<9%) and had no history of hypoglycaemic episodes during the last year. Each diver performed one simulated dive to a depth of 375 kPa in a hyperbaric chamber and one control exercise at ambient pressure (randomised order). BG levels and other haematological parameters were estimated in both groups. There was no statistically significant difference in serum glucose measured in divers with T1D between the simulated dive (to 375 kPa) and serum glucose during the control exercise at the same time points. All participants with T1D experienced no symptoms and signs of hypoglycaemia. At the end of the trial, no participant with T1D had serum glucose concentrations less than 4 mmol/L (72 mg/dL).

Despite the small sample size investigated, this study provided preliminary evidence that high partial oxygen pressures do not have a major impact on serum glucose levels in subjects with T1D. They also showed that well-controlled and complication-free patients can dive under good safety conditions, reopening the discussion about the necessity of a blanket ban on scuba diving in persons with insulin-treated diabetes (Harrison, Lloyd-Smith, Khazei, Hunte, & Lepawsky, 2005; Ruder, 2006).

Into the deep, blue sea: real-world studies

A number of studies have examined the impact of diving on glucose levels of T1D patients in a real-world setting. Each study followed a different dive protocol; however, most protocols included pre- and post-dive oral carbohydrates consumption, as well as insulin-dosing adjustments when necessary, dependent on predefined BG values (Table I).

Dear G de et al. (2004), included 40 individuals with T1D [20 male, HbA1c 54–62 mmol/mol (7.1–7.8%), eight on continuous subcutaneous insulin infusion, 555 dives in total] and 43 controls (504 dives in total). Inclusion criteria for persons with T1D were absence of pregnancy, no history of diabetes-related hospitalisation during the past 12 months, lack of complications and HbA1c < 75 mmol/mol (<9%). Severe or symptomatic hypoglycaemic events were not reported during the study. Post-dive glucose concentrations below the 3.9 mmol/L (~70 mg/dL) cut-off were measured in 7% (37/555) of dives in the T1D group, as compared to 1% (6/504) ($p < .05$) in the control group.

Lerch, Lutrop, and Thurm (1996) investigated seven people with T1D (three males, 77 dives) and seven controls (three males, 77 dives). Prior to the study, patients underwent a full medical evaluation, including diabetes complication screening and subjects with poor fitness status, HbA1c > 75 mmol/mol (>9%), any complications or hypoglycaemia unawareness were excluded. Participants performed multiple dives over six consecutive days. There was a 15–20% reduction of insulin requirements during the above period. In contrast, daily carbohydrate intake was increased by approximately 50%, in order for divers to counter the risk of post-exercise hypoglycaemia.

In a different study (Pollock et al., 2006), seven adolescents (four females, mean age 16 years and three males, mean age 16.3 years) novice divers with T1D, with acceptable diabetes control ($HbA1_C$ 56 mmol/mol / 7.3 ± 1.1%), were recruited. Glucose levels were measured at 60-, 30- and 10-min pre-dive and immediately after the 42 dives performed. Pre-dive glucose was measured above 16.7 mmol/L (~300 mg/dL) in 22% of dives, whereas post-dive plasma glucose concentrations were found below 4.4 mmol/L (~80 mg/dL) in two dives by two different male divers. No symptoms or complications of hypoglycaemia were reported. Subjects received oral carbohydrate supplements before 76% of dives, due to BG levels below the safety threshold of 6.7 mmol/L (~120 mg/dL). Males were found to have greater pre–post-dive variation compared to females [−4.3 ± 4.4 mmol/L (−78 ± 79 mg/dL) vs. −0.5 ± 4.3 mmol/L (−9 ± 77 mg/dL), respectively].

Lormeau et al. (2005) studied 15 participants with T1D (mean age 40 years, 12 males, mean duration of T1D of 9 years). Suitability for diving was judged according to good metabolic control [mean $HbA1_C$ 55.2 mmol/mol/7.2% (range: 5.8–8.3%)] and absence of diabetic complications. BG levels before immersion were measured between 4.89 and 20.07 mmol/L (~89 and 365 mg/dL) and immediately post-dive between 2.86 and 15.12 mmol/L (~52 and 275 mg/dL). A mean fall in BG equal to 2.2 mmol/L (~40 mg/dL) was detected during dives.

A mean decrease in daily insulin doses by 19.3% was recorded on the last day of the diving course (including a mean reduction by 26% of the boluses and 12.3% of the basal insulin doses). No case of hypoglycaemia was observed underwater. Half of the dives demanded pre-dive carbohydrates consumption. 44 dives took place without pre-dive carbohydrate intake [due to BG levels within the safety range of 8.80–13.75 mmol/L (~160–250 mg/dL)]. Regarding these dives, BG declined during 39 dives [by more than 2.75 mmol/L (~50 mg/dL) in 21 occasions and more than 5.5 mmol/L (~100 mg/dL) in six occasions] and increased during the five other dives.

95 out of 120 planned dives were performed; two dives were cancelled due to low BG levels, one due to ketonemia and others due to factors not related to diabetes. In one participant, a continuous glucose monitoring (CGM) system was applied, which demonstrated no remarkable glucose levels variation during immersion; yet a decrease was noted within the eight hours post-dive.

In a similar design setting (Uguccioni, Pollock, Dovenbarger, Dear G de, & Moon, 1998), where

Table I. Main characteristics and findings of key studies that examined the impact of scuba diving on people with type 1 diabetes

Study (1st author, publication year)	Participants	Inclusion criteria	Study protocol	Key findings
Lerch et al. (1996)	7 individuals with T1D (77 dives)/7 controls (77 dives)	$HbA1_C$ 36.6–74.9 mmol/mol No hypo unawareness No complications No severe hypo during the last 12 mo Good physical status	11 dives per participant over 6 d Max: 30, 45 mins BG check: 60, 30- and 0-min pre-dive Dive if BG > 8.9 mmol/L Carbs if BG < 8.9 mmol/L or falling Insulin dose adjustment daily if necessary	15–20% reduction in insulin requirements No hypoglycemic events Hct rise in people with T1D which was corrected with adequate hydration
Uguccioni et al. (1998)	16 individuals with T1D	n.a.	BG check 60, 30- and 10-min pre-dive Dive if BG > 4.4 mmol/L (stable or rising)	42% of participants received carbs pre-dive No hypoglycemic events
Dear G de et al. (2004)	40 individuals with T1D (8 on CSII, 555 dives)/43 controls (504 dives)	$HbA1_C$ < 74.9 mmol/mol No complications No hospitalisation during the last 12 mo No pregnancy	Max: 20 ± 6 m, 41 ± 10 mins BG check: 60, 30- and 0-min pre-dive Dive if BG > 4.4 mmol/L (stable or rising)	42% of participants received carbs pre-dive BG < 3.9 mmol/L post-dive in 7% of dives 11 incidents of symptomatic hypo (all post-dive) Mean pre-dive BG: 10.8 ± 3.6 male, 12.4 ± 3.9 mmol/L female Mean post-dive BG: 7.8 ± 3.4 mmol/L male, 10 ± 4.2 mmol/L female
Lormeau et al. (2005)	15 individuals with T1D (1 on CSII and CGM, 95 dives)	Well-controlled (mean $HbA1_C$ 55.2 mmol/mol) No complications Short diabetes duration (mean 9 y)	Max: 20, 40 mins BG check: 60, 30- and 0-min pre-dive Dive if BG 8.8-13.8 mmol/L If BG 6.6-8.8 mmol/L take 15 g carbs and dive If BG < 6.6 mmol/L take 30 g carbs and recheck at 15 min, if > 8.8 mmol/L dive BG > 3.8 mmol/L check for ketones, if absent dive	95 out of 120 planned dives were performed 2 dives cancelled due to hypo, 1 due to ketones, others due to irrelevant to diabetes issues No hypos during dive Half of dives required carbs before diving
Pollock et al. (2006)	7 individuals with T1D (42 dives)	$HbA1_C$ < 74.9 mmol/mol No complications No hospitalisation during the last 12 mo	Max: 17, 44 mins BG check: 60, 30- and 0-min pre-dive Dive if BG > 6.7 mmol/L and rising If < 6.7 mmol/L or falling take carbs and recheck at 15 min	76% of dives required carbs before diving Average BG decrease during dive was 4.3 mmol/L 2 dives with post-dive BG < 4 mmol/L No symptomatic hypos
Adolfsson et al. (2008, 2009)	12 individuals with T1D (58 dives, 3 on CSII, 12 on CGM)/12 controls (59 dives)	No macrovascular complications or proliferative retinopathy No hypo unawareness	Max: 22, 52 mins BG check: 90, 60- and 10-min pre-dive Carbs before diving	Good CGM accuracy and survival (85% over 48 h) BG difference pre-to post-dive from 1.4 to 3.3 mmol/L in people with T1D 6 episodes of mild hypo post-dive

(*Continued*)

Table I. Continued.

Study (1st author, publication year)	Participants	Inclusion criteria	Study protocol	Key findings
Bonomo et al. (2009)	12 individuals with T1D (90 dives, 1 on CSII, 12 on CGM)	$HbA1_C$ < 69.4 mmol/mol No complications other than background retinopathy No hospitalisation during the last 12 months No hypo unawareness	Max: 21 ± 3.7 m, 46 ± 5 mins BG check 60, 30- and 10-min pre-dive Insulin if BG > 16.7 mmol/L 60 min pre-dive or >13.9 mmol/L 30 min pre-dive BG < 6.6 mmol/L or declining 15–30 g carbs Carbs underwater in case of hypo	4 incidents of mild symptomatic hypos, all due to protocol deviation Poor CGM survival (56%) and technical issues observed Mean pre-dive BG: 11.1 ± 3.4 mmol/L Mean post-dive BG: 8.8 ± 4.4 mmol/L
Pieri et al. (2016)	2 individuals with T1D (one male and one female)	No history of disease other than T1D, no diabetes complications	Suspend dive if BG > 16.7 mmol/L and rising or > 13.9 mmol/L and ketonemia Suspend dive if BG > 6.7 mmol/L Dive if BG 8.3–13.9 mmol/L and stable	Both divers showed gradual decrease in BG during diving (statistically significant only for male, median 10.2 pre-dive vs. 7.8 mmol/L post-dive) Low BG values (around ±3.9 mmol/L) during diving without hypo symptoms were occasionally reported No sensor failure up to 40 m Good credibility of obtained CGM measurements during diving

Note: Studies are presented in chronological order, from oldest to most recent.

Abbreviations: m: metres; T1D: Type 1 Diabetes; $HbA1_C$: Hemoglobin A1c; CGM: Continuous Glucose Monitoring; CSII: Continuous Subcutaneous Insulin Infusion; BG: Blood glucose; Hypo: hypoglycemia; mo: months; d: day(s); min: minutes; max: maximum; carbs: carbohydrates; Hct: hematocrit; n.a.: not applicable; y: year(s); g: gram(s); h: hour(s); Ref: reference.

16 T1D individuals were included (131 total dives over one-week period), safety profile was reconfirmed, given that no hypoglycaemic events were recorded, either during or post-dive.

Continuous glucose monitoring systems: a valuable diving partner

The underwater performance and accuracy of CGM systems (CGMS) are still under investigation. A total of 24 adults (12 with T1D and 12 controls) performed five recreational scuba dives on three consecutive days (Adolfsson, Ornhagen, & Jendle, 2008). CGMS was used by all participants. The authors aimed to assess the CGMS and plasma glucose monitoring using a monitoring regimen to identify individuals with T1D at risk of developing hypoglycaemia during diving. The number of hypoglycaemic episodes, within 10 min prediving or immediately postdiving, were significantly and positively correlated with the duration of diabetes ($p = .01$) and the percentage of SMBG values below the target of 4 mmol/L (~72 mg/dL) ($p = .02$). Moreover, the number of hypoglycaemic episodes was positively related to the total duration below the low limit (<3.9 mmol/L/<70 mg/dL), as measured by the CGM system ($p = .006$). No symptoms of hypoglycaemia were present during or immediately post-dive. Pre- and post-dive BG values differences in the group with T1D ranged from 1.4 mmol/L (~25 mg/dL) to 3.3 mmol/L (~59 mg/dL).

Adolfsson, Ornhagen, and Jendle (2009) aimed to assess the accuracy and reliability of CGMS during scuba diving in 12 individuals with T1D and 12 controls with no history of diabetes. They demonstrated a robust CGM recording and good durability of sensors under realistic diving conditions (85% of the sensors survived over 48 h). Hypoglycaemia (defined as 3.9 mmol/L/< 70 mg/dL) pre- and post-dive was detected by CGM with a positive predictive value of 0.39, negative predictive value of 0.98, sensitivity of 0.64, and specificity of 0.94.

A different study (Bonomo et al., 2009), including 12 individuals with T1D (90 dives in total), showed poorer sensor durability (56%). However, it should be noted that due to technical reasons reported in the study (e.g. accidental cable damage, defects in sensors or cables), CGM recordings were available for only 27 of 48 monitored dives by nine patients. Mean glucose measurements at 60, 30 and 10 min before diving was 11.4 mmol/L (~205.8 ± 69.6 mg/dL), 11.1 mmol/L (~200.0 ± 66.4 mg/dL) and 11.1 mmol/L (~200.5 ± 61.0 mg/dL), respectively. Mean post-dive glucose was 8.8 mmol/L (~158.9 ± 80.8 mg/dL). CGM recordings pointed towards lower glucose levels during diving, with the maximum reduction from baseline concentrations being −19.9%. Only one dive was interrupted due to hypoglycaemic symptoms. In 56 out of 90 dives (62.2%) supplementary carbohydrates or insulin were required, as per study protocol.

Pieri, Cialoni, and Marroni (2016) estimated the mean of relative difference (MRD) between CGM and capillary BG in two experienced divers with diabetes (a male and a female), during a one-week diving course. Furthermore, measurement accuracy was evaluated according to International Organisation for Standardisation (ISO) guideline 15,197. Their findings showed that two out of 26 (7.7%) MRD values marginally exceeded the ISO permitted difference of 5%, suggesting good credibility of obtained glucose CGM measurements underwater. No sensor failure up to 40 m depth was documented. Both divers showed a gradual decrease in BG levels during diving, but this was statistically significant only for the male [median pre-dive BG 10.2 mmol/L (~184 mg/dL) vs. 7.8 mmol/L (~140 mg/dL) post-dive, $p < .001$]. Low BG values (around ± 3.9 mmol/L/70 mg/dL) during diving, still without symptoms of hypoglycaemia, were occasionally reported.

To date, there are no studies to assess the accuracy and use of flash glucose monitoring during diving. Table I summarises the main characteristics and findings of key studies that examined the impact of recreational diving on people with T1D.

An interpretation of research findings

The findings of these studies, as already presented in detail, indicate that well-controlled, complication-free divers with T1D can dive safely, provided a closely monitored and strictly followed diving protocol is implemented.

In general, key determinants of safety seem to be presence of macro- and microvascular complications, diabetes duration, physical status, quality of glycaemic control, but mainly degree of adherence to safety procedures. It should be noted that prospective, cohort studies in open water that have included people with T2D are lacking, and the majority of data in this type of diabetes are coming from retrospective, questionnaire-based studies.

Defining a cut-off BG value below which diving should not be commenced plays an important role in preventing hypoglycaemia. A closer look at the results of relevant studies reveals that a pre-dive threshold of 4.4 mmol/L (~79 mg/dL) was related to a notable incidence (39 occurrences out of 598 total dives) of post-dive measurements below 3.9 mmol/L (~70 mg/dL); thus, without symptomatic incidents of hypoglycaemia (Harrison et al., 2005; Lerch et al., 1996). In contrast, these events were practically absent in the studies having set the pre-dive threshold at 6.7 mmol/L (~120 mg/dL) [Australian Diabetes Society (ADS), 2016]. In general, post-dive BG concentrations were found to be reduced between 2.2 mmol/L (~40 mg/dL) and 4.3 mmol/L (~78 mg/dL) compared to pre-dive values, though a significant inter-individual and inter-study variability was evident. Similar to other physical activities under extreme conditions (e.g. hiking and trekking at altitude), the use of CGM technology may prove exceptionally helpful, allowing an effective and flexible self-glucose management in a setting of constantly changing circumstances, that may have an unpredictable impact on glycaemic control (Koufakis, Karras, Mustafa, Zebekakis, & Kotsa, 2018). It is worth pointing out however, that CGM systems used in everyday practice at present, are not certified for submerging more than a few metres (ADS, 2016). Telemetric applications that measure BG through a subcutaneous sensor and transmit wirelessly the results in real time to the surface are currently under development (Egi et al., 2018).

A summary of recommendations

Different scientific societies have produced recommendations or guidelines to promote uncomplicated diving in people with diabetes. Tables II and III provide an analytical and comparative overview of guidelines and recommendations issued by the following societies: South Pacific Underwater Medicine Society (SPUMS) (2010), Swedish recommendations (Jendle, Adolfsson, & Ornhagen, 2012; Jendle & Adolfsson, 2019), United Kingdom Diving Medical Committee (2015), Undersea and Hyperbaric Medical Society/Divers Alert Network (UHMS/DAN consensus guidelines) (Pollock, Uguccioni, & Dear G de, 2005) and Australian Diabetes Society (ADS, 2016). Despite the dissimilarities between different recommendations, they all provide advice on four main variables:

(1) Suitability for diving. The recommendations focus on patients' age (>18 years old), satisfactory metabolic control (no commonly accepted criterion for "satisfactory" exists), lack of complications (background retinopathy is excluded), and adequate hypoglycaemia awareness.
(2) Scope of diving. There is a consensus in suggesting a maximum of 2 dives per day, a depth not exceeding 30 m and a duration of dive shorter than 60 min. The requirement for a diving partner being familiar with diabetes, but non-being diabetic himself/herself, is emphasised (Table II).
(3) Glucose management pre- and post-dive. The recommendations suggest BG checks at 60, 30 min and immediately pre-dive and BG thresholds for carbohydrate ingestion, dive postponement and cancel are defined. They also provide adequate counselling for BG check during specific time points post-dive.
(4) Management of hypoglycaemia during diving. The guidelines suggest detailed procedures for informing diving partners and for both oral and parenteral glucose administration, either underwater or after surfacing. Hypoglycaemia may mimic the clinical presentation of decompression illness, making the differentiation and management of the two clinical entities problematic by inexperienced or non-specialised personnel (Table III).

A careful appraisal of existing guidance reveals significant heterogeneity in various areas of practice (for example regarding safety BG thresholds for diving commencement, postpone or cancel); this should be attributed to the lack of strong evidence with "hard" end-points and relying on personal experience incorporated into recommendations (Johnson, 2016a, 2016b).

Figure 1 provides a schematic overview of the recommendations for safe diving in people with DM.

Implementation of guidelines into real life

A recent study (Lippmann, McD Taylor, Stevenson, Williams, & Mitchell, 2017) aimed to evaluate the medical management of the divers' health-related conditions, as well as the modifications used in their diving practices in order to diminish potential risks. The survey included 833 individuals, members of Divers Alert Network Asia-Pacific (DAN AP), diving with diabetes, cardiovascular or respiratory health problems. 25 participants (mean age 54 years, 19 males) reported to have diabetes (type not specified), with four of them being treated with insulin. 16 of them, including three out of four receiving insulin, measured their BG before diving. The frequency of pre-dive measurement ranged from one to three times, and the timing from 15 min to three hours before diving. The mean minimum BG being acceptable before diving according to responders, was 6.1 mmol/L (~110 mg/dL), ranging from 3.5 mmol/L (~63 mg/dL) to 10 mmol/L (~180 mg/dL). Five participants reported to adjust their medication dosage before diving; three used to omit their oral agents and two insulin-dependent divers reduced their insulin dose. Four

Table II. An overview of various guidelines and recommendations regarding suitability for diving and scope of diving in people with diabetes

Country/region	Australia	South Pacific	Sweden	United Kingdom	USA
Scientific society/ source	ADS	SPUMS	*Örebro* University	UKDMC	UHMS/DAN
Year	2016	2011	2012 & 2019 (update)	2005	2005
Suitability for diving					
Age	≥18	≥18	n.r.	n.r.	≥18 (≥16 in case a specialised training course completed)
Diabetes control	HbA1c ≤ 74.9 mmol/mol	HbA1c ≤ 74.9 mmol/mol	HbA1c < 63 mmol/mol	"Satisfactory control" according to treating physician	HbA1c ≤ 74.9 mmol/mol
Changes in diabetes medication	>1 y since insulin initiation, >3 m since significant changes in regimen	>1 y since insulin initiation (>6 m for T2D), >3 m since significant changes in regimen	n.r.	n.r.	>1 y since insulin initiation (>6 m for T2D), >3 m since significant changes in regimen
Self-management	Accurate use of glucose monitoring device, good knowledge of insulin, carb and exercise interaction	Good knowledge of insulin, carb adjustment	Good knowledge of insulin, carb adjustment. 4–6 BG measurements / day during the week before dive. CGM use is recommended	n.r.	Good knowledge of insulin, carb adjustment
Hypoglycemia history	No severe hypo during the last 12 m	No severe hypo during the last 12 m	No severe hypo during the last 12 m	No severe hypo during the last 12 m	No severe hypo during the last 12 m
Hypoglycemia awareness	No hypo unawareness	No hypo unawareness	No hypo unawareness	n.r.	No hypo unawareness
History of hospitalisation	No history of hospitalisation or ED attendance for hypo during the last 12 m	n.r.	No recurrent episodes of hospitalisation	No diabetes-related hospitalisation during the last 12 m	n.r.
Complications	No macrovascular and microvascular (apart from background retinopathy) complications	No significant complications	n.r.	n.r.	No significant complications
Absence of microalbuminuria	Yes	Yes	Yes	Yes	Yes
Absence of neuropathy	Yes	Yes	Yes	Yes	Yes
Absence of retinopathy greater than background retinopathy	Yes	Yes	Yes	Yes	Yes
Screening for heart disease	> 40 yo cardiac stress testing	> 40 yo cardiac stress testing	n.r.	>50 yo cardiac stress testing	>40 yo cardiac stress testing and follow-up as per local recommendations

(*Continued*)

Table II. Continued.

Country/region	Australia	South Pacific	Sweden	United Kingdom	USA
Medical assessment	Diabetes doctor (GP or endocrinologist) and doctor with post-graduate diving examiner's qualification	Diabetes doctor (GP or endocrinologist) and doctor with post-graduate diving examiner's qualification	Specialist in diabetology and physician authorised in diving medicine. Evaluation of CGM readings is recommended	Physician should certify that "diver is mentally and physically fit to dive"	Diabetes doctor (GP or endocrinologist) and doctor with post-graduate diving examiner's qualification
Frequency of medical check-up	Annual	Annual	Annual	Annual	Annual
Scope of diving					
No of dives / surface intervals	> 1 h surface interval Longer surface intervals after 2nd dive of the day	≤ 2 dives / day > 2 h surface interval	n.r.	≤2 dives/day ≤3 consecutive days	n.r.
Duration of dive	≤ 1 h	≤ 1 h	n.r.	n.r.	≤1 h
Depth	n.r.	≤ 30 m	≤ 25 m	≤ 30 m (until diver is highly experienced regarding the effect of diving on diabetes control)	≤ 30 m
Dives requiring decompression stops	Not recommended	Not recommended	n.r.	n.r.	Not recommended
Dives in overhead environments (e.g. caverns, wrecks)	Not recommended	Not recommended	n.r.	n.r.	Not recommended
Diving partner	Partner should be informed of condition and aware of appropriate response in case of hypoglycemia. Partner should not have diabetes	Partner should be informed of condition and aware of appropriate response in case of hypoglycemia. Partner should not have diabetes	Partner should not have diabetes	Partner should be regular and aware of appropriate response in case of hypoglycemia or trained nurse, paramedic, etc. Partner should not have diabetes	Partner should be informed of condition and aware of appropriate response in case of hypoglycemia. Partner should not have diabetes

Abbreviations: ADS; Australian Diabetes Society; SPUMS: South Pacific Underwater Medicine Society; UKDMC: United Kingdom Diving Medical Committee; UHMS: Undersea and Hyperbaric Medical Society; DAN: Divers Alert Network; n.r.: no specific recommendation; y: year(s); m: month(s); T2D: Type 2 Diabetes; carb: carbohydrates; BG: blood glucose; hypo: hypoglycemia; yo: year-old; ED: Emergency Department; GP: General practitioner; h: hour(s); m: metre(s); CGM: Continuous Glucose Monitoring.

Table III. An overview of various guidelines and recommendations regarding blood glucose management on the day of diving and management of hypoglycemia during diving

Country/region	Australia	South Pacific	Sweden	United Kingdom	USA
Scientific society/ source	ADS	SPUMS	*Örebro* University	UKDMC	UHMS/DAN
Year	2016	2010	2012 & 2019 (update)	2005	2005
BG management on the day of diving					
General recommendations on lead-up to dive day	No diving if unwell or BG follows an unstable pattern. Adequate hydration, avoid alcohol for 24 h before dive. For T2D on SUs, omit SU on the day of dive	No diving if unwell, excessively anxious or BG follows an unstable pattern. Adequate hydration	CGM use is recommended. If SMBG used, monitor BG 4–8 times daily. If treated with CSII adjust the basal rate (−50%) 90–120 min before dive to prevent hypo. The pump should be removed shortly before diving	Fit and mentally prepared. Adequate hydration. Aim BG levels at the higher normal range	No diving if unwell, excessively anxious or BG follows an unstable pattern. Adequate hydration
Pre-dive					
BG testing	Test BG 60 min, 30 min and immediately pre-dive to ensure no downward trend	Test BG 60 min, 30 min and immediately pre-dive to ensure no downward trend	Test BG 60 min, 30 min and immediately pre-dive to ensure no downward trend	n.r.	Test BG 60 min, 30 min and immediately pre-dive to ensure no downward trend
BG threshold to allow diving	8.3–16.7 mmol/L and stable or rising immediately pre-dive	9 mmol/L and stable or rising immediately pre-dive	7–12 mmol/L and stable	n.r.	8.3 mmol/L and stable
BG and carb management protocol	6.6–8.3 mmol/L: oral 15 g carb <6.6 mmol/L: oral 30 g carb	n.r.	Meal 1.5–2 h before diving. Additional 15–30 g carb/70 kg BW before diving. If BG < 5 mmol/L or falling, additional 10–15 g carb prior to dive	n.r.	n.r.
Postpone dive if	>16.7 mmol/L and check ketones	BG < 9 mmol/L or falls between any two checks	n.r.	n.r.	BG < 8.3 mmol/L or falls between any two checks
Cancel dive if	Ketones > 1 mmol/L	> 16 mmol/L	n.r.	n.r.	n.r.
Post-dive					
BG management at end of dive	Check BG immediately post-dive and manage appropriately	Check BG immediately post-dive	Check BG immediately post-dive	Check BG on arrival on boat. Any hypo symptoms should be immediately reported	Check BG immediately post-dive
BG management for the rest of the day	n.r.	Frequent BG checks for 12–15 h after dive	n.r.	n.r.	Frequent BG checks for 12–15 h after dive
Documentation	Log all dives and BG management for future use	Log all dives and BG management for future use	Keep logbook of dives and BG management	n.r.	Log all dives and BG management for future use
Management of hypoglycemia during diving					
Training and preparation	n.r.	n.r.	Practice in ingesting gels underwater is recommended	n.r.	n.r.
Signal in case of hypoglycemia	L-shape made by thumb and index finger	L-shape made by thumb and index finger	L-shape made by thumb and index finger	n.r.	L-shape made by thumb and index finger

(*Continued*)

Table III. Continued.

Country/region	Australia	South Pacific	Sweden	United Kingdom	USA
Oral glucose	If trained, glucose paste can be consumed underwater, but the priority should be to ascend to surface	Should be carried in readily accessible and ingestible form at surface and during all dives	Carb gel or glucose/fructose solution should be carried by both diver and partner	Oral glucose tablets or tube of glucose paste should be kept in dive kit. A member of the diving group should be familiar to their use (not required for T2D on diet control or metformin)	Should be carried in readily accessible and ingestible form at surface and during all dives
Protocol upon symptoms suggestive of hypoglycemia underwater	The diver should ascend to the surface immediately, establish positive buoyancy, ingest glucose and leave the water. The informed dive partner should assist with this process. If trained, glucose paste can be consumed underwater, but the priority should be to ascend to surface	The diver should surface, establish positive buoyancy, ingest glucose and leave the water. Assistance should be available via informed partner	Signal partner then go to either decompression level or start pair ascent to surface. Carb gel should be ingested whilst underwater prior to ascent. If hypo confirmed take 20 g carbs if fully awake or 1 g glucagon IM if unconscious	n.r.	The diver should surface, establish positive buoyancy, ingest glucose and leave the water. Assistance should be available via informed partner
Parenteral glucose/ glucagon	n.r.	Should be available at surface (strongly recommended)	Should be available at surface	Should be carried in dive kit. A member of the diving group should be familiar to use	Should be available at surface (strongly recommended). Person at surface should be familiar to use

Abbreviations: ADS; Australian Diabetes Society; SPUMS: South Pacific Underwater Medicine Society; UKDMC: United Kingdom Diving Medical Committee; UHMS: Undersea and Hyperbaric Medical Society; DAN: Divers Alert Network; n.r.: no specific recommendation; BG: blood glucose; h: hour(s); min: minute(s); carb: carbohydrates; g: grams; BW: body weight; T2D: type 2 diabetes; SU: sulfonylurea; hypo: hypoglycemia; CGM: Continuous glucose monitoring; SMBG: Self-monitoring of blood glucose; CSII: Continuous subcutaneous insulin infusion.

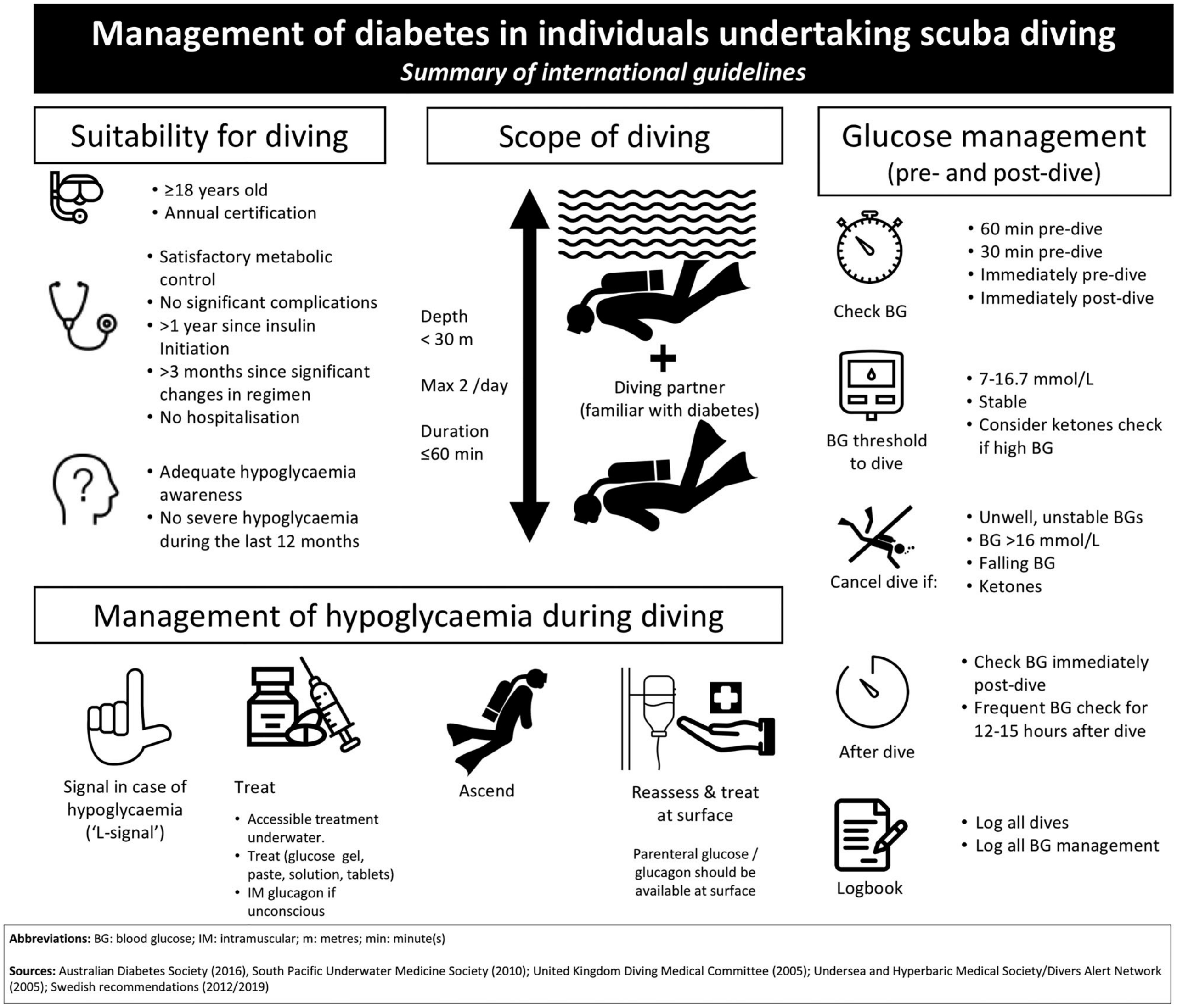

Figure 1. A schematic overview of the recommendations for safe diving in people with diabetes mellitus.

respondents reported increasing carbohydrate consumption before diving.

Only six subjects (including two insulin-treated divers) reported checking BG post-dive; however, none practiced in strict accordance to SPUMS or UHMS guidelines. 16 (64%) individuals answered that they were aware of relevant guidelines and recommendations and 10 (40%) of these responded that these recommendations have influenced their diving practice, particularly with respect to BG monitoring, increased diabetes vigilance, closer medical follow-up and careful choice of diver partner. 12 (48%) divers reported having consultations with a diving doctor, but only nine (36%) of them had frequent assessments, at intervals of 6–12 months. Participants considered as significant risks in diving with diabetes the following: loss of consciousness either underwater or at surface, confusion and DCI.

Discussion

Existing evidence in the field is limited, characterised by a small number of studies and patients involved. Moreover, there is a wide heterogeneity in terms of study designs and explored outcomes, rendering the extraction of definite conclusions challenging.

According to the outcomes of relevant studies, BG levels tend to decline during diving, probably as a result of changes in insulin requirements and resistance, due to increased physical activity and effects of hyperbaric environment on glucose tolerance. Strict adherence to safety protocols, in conjunction with optimal physical status, absence of diabetic complications (especially hypoglycaemia unawareness) and satisfactory baseline glycaemic control, seem to minimise the risk for adverse events during diving. However, healthcare providers should explain to the divers with T1D that neglecting the safety precautions may result in harm or even death.

Data on the safety of occupational diving in people with diabetes are even more limited. Older regulations approached the issue in a very strict way, excluding the vast majority of individuals with DM from becoming professional divers, because of the possibility of later disqualification due to complications [European Diving Technology Committee (EDTC), 2003]. Under specific conditions, the Committee suggested that people with DM might be trained under medical supervision and become divers exclusively for limited diving operations. In the case of diabetes diagnosis in a professional diver, it was recommended that a decision for disqualification should not be spontaneous but decided on the basis of the nature of the work and the quality of diver's glycaemic control.

Recent regulations, however, approach the issue in a more flexible way, emphasising the need for judging fitness to dive on an individual basis [Health and Safety Executive (HSE), 2015]. A requirement for professional divers' regular, detailed assessment by physicians with special interest in diabetes and diving medicine is underlined by various regulatory authorities (EDTC, 2019; HSE, 2015).

Factors to be considered are the nature of the work and diving environment, the degree of control achieved, as well as safety of the diver and partners on the diving project. In general, people with diabetes are unlikely to be certified for saturation diving (HSE, 2015). Also, it is clear that poor metabolic control, hypoglycaemic episodes or development of diabetes complications should lead to disqualification of commercial divers, due to increased safety concerns. It is also worth noting that regulations for judging fitness to dive for SCUBA diving instructors with DM fall into a grey area between recreational and occupational diving.

Conclusions

Despite the limitations of available data, it can be said that people with T1D, are capable of undertaking underwater physical challenges with safety. Studies including people with T2D are scarce to non-existing and therefore, conclusions in this group of patients cannot be drawn.

There are important gaps in our knowledge despite the significant progress been made in understanding the impact of diving on glycaemic homeostasis. Several aspects of the adaptation processes of the human body happening underwater have not yet been sufficiently elucidated. Conduction of relevant studies is difficult and costly, not being facilitated by the underwater environment which is hostile as a research setting.

Future studies in the field should focus on understanding the mechanisms behind the physiological adaptations of human glucose homeostasis under hyperbaric conditions. Development of CGM systems that can provide accurate estimation of BG concentrations underwater, could significantly contribute to this direction, thus, further promoting our understanding of the complex, still intriguing, relationship between diving and diabetes.

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