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REVIEW

Exploring Technology's Influence on Health Behaviours and Well-being in Type 1 Diabetes: a Review

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Abstract

Purpose of Review Maintaining positive health behaviours promotes better health outcomes for people with type 1 diabetes (T1D). However, implementing these behaviours may also lead to additional management burdens and challenges. Diabetes technologies, including continuous glucose monitoring systems, automated insulin delivery systems, and digital platforms, are being rapidly developed and widely used to reduce these burdens. Our aim was to review recent evidence to explore the influence of these technologies on health behaviours and well-being among adults with T1D and discuss future directions.

Recent Findings Current evidence, albeit limited, suggests that technologies applied in diabetes self-management education and support (DSME/S), nutrition, physical activity (PA), and psychosocial care areas improved glucose outcomes. They may also increase flexibility in insulin adjustment and eating behaviours, reduce carb counting burden, increase confidence in PA, and reduce mental burden.

Summary Technologies have the potential to promote health behaviours changes and well-being for people with T1D. More confirmative studies on their effectiveness and safety are needed to ensure optimal integration in standard care practices.

Keywords Diabetes technology · Continuous glucose monitoring · Automated insulin delivery · Health behaviour · Well-being · Type 1 diabetes

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Introduction

More than 8.4 million individuals live with type 1 diabetes (T1D) globally, and the prevalence is projected to double by 2040 [1]. T1D is an autoimmune disease characterized by the destruction of pancreatic beta cells, leading to insulin deficiency, hyperglycaemia, and subsequent microvascular and macrovascular complications [2]. The aim of T1D management is to effectively deliver exogenous insulin to maintain normoglycemia in order to prevent diabetes-related complications while minimizing its psychosocial burden [3]. A recent guideline points out that to achieve these aims, cultivating positive health behaviours and promoting psychological well-being are fundamental [4]. Specifically, five areas warrant attention: diabetes self-management education and support (DSME/S), medical nutrition therapy, routine physical activity (PA), tobacco cessation counselling, and psychosocial care [4]. Integrating these strategies into daily T1D management, however, could become a substantial burden to many people living with T1D (PwT1D).

To reduce this burden, diabetes technologies are being rapidly developed and have been widely adopted across the globe [5–10]. These technologies can assist PwT1D with their self-management, including lifestyle modifications, glucose monitoring, and therapy adjustments [4]. Wearable technologies are revolutionizing diabetes care, and one example is the continuous glucose monitoring (CGM) systems which measure interstitial glucose and provide continuous information on glucose profile and dysglycaemia alerts [11]. Combination of continuous subcutaneous insulin infusion (CSII) and CGM forms sensor-augmented pump (SAP) which allows predictive low-glucose suspend feature, further reducing risks of hypoglycemia [12]. Automated insulin delivery (AID) systems, combining CGM, CSII, and a control algorithm, can automatically modulate insulin infusion to address both hypoglycaemia and hyperglycemia [13]. In this review, AID refers to single-hormone hybrid closed-loop systems, unless specified. Beyond wearable technologies, digital platforms including websites, software, and mobile applications (app) have been developed to facilitate diabetes education and support, insulin dose estimations, carb counting (CC), etc.

We reviewed recent literature (published within the past 5 years until April 2023) to explore the influence of these advanced technologies on health behaviours and psychological well-being among non-pregnant adults with T1D, and discuss future directions. We also searched the International Clinical Trials Registry for ongoing trials. A complete methodology of search strategies can be found in supplementary material 1.

Diabetes Self-Management Education and Support

The aim of DSME/S is to provide evidenced-based information and strategies to support and educate PwT1D in various aspects of diabetes management, empowering PwT1D to make confident decisions, engage in self-care behaviours, and sustain self-management [14]. Examples of technology used in DSME/S interventions include short message services, mobile and/or web apps, and social media platforms. Compared to in-person approaches, the strength of digital DSME/S interventions include increased accessibility for a larger proportion of PwT1D and availability of information at any time [15], no travel time and decreased sense of stigmatization [16]. In this section, only technologies targeting multiple positive health behaviours are considered; otherwise, they are discussed in relevant sections below.

Influence of digital DSME/S use on health outcomes varies among interventions, due to the format of delivery, type of features, program length, and population. For instance, *TangTangQuan* is a free mobile DSME/S app for PwT1D in China, composed of four components: personal diabetes diary, dietary panel, diabetes education modules, and a peer support community. A longitudinal cohort study including 693 adults with T1D suggested that relative to baseline, glycaemic improvements were observed after 12 months of app use (HbA1c: $6.9 \pm 1.3\%$ vs. $6.6 \pm 1.3\%$, $p < 0.001$; fasting blood glucose: 7.57 ± 2.28 mmol/L vs. 7.22 ± 2.40 mmol/L, $p = 0.006$; postprandial blood glucose: 8.35 ± 2.25 mmol/L vs. 8.06 ± 2.47 mmol/L, $p = 0.021$), especially among those more engaged in peer support [17••]. Other examples of digital DSME/S interventions being investigated are the Support platform [18]. Support is a self-guided free online web app, including learning modules, discussion forums, and virtual reward points, for PwT1D in Canada. A prospective study is ongoing to evaluate users' satisfaction, engagement, and efficacy to change the fear and the frequency of hypoglycaemia among adult PwT1D (NCT04233138) [19].

Medical Nutrition Therapy

International guidelines recommend medical nutrition therapy provided by a registered dietitian as part of diabetes care [20–22]. However, adopting a specialized diet (e.g., low carbohydrate) or tracking intake (e.g., CC) can amplify the burden of diabetes management. New technologies can reduce these challenges to reach treatment goals.

Wearable Technologies

A main challenge around insulin adjustments is hypoglycaemia, a common complication mainly treated with simple carbohydrates [23]. Recent literature shows significant reduction of hypoglycaemic events with the use of wearable technology [24]. In a sample of adults with T1D treated by multiple daily injections (MDI), real-time CGM (rt-CGM) users were more proactive in preventing level-2 hypoglycaemia (defined as ≤ 3.0 mmol/L) by taking carbohydrates at a higher glucose threshold (4.4 ± 0.8 vs 3.9 ± 0.8; $p = 0.005$) [25••]. SAP users also reported needing less carbohydrates to treat hypoglycaemia, owing to the system's insulin suspend features [26]. These results suggest that both rt-CGM and SAP may reduce the burden of hypoglycaemia for PwT1D by allowing for earlier detection of impending hypoglycaemia and a corresponding reduced amount of rescue carbohydrate, when compared to systems without rt-CGM. Lower carbohydrate intake could reduce the risks of rebound hyperglycaemia and weight gain [26]. Moreover, the use of CGM might also influence one's relationship with food. A qualitative study found that intermittently scanned CGM (is-CGM) use increased self-awareness of food intake, which promoted more flexible eating behaviours for some participants but led others to develop a more restrictive relationship with food [27•]. Conversely, an interventional study found that after 12 weeks of is-CGM use, neither food variety, coefficient of variance (glycemic variability), nor HbA1c changed [28]. While close monitoring of food intake is central in T1D management, it has also been shown to increase the risk of disordered eating behaviours in PwT1D [27•]. A recent systematic review, exploring the use of technology in the context of disordered eating behaviours, found limited inconclusive results, indicating that further research is required to better understand technology use in this context [29].

Postprandial glycaemic fluctuations contribute significantly to the overall glycaemic outcomes; thus, it is imperative to optimize prandial insulin administration [30]. Of the currently available commercial AID systems, CC is still required as current algorithms require meal-announcement with carbohydrate intake to provide appropriate bolus doses. A 3-week non-inferiority trial with 30 adults using AID compared glycaemic outcomes using conventional CC and a simplified qualitative meal-size estimation (based on carbohydrate content). The authors reported significantly higher time in range (TIR, 3.9 to 10.0 mmol/L) with the conventional CC method (74.1 ± 10.0% vs 70.5 ± 11.2%, $p = 0.018$), lower time above range (TAR > 10.0 mmol/L, 24 ± 10% vs 28 ± 11%, $p = 0.014$), and similar time below range (TBR, < 3.9 mmol/L) [31]. Although non-inferiority was not achieved, the meal-size estimation arm still had TIR within target (≥ 70%) and low TBR (1.6%) [31]. More recent advances may reduce the need for CC and its related burden. Algorithms such as the recently FDA approved AID device (iLET Bionic Pancreas) only requires a qualitative estimation of carbohydrate content (compared to the usual amount for the user) instead of quantitative CC. In this 13-week RCT, iLet users reported higher TIR (65 ± 9% vs. 54 ± 17%, $p < 0.001$) and lower TAR (33 ± 9% vs. 44 ± 18%, $p < 0.001$) compared to standard care (MDI or CSII with rt-CGM, or AID) without a difference in TBR [32••].

While current nutrition guidelines focus on carbohydrate intake, there is established evidence that protein and fat content also influence postprandial glycemia [33]. Earlier studies suggested that CSII offers more flexibility in insulin dose adjustment [34, 35]; however, the more recent advancement in AID has the potential to effectively manage postprandial glycemia, even with varied meal compositions as it can modulate insulin infusion in response to glucose changes [36]. A randomized cross-over study compared the glycaemic response to high fat and/or high protein meals in participants using AID [36]. The study found that high fat and high protein meals resulted in a delayed postprandial glycaemic peak and needed a higher basal rate for 5-h post-meal, compared to the standard meal. Additionally, compared to standard meal (TIR 43 [32–65] %) and high protein meal (54 [27–72] %), high fat meal (38 [23–74] %), and high fat and high protein meal (34 [16–77] %) had the lowest TIR, although statistical significance was not reached [36]. TBR was similar (0%) suggesting that postprandial hyperglycaemia with high fat meals remains challenging even with an AID. Future algorithms should be developed to account for diverse meal compositions [36].

AID systems might also offer additional support to people following special diets (e.g., low carbohydrate diet). A study assessed the association between carbohydrate intake and glycaemic management in 36 AID users by comparing the groups based on percent time spent in auto-mode and their average daily carbohydrate consumption (low (100.9 ± 69.9 g/day) vs medium (171.2 ± 53.4) vs high (222.7 ± 70.6)) [37]. Participants in the low carbohydrate group had higher TIR (77.4 ± 15.4 vs 70.4 ± 17.8, $p < 0.001$) and lower TAR (20.1 ± 14.7 vs 27.2 ± 18.4, $p < 0.001$) compared to the high carbohydrate group. The results were especially prominent among AID users who spent more than 90% of the time on auto-mode with higher TIR (82 ± 11.8 vs 73.8 ± 16.3, $p < 0.001$) and lower TAR (16.2 ± 11.5 vs 24.2, $p < 0.001$). The TBR was similar between the groups.

These results show significant potential for certain AID algorithms to reduce the burden of prandial insulin administration while maintaining effective glycaemic management. However, there remains a need to further improve these technologies to respond faster to glucose fluctuations (e.g., improved insulin pharmacodynamics and CGM accuracy, more advanced AID algorithm) to potentially reduce the need for CC by users (ACTRN12622001400752).

Digital Platforms

The use of mobile apps to help with CC and bolus estimation for T1D has been increasing due to their convenience, with a variety of mobile apps to choose from. A study surveying adults with diabetes, 1052 of whom live with T1D, found that more than half PwT1D relied on apps for their self-management (such as bolus calculator and carbohydrate intake tracking). Using the Summary of Diabetes Self-Care Activities Questionnaire [38] to measure self-care behaviours, participants who used an app reported improved overall scores, specifically in the general diet subscale and blood glucose monitoring subscale [39]. While current applications continue to rely on input from the user, future technologies integrating artificial intelligence are currently being tested to utilize food image recognition systems to replace manual CC by PwT1D (jRCTs042210167).

Physical Activity

Despite the numerous benefits of engaging in PA, only ~ 30% of PwT1D compared to ~ 50% of individuals without diabetes meet the recommended 150 min of moderate to vigorous PA per week [40, 41]. Specific barriers to PA for PwT1D, notably fear of hypoglycaemia and significant glycaemic variations [42, 43] might be alleviated by technological developments.

Wearable Technologies

Glucose management for PwT1D during PA is easier with CGM [44], and the glycaemic benefits depend on the type of CGM. A study that compared rt-CGM with is-CGM during 4 days with consecutive exercise found the former reduced TBR (6.8 ± 5.5% vs. 11.4 ± 8.6%, $p = 0.018$) and increased TIR (78.5 ± 10.2% vs. 69.7 ± 16%, $p = 0.015$) during exercise in 60 adult PwT1D using either MDI or CSII, indicating the extra benefits of alerts [45]. Whether using a CGM contributes to an increase in time spent exercising remains unclear. A prospective national registry in the Netherlands included 1365 participants with diabetes using insulin (1054 PwT1D). The study found that after 1 year of is-CGM use, 37% of participants reported exercising more frequently [46]. However, a sub-analysis of the GOLD randomized trial including 116 adult PwT1D revealed no change in amount of PA, estimated by the International PA Questionnaires (IPAQ) scale [47], between four month rt-CGM and self-monitoring blood glucose, despite improvements in hypoglycemia and fear of hypoglycaemia for CGM group [48]. This may indicate that apart from hypoglycaemia, barriers unrelated to diabetes, including lack of time and motivation, may also hinder PwT1D from PA participation.

The accuracy of CGM tends to decrease during periods of increased activity [49, 50•, 51, 52], due to rapid changes in glycaemia, increased glucose uptake by muscles, and mechanical forces applied to the sensor [49, 50•, 51, 52]. In most cases, however, the decreased accuracy is unlikely to result in a decision that could jeopardize safety [50•, 51]. Considering these data, the use of CGM data to determine insulin dosage and monitor hypoglycaemia trends during exercise can be considered while being interpreted with caution [4].

Compared with CSII + CGM therapy, AID improved overnight and whole day TIR and TAR without increasing TBR, in a small sample size ($N = 13$) crossover RCT evaluating a 3-day period with daily exercise interventions [53]. Using PA specific AID settings could increase those benefits, especially lowering hypoglycaemia risk. A study which evaluated the TBR during 60 min of aerobic exercise and 1 h after found that TBR was 13.0 ± 19.0% when no strategy was applied, but was reduced to 7.0 ± 12.6% when target glucose was increased 1 h prior to exercise, and was further reduced to 2.0 ± 6.2% when a 33% reduction in meal bolus was applied 1 h prior to exercise in addition to increased target $p < 0.0001$ and $p = 0.005$, respectively) [54]. Additionally, two other recent studies demonstrated the glycaemic benefits of pre-exercise strategies with increased TIR and decreased TBR when pre-exercise glucose target was increased and meal bolus was reduced 1–2 h prior to exercise with AID use [55, 56].

While the previously mentioned studies assessed the benefit of strategies applied 1–2 h prior to exercise, new and future technologies are aiming to reduce the need for PwT1D to announce planned activity to AID systems. Adding PA detection from accelerometer or physiological data (e.g., heart rate, skin moisture) could be an effective strategy to improve the performance of AID systems around unannounced PA. Detection systems have been shown to detect the start of PA within 1 min, allowing for prompt insulin reduction before significant glucose decline [57]. During a 3-day inpatient study which included six unannounced exercise sessions including moderate aerobic, high intensity interval, and resistance training, 10 PwT1D using AID with PA detection spent 0.88 ± 2.15% time below 3.0 mmol/L and 1.34 ± 1.55% time between 3.0 and 3.9 mmol/L during and 2 h after the exercise sessions [58]. An alternative approach to improving the performance of AID during activity is based on machine learning of previous exercise habits. A crossover RCT including 15 adults with T1D evaluated the effect of an AID system (APEX) which used artificial intelligence to identify existing exercise behaviours, and prospectively adjust insulin delivery [58]. Compared with a conventional AID system, the APEX system significantly reduced hypoglycaemic episodes during exercise (13 vs. 5) and the 4 h following exercise (11 vs. 2). These innovative systems, driven by artificial intelligence, are providing promising solutions that substantially alleviate glucose management burden during physical activity. Larger sample size studies investigating various exercise types and intensities will be needed to provide confirmatory results.

Another avenue for improving AID with respect to hypoglycaemia prevention around PA is dual-hormone systems, featuring liquid, stable glucagon, to increase blood glucose concentration to maintain target range. Compared to single-hormone AID, a dual-hormone AID system was associated with reduced TBR during and 4 h after unannounced exercise (8.3% [0.0–12.5] vs 0.0% [0.0–4.2], $p=0.025$), but was associated with greater TAR (6.3% [0.0, 12.5] vs. 20.8% [0.0–47.9], $p=0.038$), respectively [59]. In addition to intra-activity hypoglycaemia, the risk for nocturnal hypoglycaemia is high following PA, mainly due to persisting elevated insulin sensitivity. In a recent pooled analysis involving two available trials comparing dual-hormone to single-hormone AID, 41 adult participants spent 94.0 ± 11.0% and 83.1 ± 20.5% ($p<0.05$) in target range and 0 (0, 20.1)% vs 0 (0,0)% ($p<0.001$) TBR during the overnight period after exercise, respectively [60•]. Dual-hormone AID may also reduce fear of hypoglycaemia during exercise, although evidence remains scarce [61]. Overall, despite its costs and system complexity, dual-hormone AID warrants more attention regarding both clinical studies and product development, to offer an alternative option for PwT1D who could not attain optimal PA glucose targets or have fear of hypoglycaemia keeping them from PA despite using a single-hormone AID [62].

Digital Platforms

The online T1D and exercise education platform (ExT1D) provided effective training and education for reducing exercise related hypoglycaemic events. Compared to standard treatment, the ExT1D intervention reduced the median frequency and duration of exercise-related hypoglycaemic events by 43% and 52%, respectively [63]. Personalized digital health information such as CGM glucose, physical activity, sleep, and mood can substantiate human delivered exercise support for PwT1D as was shown in a recent study [64]. Specifically, this study of adults with T1D ($n=17$) found that after 10 weeks of expert delivered feedback based on personalized data, and other informational and motivation resources (exercise videos, text based coach, self-monitoring diary), physical activity participation increased from a median of 0 to 64 min per week with no severe hypoglycaemia or ketoacidosis events [64].

Smoking Cessation: Tobacco and E-Cigarettes

The estimated global prevalence of current smokers living with T1D ranges between 10 and 30% [65], which is comparable to the general population (17%) [66]. Smoking can increase insulin resistance and is a risk factor for developing microvascular and macrovascular complications, as well as increased glycaemic variability and hypoglycaemia [67, 68]. While smoking abstinence can reduce morbidity and mortality, it can cause significant glycaemic fluctuations as it increases insulin sensitivity and leads to weight fluctuations that can impact glucose management [67, 68].

Wearable technologies such as CGMs might help reduce the unexpected glycaemic variability associated with smoking cessation. However, research is needed to explore their effectiveness in this context. There is currently a growing interest in exploring CGM as a behaviour change tool [69] with some interest to understand how the use of CGM during smoking cessation can provide further perspectives to tailor cessation interventions [70]. Digital platforms can also be used to promote and facilitate smoking cessation. While the current evidence is not specific to T1D, research suggests that technologies such as mobile apps [71] and chatbots [70] can help facilitate smoking cessation in the general population, by offering punctual and personalized support to promote cessation and abstinence [71, 72]. Further research should explore these platforms in T1D as this population has additional diabetes-specific challenges that might not be addressed in the current literature.

Psychosocial Care

The burden of daily decisions related to diabetes management often contributes to depression and mental health challenges related to diabetes. Notably, 42 to 54% of PwT1D experience diabetes distress [73] and the prevalence of major depression is double that of the general population [74]. These challenges can impair PwT1D's ability to effectively manage T1D and thus compromise glucose outcomes [75]. Current technologies can help implement effective psychosocial care.

Wearable Technologies

Overall, the impact of CGM use on psychosocial aspects in adult PwT1D is positive. A post hoc analysis of a prospective study suggested that the rate of depressive disorder decreased after initiation of is-CGM for 12 months in 527 adult PwT1D [75]. Their mental well-being also improved with a significant increase in the Mental Component Score. Furthermore, a prospective observational multicentre study found a higher Diabetes Treatment Satisfaction Questionnaire score (28.0 [95% CI 26.1; 29.9] vs. 30.4 [28.9; 32.6]; $p<0.0001$) in 1913 adults with T1D after 12-month use of is-CGM, compared with baseline (without CGM) [76]. The other quality

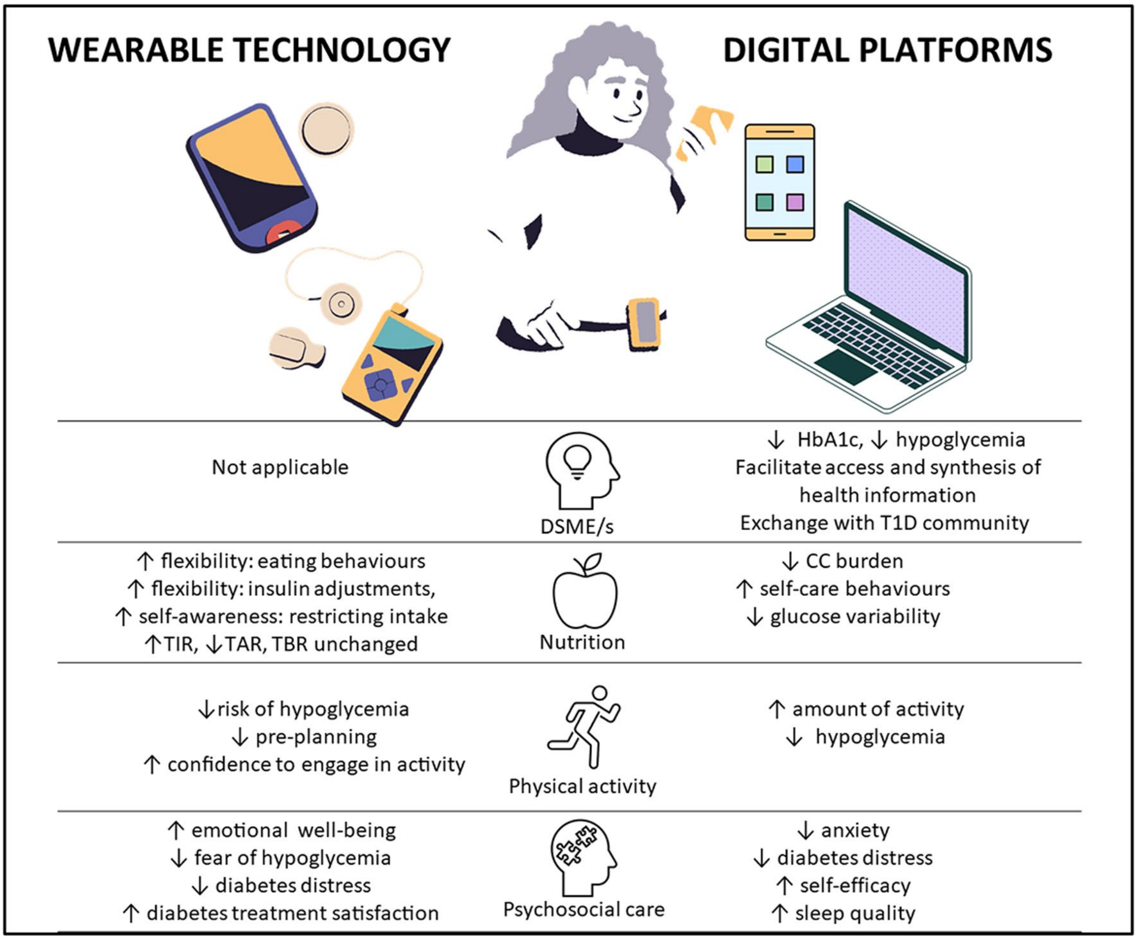

Fig. 1 Summary of the influence of technology on lifestyle behaviours, glucose outcomes, and well-being for type 1 diabetes based on recent literature. Abbreviations: carbohydrate counting (CC), Diabetes Self-Management, Education and Support (DSME/S), haemoglobin A1c (HbA1c), time above range (TAR), time below range (TBR), time in range (TIR), type 1 diabetes (T1D)

of life scales (Health Survey questionnaire, Problem Areas in Diabetes, Hypoglycemia Fear Survey –Worry) remained unchanged, possibly due to the already high quality of life at baseline. The same group further investigated the impact of rt-CGM in a 24-month prospective observational study including 441 adult PwT1D using CSII [77]. Improvement in general quality of life, diabetes-related emotional distress, and fear of hypoglycaemia were observed at month 12 and sustained throughout the 24-month follow-up, particularly in those with impaired awareness of hypoglycaemia. While most studies suggest positive impact of CGM use, it is worth noting that a cross-sectional study including 274 adults with T1D found that is- and rt-CGM users, compared to non-CGM users, reported more diabetes-related anxiety and emotional burden, possibly due to pain and skin reactions related to CGM, despite the beneficial effect on glycaemic management and fear of hypoglycaemia [78].

Alongside CGM, AID systems help reduce some psychosocial burdens. AID reduced fear of hypoglycaemia [79–83] and increased overall emotional well-being [84–87] compared with either CGM + CSII or MDI, among adults with T1D. Improvement in diabetes-related distress was observed in three prospective studies [82, 88, 89••], while two other retrospective observational studies revealed no change [83, 86]. Whether AID use is associated with improved sleep quality is controversial: three studies of older adults with T1D [88, 90, 91] suggested no difference in Pittsburgh Sleep Quality Index score between AID and SAP treatment. An Australian RCT [91] comparing AID and SAP suggested a poorer sleep quality, assessed by daily diary sleep quality ratings, with AID treatment, possibly due to the more frequent alarms during AID intervention. On the other hand, two studies, including one in older adults, reported improved sleep quality [79, 81, 82]. Moreover, a large sample prospective study ($N = 1435$) suggested that continued use of AID resulted in a reduction in the overall impact of diabetes on participants' lives and an improvement in device-related satisfaction [84].

Table 1 Selected ongoing studies exploring technology use in health behaviours and well-being for type 1 diabetes

Study	Health behaviour or well-being	Study design and intervention	Participants	Outcomes of interest
NCT04233138	DSME/S	One arm prospective interventional study, assessing the use of SUPPORT platform, an online training platform for type 1 diabetes self-management education and support	275 adults with T1D (≥ 18 years old)	Frequency and fear of hypoglycaemia, HbA1c, knowledge about diabetes self-management, satisfaction, and engagement of the platform
ISRCTN74114336	DSME/S	Three-arm RCT, comparing (1) interactive messaging system + agenda setting tool + external support worker, (2) interactive messaging system + agenda setting tool + internal Support Worker, and (3) usual care The role of support worker is to coordinate messaging system and use of the agenda setting tool	100 adults with T1D (18–25 years old)	HbA1c, episode of diabetic ketoacidosis and severe hypoglycaemia, diabetes related distress, diabetes related quality of life, self-management, level of clinic engagement, perceived level of control, feasibility, and acceptability of the platform
jRCTs042210167 (CARB-LIFE)	Nutrition (carbohydrate counting)	RCT study evaluating a carbohydrate-counting smartphone application with food image recognition system (control group: standard of care)	56 PwT1D (6–70 years old)	HbA1c, glycaemic outcomes measured by CGM (e.g., TIR, TBR, TAR), diabetes therapy-related quality-of-life
ACTRN12622001400752 (CLOSE IT)	Nutrition (carbohydrate counting)	RCT study, comparing with and without manual mealtime boluses in an open-source automated AID with auto-correction bolus feature	75 adults with T1D (18–70 years old)	Glycaemic outcomes measured by CGM (e.g., TIR, TBR, TAR), semi-structured interview on experiences using the study AID system
DRKS00030738	Physical activity	Compares a prototype of a CGM-based training application (app) to the EASD/ISPAD position statement-based approach (paper) for TIR during physical activity. Both groups perform three different training sessions and use either app or paper to ensure the most stable blood sugar control possible	11 adults with T1D (18–65 years old)	Glycaemic outcomes measured by CGM (e.g., TIR, TBR, TAR)
NCT04771403	Physical activity	RCT study testing the efficacy of an AID system that modulates insulin delivery based on activity level during physical activity (control group: an AID that can only detect physical activity)	25 adults with T1D (21–50 years old)	Glycaemic outcomes measured by CGM (e.g., TIR, TBR, TAR)

Table 1 (continued)

Study	Health behaviour or well-being	Study design and intervention	Participants	Outcomes of interest
NCT05734313	Psychosocial care	RCT study comparing Unified Protocol for Cognitive Behavioural Therapy (UP-CBT) + CGM and CGM alone UP-CBT consists of five core modules that target negative emotionality and aversive reactions to emotional experiences	150 adults with T1D (18–35 years old)	Anxiety and depressive symptom severity

Abbreviations: *AID* automated insulin delivery, *CGM* continuous glucose monitor, *DSME/S* Diabetes Self-Management, Education and Support, *EASD* European Association for the Study of Diabetes, *HbA1c* haemoglobin A1c, *ISPAD* International Society for Pediatric and Adult Diabetes, *PwT1D* people with type 1 diabetes, *RCT* randomized control trial, *TAR* time above range, *TBR* time below range, *TIR* time in range, *T1D* type 1 diabetes

Digital Platforms

Telemedicine and virtual group appointments can also play a positive role in maintaining well-being. After four visits over 12 months, two studies found that telehealth visits followed by virtual group appointments, compared to in-person medical visits and telehealth visits only, resulted in significant improvement in diabetes distress, self-efficacy, and the ability to talk about their illness [92, 93]. Neither study revealed a difference in depressive symptoms, quality of life, or self-confidence for any of the groups [92, 93].

A study investigating the impact of ten 50-min psychological therapy sessions via real-time texting over 3 months observed a significant decrease in HbA1c and anxiety, but no change in diabetes distress or depressive symptoms among 71 adults with T1D [94•]. Furthermore, a parallel RCT investigated sleep quality, diabetes distress, and glycaemic management in 14 adult PwT1D [95]. The 8-week study had two parallel arms: Sleep-Opt-In with weekly digital lessons related to sleep, phone calls with a trained sleep coach, and sleep tracking vs. the Healthy Living Attention arm with weekly general health emails and phone calls with a healthy living coach. After 8 weeks, the Sleep-Opt-In group showed an improvement in sleep regularity, daytime sleepiness, and general fatigue, while these worsened in the other group. They also had lower diabetes distress and fewer depressive symptoms [95]. Though no RCTs have evaluated the combination of both telemedicine and wearable technology yet, an upcoming RCT will evaluate the use of a telemedicine-delivered cognitive behavioural therapy program alongside the use of CGM, compared to the use of CGM only, in young adults with T1D living with anxiety and depression (NCT05734313).

In summary, there are an emerging number of original articles on technology use and its impact on psychosocial care in the adult population with T1D [96, 97]. Collectively, they highlight that the use of technology is often associated with improved well-being, reduced fear of hypoglycaemia, and reduced depressive symptoms. Research with larger sample sizes in PwT1D is needed, as most existing literature combines T1D and T2D populations, who may not share the same level of psychosocial burdens. Furthermore, several studies group adolescents and adults together. Future studies investigating the impact of technology or telehealth integration on psychosocial care into an individuals' treatment plan during different life stages are necessary.

Conclusions

Maintaining positive health behaviours facilitate better health outcomes (glucose and well-being) for PwT1D. However, enforcing these behaviours may also lead to burdens and challenges (e.g., intensive DSME/S may cause psychosocial burden, physical activity can lead to higher risks for hypoglycemia) which impede the realization of such health goals. Advanced diabetes technologies including CGM, AID, and digital platforms alleviate some management burden and allow for more informed decisions (Fig. 1). Nevertheless, reaching optimal glycaemic and psychological outcomes in PwT1D remains challenging, even for those with access to these technologies [4, 5, 9]. Research investigating why this state persists is scarce, and therefore, implementation research studying how to translate benefits of technologies in real-life conditions warrants more attention.

Current diabetes technologies are mostly designed around insulin delivery. Considering the complexity of T1D (e.g., large intra- and interpersonal variation), pharmacotherapy may remain insufficient to achieve optimal diabetes outcomes. Positive health behaviours and well-being interventions provide huge opportunities to supplement T1D treatment [4, 98]. Technologies designed around these interventions should be encouraged and their integration with current AID systems should be a future focus of development.

Uptake of technologies does not guarantee high user engagement. Yet the benefits of technology use usually depend on the level of engagement and adherence [4]. Those having difficulty devoting time and adhering are, in most cases, also individuals prone for suboptimal health outcomes and to whom technologies can offer the most benefits. A balance between device complexity and functionality should be achieved to ensure PwT1D can obtain benefits without being overwhelming. Relevant studies should not only assess glucose outcomes, but patient-reported outcomes and patient-reported experience, to facilitate understanding of both health benefits and users' experience and burden [99]. These studies will provide crucial information on engagement and adherence (including accessibility, usage, cost, and training), which is key to the successful implementation of these technologies. Practical barriers faced by healthcare professionals should also be assessed to provide a more rounded understanding.

Education and support play a major role [100]. Apart from comprehensive training at initiation, consistent training as well as routine clinical re-assessment of technology use should be implemented to sustain the benefits of technology, and to identify those who would benefit from alternative options. Policy-makers need to encourage opportunities for consistent diabetes education and support, by ensuring proper policies are in place to better support the integration of diabetes education in clinical practice, to both PwT1D and healthcare professionals.

Recommendations for digital platforms in managing T1D remains difficult, mainly due to the lack of high-level evidence and validations of such platforms by regulators. Cost-effectiveness studies are rare, yet will facilitate future uptake and health coverage of these digital platforms, especially mobile applications.

In summary, technologies possess the potential to promote health behaviours changes and well-being for PwT1D, and therefore facilitate the realization of favorable health outcomes. A few ongoing studies are summarized in Table 1. More confirmative studies elucidating the effectiveness and safety of these technologies in a broad and diverse population, along with implementation and cost-effectiveness studies, are urgently needed to ensure optimal integration of technologies in standard care practices. Collaborative engagement involving researchers, healthcare professionals, PwT1D, industry, and government remains vital and should be encouraged to accelerate this process.

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Declarations

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- • Of importance
- •• Of major importance

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