scientific reports

Check for updates

OPEN

Impact of heatwaves on glycemic control in adults with type 1 diabetes using hybrid closed-loop systems

Jesus Moreno-Fernandez[1,2]✉, Luz María López[3], Esther Maqueda[4], Iván Quiroga[5], Javier González[6], Amparo Marco[4], Sandra Herranz-Antolín[7], Adriana Martínez[8], Diana Edith[9], Ignacio González-Maroto[1], Marina Jara[3], Marta Gallach[3], Alejandro Gratacós[4], María Ruíz de Ancos[4] & José-Ramón Muñoz-Rodriguez[1,2]

To evaluate the effect of the August´s 2023 heatwaves over glycemic control in adults with type 1 diabetes (T1D) treated with advance hybrid closed-loop systems (AHCL). Cross-sectional retrospective analysis of adult patients with T1D in Castilla-La Mancha (south-central Spanish region) using AHCL during the August´s 2023 heatwaves period. Primary outcome was change in time in range (TIR) 3.0–10 mmol/L (70–180 mg/dL) of interstitial glucose after the end of the heatwaves period. A total of 193 T1D patients were analyzed. TIR remained constant after the end of the heatwaves period (0.5% [95% CI -0.3, 1.3; $P = 0.236$]). No differences were observed among the rest of glycometric index. The percentage of patients meeting all the recommendations of the International Consensus of Time in Range was similar during the heatwaves period than after it ended (44.6% vs. 45.6%, $P = 1.000$). Finally, the percentage of time in automatization and daily insulin dose also stayed stable (0.5% [95% CI -1.4, 2.4; $P = 0.601$] and 0.0 UI/day [95% CI -1.0, 1.0; $P = 0.981$], respectively). Adults with T1D treated with AHCL maintained glycemic control during August´s 2023 heatwaves. These data raise the possibility that AHCL systems could help protect T1D patients from the effects of heatwaves on glycemic control.

Keywords Heatwave, Climate change, Advanced hybrid closed-loop, Type 1 diabetes

Climate change may be the greatest health threat of the twenty-first century, impacting lives both directly and indirectly, through undermining the environmental and social determinants of health[1]. Global warming is consequence of the impact of humans' activities on Earth´s ecosystem[2,3]. The interest in their effects on human health has increased over the last few decades[4]. Hot ambient conditions and associated heat stress can increase mortality and morbidity[5].

A heatwave is considered to be one of the most dangerous expressions of global warming, being increasingly frequent[6]. It is defined as an extended period of hot weather relative to the expected conditions of the area at that time of year[7]. Heatwaves increase deaths from cardiovascular and respiratory conditions and are also associated with more suicides[8,9]. Vulnerable people are most susceptible to heatwaves[10,11].

People living with diabetes is a well-known population especially sensitive to the effect of heatwaves[12,13]. Type 1 diabetes (T1D) is the second more frequent type of diabetes, however its common diagnosis in childhood or adolescence and its socio-health repercussions make it a health care challenge[14]. The burden of T1D is vast and

[1]Ciudad Real General University Hospital. Ciudad Real, Obispo Rafael Torija, St, Ciudad Real 13005, Spain. [2]Castilla-La Mancha Health Research Institute, Road Finca la Peraleda, Toledo 45071, Spain. [3]Department of Endocrinology and Nutrition, Albacete University Hospital, Hermanos Falco St, 37, Albacete 02006, Spain. [4]Department of Endocrinology and Nutrition, Toledo University Hospital, Rio Guadiana Av, Toledo 45007, Spain. [5]Department of Endocrinology and Nutrition, Virgen del Prado Hospital, Talavera de la Reina (Toledo), Extremadura Av, Toledo 45600, Spain. [6]Department of Endocrinology and Nutrition, Virgen de la Luz Hospital, Hermandad de Donantes de Sangre St, 1, Cuenca 16002, Spain. [7]Department of Endocrinology and Nutrition, Guadalajara University Hospital. Guadalajara, Donantes de Sangre St, Guadalajara 19002, Spain. [8]Department of Endocrinology and Nutrition, Valdepeñas Hospital. Valdepeñas (Ciudad Real), Donantes de Sangre St, Valdepeñas (Ciudad Real) 19002, Spain. [9]Department of Endocrinology and Nutrition, Santa Barbara Hospital. Puertollano (Ciudad Real), Malagón St, Puertollano. Ciudad Real 13005, Spain. ✉email: jmorenof@sescam.jccm.es

is expected to increase rapidly. There were about 8.4 million individuals worldwide with T1D in 2021[15]. The age-standardised global prevalence of type 1 diabetes is expected to increase by 23·9% from 2021 to 2050[16]. People living with T1D needs to adjust continuously insulin therapy to their glucose levels. In the last decade, glycemic control had technological advanced through the implementation of AHCL therapy. An AHCL system combines continuous glucose monitoring (CGM) technology and insulin pumps with intelligent algorithms to partially automate diabetes management and improve the quality of life for patients[17]. This technology allows patients to attain better glycemic control compared with traditional daily insulin injections[18]. In fact, AHCL effectiveness results have been validated in several randomized controlled trials and real-world data studies[19–21]. Therefore, AHCL is considered since 2022 the preferred insulin delivery method for people living with T1D and health services are moving towards universal coverage of this technology[22].

Some descriptive studies showed a diverse relationship between glucose levels and temperature in different climate zones[23–25]. The effect of heat stress on glycaemic control in people with T1D is even less known. The lowest glycated haemoglobin A1c (HbA1c) levels were observed in summer and the highest in winter months in humid subtropical and continental climates in young and adult T1D patients[26,27]. In a previous study we described how adults with T1D treated with multiple daily injections (MDI) had better glycemic control during the historic European heatwave of 2022 compared to the following period in Spain raising concerns about the effect of global warming over diabetes control[28]. To date, this is the only available information on the impact of extreme heat events on patients with T1D.

There is no published data about the use or achieved glycemic control with AHCL systems in T1D patients during periods of extreme heat. We hypothesized that AHCL, with automated adaptive insulin systems, could protect T1D patients against a possible worsening in glycemic control related with heatwaves. The aim of the present study was to evaluate the effect of August´s 2023 heatwaves over glycemic control in adults with T1D treated with AHCL.

Methods

Study design and ethics

A cross-sectional multicenter observational study was designed to assess the effect of August´s 2023 heatwaves among adult T1D patients. The protocol was approved by the Castilla-La Mancha Public Health System (Servicio de Salud de Castilla-La Mancha, SESCAM) Ethic Committee, Ciudad Real General University Hospital Institutional Review Board (reference C-674), and conducted in accordance with the Declaration of Helsinki and Good Clinical Practice. All patients signed the informed consent form approved by the Institutional Review Board. The protocol was publicly registered at ClinicalTrials.gov (NCT06214780).

The study was based in the Castilla-La Mancha region (79.463 Km^2) located in South-central Spain. Here, we present data from seven public health care areas (Albacete, Ciudad Real, Cuenca, Guadalajara, Puertollano, Talavera de la Reina and Toledo).

Meteorologists tend to consider a heatwave as an increase of 5 °C above the average maximum temperature from 1961 to 90 that lasts for 5 days or longer, although each country can use its own definition. In fact, heatwaves are defined in Spain as episodes of at least three consecutive hot days with ≥ 10% of the weather stations recording temperatures over the percentile 95 of the higher July-August daily temperatures from the 1971–2000 period. Summer of 2023 was the fifth warmest for the summer season. Actually, August´s 2023 was the warmest European August on record, and warmer than all other previous months except July 2023. This warm anomaly hit South Europe with special intensity through consecutive heatwaves[29,30]. There were two heatwaves in mainland Spain during August´s 2023: the first between the 6th and 13th, and the second between the 18th and 25th. The maximum temperature recorded in the Community of Castilla La Mancha, was 43.0 º C on the 9th of August, in Almagro (Ciudad Real)[31,32].

The trial was designed to detect a TIR between-period difference of 10%, equivalent to a clinically significant difference HbA1c of 0.6% (7 mmol/mol)[33]. One hundred and ninety-three subjects had > 90% power to detect a 10% TIR difference between both periods of time, at the 0.05 significance level, accepting an alpha risk of 0.05 and a beta risk of less than 0.2 in bilateral contrast. We settled a summer´s TIR of 58% according to our population[28]. A consecutive sampling was conducted in the participant centers until sufficient subjects were enrolled.

Participants

All adult (≥ 18 yrs.) T1D patients treated with ACHL during ≥ 3 months followed in the Castilla-La Mancha Public Health Service with active paired data from the August´s 2023 heatwave phase and the subsequent 21-days period were included. Exclusion criteria were presence of other types of diabetes other than T1D, being treated with therapies other than AHCL, not having paired data from both time periods. HbA1c values were not considered for inclusion in the study.

Variables and outcomes

The primary end-point was mean change in time in range (TIR, [70–180 mg/dL (3.9–10.0 mmol/L]) of interstitial glucose after the end of the heatwaves period. The secondary outcomes included changes in:(1) glycometric index, including: time above range level 2 (TAR2) > 250 mg/dL (> 13.9 mmol/L), time above range level 1 (TAR1) 180–250 mg/dL (10.0–13.9 mmol/L), time bellow range level 1 (TBR1) 54–70 mg/dL (3.0–3.9 mmol/L) and time bellow range level 2 (TBR2) < 54 mg/dL (< 3.0 mmol/L) of interstitial glucose, glucose management indicator (GMI), and variation coefficient (VC); (2) percentage of patients fulfilling the recommendations of the International Consensus of Time in Range[34]; (3) AHCL use, including percentage of time in AHCL automatization, defined as the proportion of time during which the insulin delivery is controlled automatically by the system's algorithm, and insulin dose (basal, bolus, total). AHCL systems used during the study included all four models marketed in Spain at the time: Medtronic Minimed 780G (MM780G) with SmartGuard (Medtronic PLC, Dublin, Ireland), Tandem t: Slim X2 (TSX2) with Control-IQ (Tandem Inc, San Diego, USA), Ypsopump with CamAPS FX (Ypsomed Inc, Burgdorf, Switzerland), and Accu-Chek Insight with Diabeloop G1 (DBLG1) (Diabeloop SA, Grenoble, France). Variables were collected through medical chart revision and the specialized online AHCL webpages for Medtronic (https://carelink.medtronic.eu/), Glooko (https://eu.my.glooko.com/users/), and Diabeloop (https://www.your-loops.com/login). Data were obtained from the three-weeks period (5th-26th August 2023), including the two aforementioned consecutive heatwaves, and the three-weeks subsequent period (27th August to 17th September 2023) with no heatwaves.

Statistical analysis

Cross-sectional and longitudinal/retrospective analysis for patients meeting inclusion criteria were performed. Quantitative variables are expressed as means and standard deviation (SD) or median and range; qualitative variables are presented as total number of events and percentage. Kolmogorov-Smirnov test was used to evaluate the normality of quantitative variables. A paired Student's t-test or a Wilcoxon signed-rank test were used for the analysis of differences. Comparisons between proportions were analyzed using a chi-squared test. Mann-Whitney U and Wilcoxon signed-rank nonparametric tests were used to analyze statistical differences between groups and differences between during and after the heatwaves period, respectively. A bivariate analysis was performed to determine which variables could be candidates in a linear regression model with the variable difference in TIR during the follow-up as the dependent variable. Those that obtained the lowest p-values in this analysis were evaluated in a multivariable linear regression model for the TIR difference. Statistical significance was defined as $P<0.05$. Analyses were performed with IBM SPSS software version 28.0 for Windows (SPSS Inc., Chicago, IL) and graphics with R 4.1.2 (R Statistics, Vienna, Austria).

Results

A total of 193 T1D patients meeting inclusion criteria were evaluated. The patients (67% women) showed a median age of 41.1 years (IQ range 21.0 years). Diabetes duration was 24.0 ± 10.2 years and time under AHCL system treatment was 2.6 ± 1.4 years at the time of data gathering. The most frequent used AHCL systems were MM780G (49.7%) and TSX2 (36.8%), followed by DBLG1 (7.8%) and CamAPS FX (5.7%). 30% of the patients had chronic diabetes complications. Their last mean HbA1c level before the August´s 2023 heatwaves period was 6.8 ± 0.8% (51 ± 9 mmol/mol). Distribution of patients according to their public health area can be thoroughly consulted in the Supplementary Material.

Glycemic control

TIR remained constant after the end of the heatwaves period (0.5% [95% CI −0.3, 1.3; $P=0.236$]). No differences were observed among the rest of glycometric index (Table 1). Nor did we detect within-group differences along the time in the analysed glycometric variables. Only when comparing intergroup changes in the glycometric variables over time did we detect a statistically significant difference between changes in VC between MM780G and TSX2 (0.7% vs. −1.2%, $P=0.035$). Rest of changes in glycometric index according to AHCL system can be observed in Table 2.

Each of the recommendations of the International Consensus of Time in Range was fulfilled by a similar percentage of patients during the heatwaves period compared to the subsequent interval (Fig. 1). In fact, the percentage of patients meeting all the recommendations did not change after the end of the heatwaves period (44.6% vs. 45.6%, $P=1.000$).

A multiple linear regression was performed to assess the effect of sex, age, diabetes duration, chronic complications, BMI, last HbA1c level, type of AHCL system and percentage of time in automatization, during

Variable	During HW	After HW	MDC (CI 95%)
GMI, % (mmol/mol)	6.8 ± 0.4 (51 ± 5)	6.8 ± 0.5 (51 ± 6)	0.0 (−0.1 to 0.0, $P=0.175$)
TAR2, %	5.1 ± 5.8	4.9 ± 5.5	−0.2 (−0.6 to 0.2, $P=0.378$)
TAR1, %	18.3 ± 9.4	18.1 ± 9.2	−0.1 (−0.9 to 0.6, $P=0.707$)
TIR, %	74.5 ± 13.1	75.0 ± 12.5	0.5 (−0.3 to 1.3, $P=0.236$)
TBR1, %	1.8 ± 1.5	1.7 ± 1.5	−0.1 (−0.3 to 0.1, $P=0.262$)
TBR2, %	0.3 ± 0.6	0.3 ± 0.6	−0.1 (−0.1 to 0.0, $P=0.238$)
VC, %	32.4 ± 5.7	32.3 ± 5.7	−0.1 (−0.7 to 0.5, $P=0.717$)

Table 1. Glycemic control during and after the heatwaves period. Data are expressed in percentages and mean ± SD. HW, heatwaves period; MDC, mean difference in change; CI, confidence interval; GMI, glucose management index; TAR2, time above range level 2 of interstitial glucose > 250 mg/dL (13.9 mmol/L); TAR1, time above range level 1 of interstitial glucose 180–250 mg/dL (10.0–13.9 mmol/L); TIR, time in range of interstitial glucose 70–180 mg/dL (3.9–10.0 mmol/L); TBR1, time below range level 1 of interstitial glucose 54–70 mg/dL (3.0–3.9 mmol/L); TBR2, time below range level 2 of interstitial glucose < 54 mg/dL (3.0 mmol/L); VC, variation coefficient.

	MM780G (*n* = 96)	TSX2 (*n* = 71)	DBLG1 (*n* = 15)	CamAPS FX (*n* = 11)
GMI, %	0.0 (−0.1 to 0.0; *P* = 0.52)	0.0 (−0.2 to 0.1; *P* = 0.19)	0.1 (−0.1 to 0.2; *P* = 0.29)	−0.1 (−0.2 to 0.1; *P* = 0.43)
TAR2, %	0.2 (−0.3 to 0.6; *P* = 0.57)	−0.6 (−1.4 to 0.2; *P* = 0.1)	0.0 (−2.3 to 2.3; *P* = 1.0)	−1.0 (−2.5 to 0.5; *P* = 0.17)
TAR1, %	−0.1 (−0.8 to 0.7; *P* = 0.55)	−0.2 (−1.5 to 1.2; *P* = 0.15)	0.9 (−1.6 to 3.4; *P* = 0.78)	−1.9 (−5.6 to 1.9; *P* = 0.08)
TIR, %	0.2 (−0.8 to 1.2; *P* = 0.7)	1.1 (−0.6 to 2.7; *P* = 0.19)	−1.6 (−4.8 to 1.5; *P* = 0.27)	2.7 (−2.1 to 7.5; *P* = 0.22)
TBR1, %	−0.1 (−0.3 to 0.2; *P* = 0.84)	−0.2 (0.4 to −0.1; *P* = 0.79)	−0.1 (−0.8 to 0.6; *P* = 0.43)	0.4 (−0.1 to 0.9; *P* = 0.27)
TBR2, %	0.0 (−0.1 to 0.1; *P* = 0.44)	−0.1 (−0.3 to 0.0; *P* = 0.15)	0.0 (−0.3 to 0.3; *P* = 1.0)	−0.3 (−0.7 to 0.2; *P* = 0.16)
VC, %	0.7 (−0.2 to 1.5; *P* = 0.1)	−1.2 (−2.1 to −0.3; *P* = 0.13)	−0.7 (−3.9 to 2.5; *P* = 0.63)	0.3 (−2.7 to 2.1; *P* = 0.76)

Table 2. Mean difference changes in glycometric index in individual AHCL models. Data are expressed in mean difference in change (95% confidence interval; P value). AHCL, advanced hybrid closed-loop; MM780G, Medtronic Minimed 780G; TSX2, Tandem t: Slim X2; DBLG1, Diabeloop G1; GMI, glucose management index; TAR2, time above range level 2 of interstitial glucose > 250 mg/dL (13.9 mmol/L); TAR1, time above range level 1 of interstitial glucose 180–250 mg/dL (10.0–13.9 mmol/L); TIR, time in range of interstitial glucose 70–180 mg/dL (3.9–10.0 mmol/L); TBR1, time below range level 1 of interstitial glucose 54–70 mg/dL (3.0–3.9 mmol/L); TBR2, time below range level 2 of interstitial glucose < 54 mg/dL (3.0 mmol/L); VC, variation coefficient.

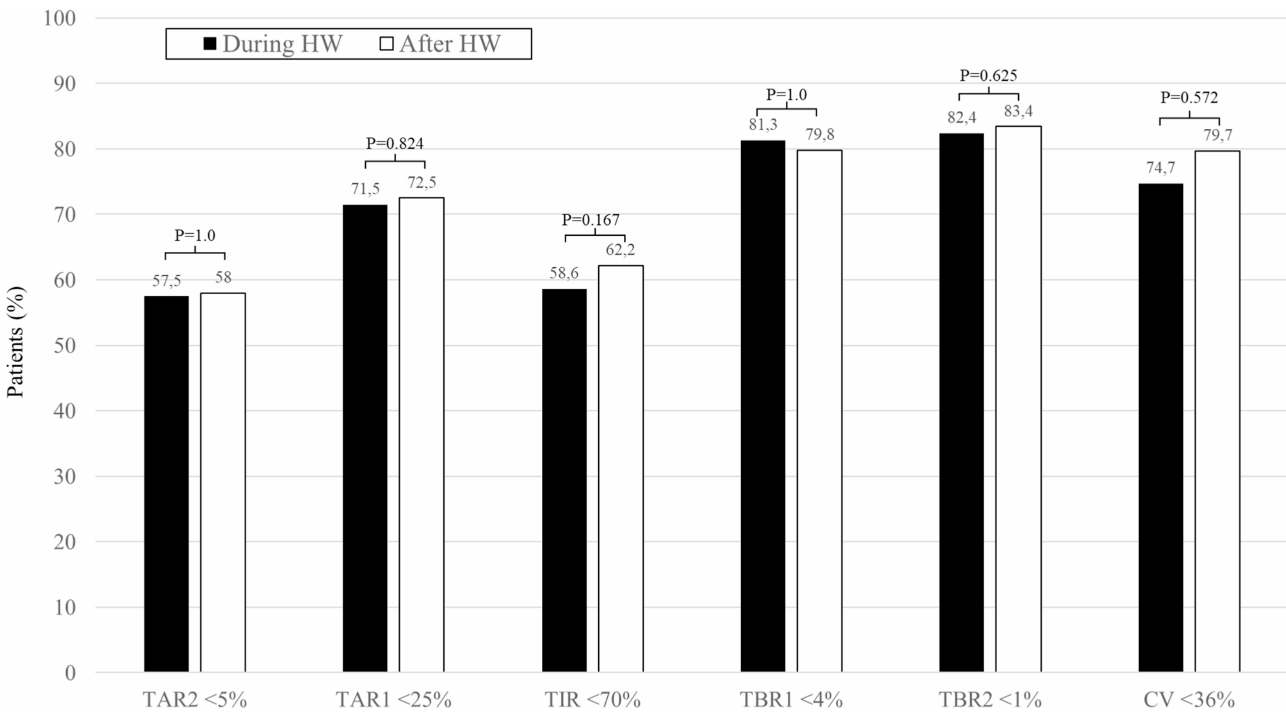

Fig. 1. Title: Patients meeting the International Consensus of Time in Range recommendations. Caption: Interstitial glucose measurements for: TAR2, time above range > 13.9 mmol/L (250 mg/dL), TAR1, time above range 10.0–13.9.0.9 mmol/L (180–250 mg/dL); TIR, time in range 3.9–10.0 mmol/L (70–180 mg/dL); TBR1, time below range 3.0–3.9.0.9 mmol/L (54–70 mg/dL); TBR2, time bellow range < 3.0 mmol/L (54 mg/dL); VC, variation coefficient < 36%. HW, August´s 2023 heatwaves period.

the heatwaves period on the TIR change after the heatwaves period. The overall model was non-significant (*P* = 0.599), and these variables were not shown to explain the change in TIR.

AHCL use

Finally, the percentage of time in automatization and insulin dose also stayed stable (0.5% [95% CI −1.4, 2.4; *P* = 0.601] and 0.0 UI/day [95% CI −1.0, 1.0; *P* = 0.981], respectively). Rest of AHCL system usage parameters can be consulted in Table 3.

Those patients with time in automatization ≥ 95% during the heatwaves period showed lower TBR1 (1.5% vs. 2.3%, *P* = 0.01) and TBR2 (0.2% vs. 0.6%, *P* = 0.003) compared with those patients with time in automatization < 95%. An additional lower CV was also detected between both groups of patients (31.2% vs.

Variable	During HW	After HW	MDC (CI 95%)
Time in automatization, %	92.1 ± 15.2	92.6 ± 17.0	0.5 (−1.4 to 2.4, *P* = 0.601)
Daily total dose, IU	43.7 ± 19.4	43.7 ± 18.7	0.0 (−1.0 to 1.0, *P* = 0.981)
Daily insulin requirements, IU/Kg	0.59 ± 0.21	0.59 ± 0.20	0.00 (−0.01 to 0.01, *P* = 0.943)
Daily basal insulin, %	43.6 ± 11.3	43.8 ± 10.9	0.1 (−0.7 to 1.1, *P* = 0.802)
Daily bolus insulin, %	56.4 ± 11.4	56.1 ± 11.1	−0.1 (−1.1 to 0.7, *P* = 0.629)

Table 3. AHCL time in automatization and amount of insulin per day during and after the heatwave. Data are expressed in percentages and mean ± SD. AHCL, advanced hybrid closed-loop; HW, heatwaves period; MDC, mean difference in change; CI, confidence interval; IU, international unit of insulin.

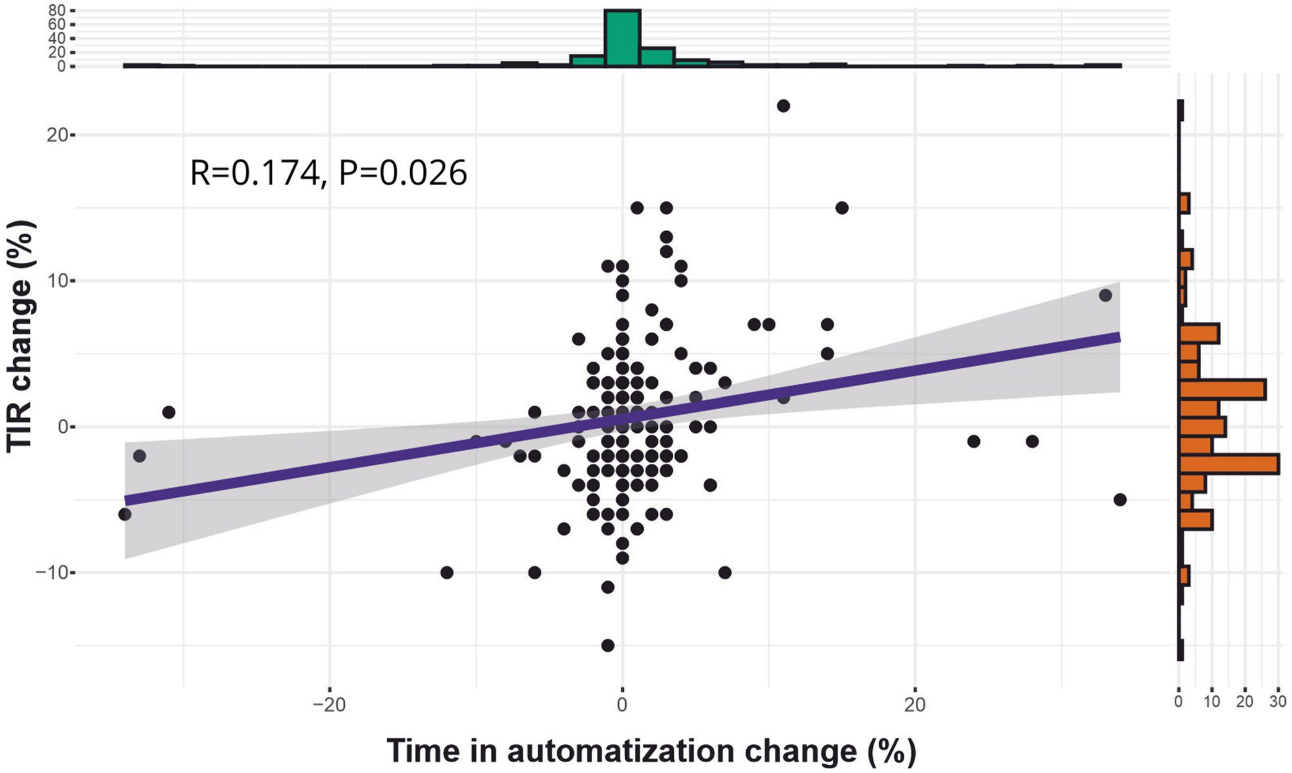

Fig. 2. Title: Correlation between change in time in range and change in percentage of time in automatization during and after August´s 2023 heatwaves period. Caption: TIR, time in range of interstitial glucose 3.9–10.0 mmol/L (70–180 mg/dL).

34.1%; *P* = 0.002). Furthermore, a direct correlation (*R* = 0.174, *P* = 0.026) between change in TIR and change in percentage of time in automatization during and after the heatwaves period was detected (Fig. 2).

Discussion

The novelty of our present results resides in the first observational description of the effect of heatwaves over glycemic control among adult T1D patients treated with AHCL systems. The main finding was that glycemic control remained stable after the end of the heatwaves period whereas correlation between TIR and time in automation could be detected.

Few studies have explored the association between ambient temperature and glucose metabolism. It seems that there is an inverse relationship between the air temperature and glycemic control[35–37]. In fact, a circannual seasonal HbA1c pattern with peak levels occurring in winter months has been described in the South of Europe[38]. However, previous data did not show this seasonal pattern in a Mediterranean population[39]. In fact, we previously observed better glycemic control among MDI treated adult T1D patients during the summer´s 2022 historic Spanish heatwave compared to the following 2-week period (a worsening of 4% in TIR), being in line with the glucose-temperature inverse relationship[28]. However, here we did not find this connection in adult T1D patients treated with AHCL systems, reinforcing the possible protective role of AHCL systems under extreme weather conditions.

AHCL technology allow for continuous adaptation of insulin requirements to glucose levels. This treatment option is superior to MDI in terms of achieved glycemic control and patient reported outcomes[17]. People living with diabetes face daily multiple disturbances that can affect their glucose levels[40–42]. As aforementioned, extreme heat can alter glycemic control in people living with patients. The data presented reflect how the glycemic control of AHCL-treated patients is not affected by heatwaves, regardless of the type of AHCL used. In fact, the limited information on observational comparative studies between AHCL devices does not show superiority between systems[21]. It seems possible that AHCL systems could allow a better adaptation to heat-induced glycemic changes during heatwaves. We only detected a greater improvement in glycaemic variability (VC) in favor of TSX2 compared to MM780G. This benefit, although statistically significant, is clinically insufficient to recommend one device over the other in extreme heat situations. The possibility of adapting the basal rate or sensitivity index by the patients in the TSX2 model could be behind these potential benefits. Unfortunately, our study did not consider the analysis of device settings as well as changes in device settings.

A greater percentage of time in automatization with AHCL system is a well-known predictor of their benefits over glycemic control[43]. Standardized recommendations for AHCL use stablish a ≥ 95% of time in automatization[44]. Here, we observed that those users fulfilling this guidance during the heatwaves period achieved better glycometric hypoglycemic index than those patients using AHCL in automatization mode < 95% of the time. This result helps to prove the benefits of AHCL system, even in extreme-temperature situations, reducing the possible impact of heatwaves on glycemic control.

The GMI is a widely used metric that provides an estimate of glycemic control based on the mean sensor glucose concentration obtained from continuous CGM data. It serves as a valuable tool for assessing long-term glycaemic trends and guiding clinical decision-making, especially in individuals using advanced technologies such as AHCL systems[45]. Importantly, no significant differences in GMI were found between the two time periods analysed, nor among the different AHCL systems employed. These findings suggest that glycaemic control remained stable over time and was consistent across the various technologies evaluated.

Extreme weather conditions can modify human behaviour. High ambient temperatures lead to a reduction in outdoor physical activity and time spent in open-air spaces[46]. Furthermore, heatwave-protective measures include avoiding unnecessary exposure to outdoor temperature[47]. Similarly, COVID-19 caused by the severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2) provoked a global lockdown with restrictive mobility measures in most of the countries[48]. Noticeably, glycemic values in people with T1D significantly improved during COVID-19 lockdown, which may be associated with positive changes in self-care and digital diabetes management[49]. There are various hypotheses as to why the glycemic values of T1D patients improved because of the lockdown. For example, this could be due to more time for T1D self-care, more regular daily lifestyle, stricter daily routine including scheduled meals, and better compliance with insulin therapy[50,51]. In fact, we previously described that T1D patients on MDI plus CGM achieved a 60.8% of TIR during the summer´s 2022 historic heatwave, a higher percentage than previously reported Autumn and Winter CGM gathered data (57.8%) in a cohort from the same population[28,52]. In the present study we observed that attained TIR through ACHL systems during the heatwaves period was even clinically superior (74.9%).

Strengths of the study include that this is the first study that shows the effect of heatwaves over glycemic control among people with diabetes treated with AHCL. This is also one of the few multicentre studies gathering direct information about AHCL use and glycemic control from a wide cohort of adult T1D patients from a public health system.

Nevertheless, there are some limitations inherent to this study. Firstly, the very design of the study limits the applicability of the results. Our data came from a restrospective study where a great amount of possible missed data could exist. We tried to reduce this bias by only selecting patients with paired glycometric data from the two compared periods. Moreover, although the number of participants was limited, this is, to our knowledge, the study with the largest sample size to date addressing this specific aspect. While our patients were recruited from a multicentre framework, all participating centres are located within the same geographical region in south-central Spain. Gathering further data from other areas affected by extreme heat could enhance the generalisability of our findings to broader settings. Secondly, we suppose that patients were geographically located in Castilla-La Mancha during the heatwave although we cannot confirm this assumption because we were not able to record their exact geographical location. However, August´s heatwaves affected almost entirely Spain and most of southern Europe, so the possibility of patients to be affected by the heatwave was high in any case even if they were not in Castilla-La Mancha at that moment. Thirdly, we could only access to three-weeks glycemic control data from the heatwaves period and its subsequent interval, whereas some studies use annual trends. Two short heatwaves took place in July´s 2023 (9th −12th and 17th −20th of July). If these two heat waves had been considered, we could have obtained a more complete picture of their effect on glycaemic control. However, both periods only add up to 8 days, and if these periods of time had been included, a total of 17 more days would have been included in the analysis, most of them without extreme temperatures, which would mean assuming an underestimation of the possible effect of heat waves on glycaemic control. Nevertheless, for the first time glycemic control during weather-related anomalies in AHCL-treated patients was analyzed and this information should be considered of interest. Fourthly, although last summer´s 2023 heatwave finished on 26th August, temperatures continued to be high for a few weeks, even higher than normal for our region and season, so observed change in glycemic control could be underestimated. Finally, glycaemic control depends on multiple factors, including the dietary patterns of people with diabetes. Daily carbohidrate intake was inversely associated with glycemic control in adults with T1D using an AHCL systems[53]. Unfortunately, we did not consider this aspect in the study design, and it would have been of interest to examine the effect of carbohydrate intake in relation to heat waves and its potential impact on glycaemic control.

In conclusion, we observed that patients with T1D treated with AHCL maintained good glycemic control during a heatwaves period, with no deterioration in the subsequent period. These findings suggest a possible role of AHCL systems in mitigating the impact of extreme temperatures on glycaemic control, although further research is needed. Effect of climate change over health will be a major issue in the following years.

Data availability

The data that support the findings of this study are not openly available due to reasons of sensitivity and privacy. Data are available from the corresponding author upon reasonable request and evaluation of all authors. Data are located in controlled access data storage at Ciudad Real General University Hospital.

Received: 29 April 2025; Accepted: 30 September 2025
Published online: 06 November 2025

References

1. Campbell-Lendrum, D., Neville, T., Schweizer, C. & Neira, M. Climate change and health: three grand challenges. *Nat. Med.* **29** (7), 1631–1638 (2023).
2. Rossati, A. Global warming and its health impact. *Int. J. Occup. Environ. Med.* **8** (1), 7–20 (2016).
3. Zandalinas, S. I., Fritschi, F. B., Mittler, R., Global & Warming Climate Change, and environmental pollution: recipe for a multifactorial stress combination disaster. *Trends Plant. Sci.* **26** (6), 588–599 (2021).
4. Corpuz J.C.G. Heatwaves, wildfires and global warming: a call to public health action. *J. Public. Health (Oxf)*. **46**(2), e326-327 (2024).
5. Ebi, K. L. et al. Hot weather and heat extremes: health risks. *Lancet Lond. Engl.* **398** (10301), 698–708 (2021).
6. The Lancet null. Heatwaves and health. *Lancet Lond. Engl.* **392** (10145), 359 (2018).
7. Xu, Z., FitzGerald, G., Guo, Y., Jalaludin, B. & Tong, S. Impact of heatwave on mortality under different heatwave definitions: A systematic review and meta-analysis. *Environ. Int.* **89–90**, 193–203 (2016).
8. Mayrhuber, E. A. S. et al. Vulnerability to heatwaves and implications for public health interventions - A scoping review. *Environ. Res.* **166**, 42–54 (2018).
9. Kovats, R. S. & Kristie, L. E. Heatwaves and public health in Europe. *Eur. J. Public. Health*. **16** (6), 592–599 (2006).
10. Xu, Z. et al. The impact of heat waves on children's health: a systematic review. *Int. J. Biometeorol.* **58** (2), 239–247 (2014).
11. Håkansson, M., Durgun, Ö. & Eriksson, K. None of Us was prepared'-Caring for vulnerable people during the heatwave in Sweden in 2018. *J. Emerg. Manag West. Mass.* **21** (4), 287–300 (2023).
12. Moon, J. The effect of the heatwave on the morbidity and mortality of diabetes patients; a meta-analysis for the era of the climate crisis. *Environ. Res.* **195**, 110762 (2021).
13. Song, X. et al. Impact of short-term exposure to extreme temperatures on diabetes mellitus morbidity and mortality? A systematic review and meta-analysis. *Environ. Sci. Pollut Res. Int.* **28** (41), 58035–58049 (2021).
14. Syed, F. Z. Type 1 diabetes mellitus. *Ann. Intern. Med.* **175** (3), ITC33–48 (2022).
15. Gregory, G. A. et al. Global incidence, prevalence, and mortality of type 1 diabetes in 2021 with projection to 2040: a modelling study. *Lancet Diabetes Endocrinol.* **10** (10), 741–760 (2022).
16. Global & national burden of diabetes. From 1990 to 2021, with projections of prevalence to 2050: a systematic analysis for the global burden of disease study 2021. *Lancet Lond. Engl.* **402** (10397), 203–234 (2023).
17. Akturk, H. K. & McKee, A. M. Emerging technologies and therapeutics for type 1 diabetes. *Endocrinol. Metab. Clin. North. Am.* **53** (1), 81–91 (2024).
18. Choudhary, P. et al. Advanced hybrid closed loop therapy versus conventional treatment in adults with type 1 diabetes (ADAPT): a randomised controlled study. *Lancet Diabetes Endocrinol.* **10** (10), 720–731 (2022).
19. Brown, S. A. et al. Six-Month Randomized, multicenter trial of Closed-Loop control in type 1 diabetes. *N Engl. J. Med.* **381** (18), 1707–1717 (2019).
20. Day-and-night. glycaemic control with closed-loop insulin delivery versus conventional insulin pump therapy in free-living adults with well controlled type 1 diabetes: an open-label, randomised, crossover study - PubMed [Internet]. [cited 2024 May 30]. Available from: https://pubmed.ncbi.nlm.nih.gov/28094136/
21. Beato-Víbora, P. I. et al. A multicenter prospective evaluation of the benefits of two advanced hybrid Closed-Loop systems in glucose control and Patient-Reported outcomes in a Real-world setting. *Diabetes Care*. **47** (2), 216–224 (2024).
22. American Diabetes Association Professional Practice Committee. 7. Diabetes Technology: Standards of Care in Diabetes-2024. Diabetes Care. ;47(Suppl 1):S126–44. (2024).
23. Luo, J. et al. The relationship between ambient temperature and fasting plasma glucose, temperature-adjusted type 2 diabetes prevalence and control rate: a series of cross-sectional studies in Guangdong Province, China. *BMC Public. Health*. **21** (1), 1534 (2021).
24. Sakura, H., Tanaka, Y. & Iwamoto, Y. Seasonal fluctuations of glycated hemoglobin levels in Japanese diabetic patients. *Diabetes Res. Clin. Pract.* **88** (1), 65–70 (2010).
25. Garde, A. H., Hansen, A. M., Skovgaard, L. T. & Christensen, J. M. Seasonal and biological variation of blood concentrations of total cholesterol, dehydroepiandrosterone sulfate, hemoglobin A(1c), IgA, prolactin, and free testosterone in healthy women. *Clin. Chem.* **46** (4), 551–559 (2000).
26. Mianowska, B. et al. [One-year variability of HbA1c in children and adolescents with type 1 diabetes - preliminary results]. *Pediatr. Endocrinol. Diabetes Metab.* **17** (1), 20–25 (2011).
27. Mianowska, B. et al. HbA(1c) levels in schoolchildren with type 1 diabetes are seasonally variable and dependent on weather conditions. *Diabetologia* **54** (4), 749–756 (2011).
28. Moreno-Fernandez, J. et al. Effect of the historic Spanish heatwave over glycemic control in adult patients with type 1 diabetes. *Sci. Total Environ.* **889**, 164045 (2023).
29. European summer. : a season of contrasting extremes | Copernicus [Internet]. [cited 2024 Jun 3]. (2023). Available from: https://climate.copernicus.eu/european-summer-2023-season-contrasting-extremes
30. Surface air temperature for August. 2023 | Copernicus [Internet]. [cited 2024 Jun 3]. Available from: https://climate.copernicus.eu/surface-air-temperature-august-2023
31. https://www.aemet.es/documentos/es/noticias/2023/avance_climatico_agosto_2023.pdf [Internet]. [cited 2024 Jun 3]. Available from: https://www.aemet.es/documentos/es/noticias/2023/avance_climatico_agosto_2023.pdf
32. https://www.aemet.es/documentos/es/serviciosclimaticos/vigilancia_clima/resumenes_climat/ccaa/castilla-la-mancha/avance-climat_clm_ago_2023.pdf [Internet]. [cited 2024 Jun 3]. Available from: https://www.aemet.es/documentos/es/serviciosclimaticos/vigilancia_clima/resumenes_climat/ccaa/castilla-la-mancha/avance-climat_clm_ago_2023.pdf
33. Beck, R. W. et al. The relationships between time in Range, hyperglycemia Metrics, and HbA1c. *J. Diabetes Sci. Technol.* **13** (4), 614–626 (2019).
34. Battelino, T. et al. Clinical targets for continuous glucose monitoring data interpretation: recommendations from the international consensus on time in range. *Diabetes Care*. **42** (8), 1593–1603 (2019).
35. Tien, K. J. et al. The impact of ambient temperature on HbA1c in Taiwanese type 2 diabetic patients: the most vulnerable subgroup. *J. Formos. Med. Assoc. Taiwan. Yi Zhi*. **115** (5), 343–349 (2016).
36. He, M. Z. et al. Intermediate- and long-term associations between air pollution and ambient temperature and glycated hemoglobin levels in women of child bearing age. *Environ. Int.* **165**, 107298 (2022).
37. Tseng, C. L. et al. Seasonal patterns in monthly hemoglobin A1c values. *Am. J. Epidemiol.* **161** (6), 565–574 (2005).

38. Pereira, M. T. R., Lira, P., Bacelar, D., Oliveira, C. & de Carvalho, J. C. Seasonal variation of haemoglobin A1c in a Portuguese adult population. *Arch. Endocrinol. Metab.* **59** (3), 231–235 (2015).
39. Gomez-Huelgas, R. et al. Seasonal variability of glycated hemoglobin in a diabetic population from Southern Europe. *J. Diabetes Complications*. **27** (6), 618–620 (2013).
40. Silva, F. M. et al. Fiber intake and glycemic control in patients with type 2 diabetes mellitus: a systematic review with meta-analysis of randomized controlled trials. *Nutr. Rev.* **71** (12), 790–801 (2013).
41. Colberg, S. R. et al. Physical Activity/Exercise and diabetes: A position statement of the American diabetes association. *Diabetes Care*. **39** (11), 2065–2079 (2016).
42. McCowen, K. C., Malhotra, A. & Bistrian, B. R. Stress-induced hyperglycemia. *Crit. Care Clin.* **17** (1), 107–124 (2001).
43. Passanisi, S. et al. Sustained effectiveness of an advanced hybrid Closed-Loop system in a cohort of children and adolescents with type 1 diabetes: A 1-Year Real-World study. *Diabetes Care*. **47** (6), 1084–1091 (2024).
44. Chico, A., Moreno-Fernández, J., Fernández-García, D. & Solá, E. The hybrid Closed-Loop system tandem t:slim X2™ with Control-IQ technology: expert recommendations for better management and optimization. *Diabetes Ther.* **15** (1), 281–295 (2024).
45. Bergenstal, R. M. et al. Glucose management indicator (GMI): A new term for estimating A1C from continuous glucose monitoring. *Diabetes Care*. **41** (11), 2275–2280 (2018).
46. Tucker, P. & Gilliland, J. The effect of season and weather on physical activity: a systematic review. *Public. Health*. **121** (12), 909–922 (2007).
47. van Loenhout, J. A. F. et al. Heatwave-protective knowledge and behaviour among urban populations: a multi-country study in Tunisia, Georgia and Israel. *BMC Public. Health*. **21** (1), 834 (2021).
48. Onyeaka, H., Anumudu, C. K., Al-Sharify, Z. T., Egele-Godswill, E. & Mbaegbu, P. COVID-19 pandemic: A review of the global lockdown and its far-reaching effects. *Sci. Prog.* **104** (2), 368504211019854 (2021).
49. Eberle, C. & Stichling, S. Impact of COVID-19 lockdown on glycemic control in patients with type 1 and type 2 diabetes mellitus: a systematic review. *Diabetol. Metab. Syndr.* **13** (1), 95 (2021).
50. Mesa, A. et al. The impact of strict COVID-19 lockdown in Spain on glycemic profiles in patients with type 1 diabetes prone to hypoglycemia using standalone continuous glucose monitoring. *Diabetes Res. Clin. Pract.* **167**, 108354 (2020).
51. Capaldo, B. et al. Blood glucose control during lockdown for COVID-19: CGM metrics in Italian adults with type 1 diabetes. *Diabetes Care*. **43** (8), e88–e89 (2020).
52. Moreno-Fernandez, J. et al. To evaluate the use and clinical effect of intermittently scanned continuous glucose monitoring in adults with type 1 diabetes: Results of a multicentre study. Endocrinol Diabetes Nutr [Internet]. 2023 Feb 21 [cited 2023 Apr 4]; Available from: https://www.sciencedirect.com/science/article/pii/S2530016423000174
53. Lehmann, V. et al. Lower daily carbohydrate intake is associated with improved glycemic control in adults with type 1 diabetes using a hybrid Closed-Loop system. *Diabetes Care*. **43** (12), 3102–3105 (2020).

Acknowledgements
The authors are very grateful to Castilla-La Mancha Endocrine, Diabetes and Nutrition Society (SCAMEND) for their support in promoting this study.

Author contributions
JMF designed the study. JMF wrote the study protocol and published it in a public registry. LMLJ, IQL, JGL, AMM, EMV, SHA, AMA, DES, IGM, MGM, ARGG, MRA, and JMF, gathered the data. JRMR contributed to the interpretation of the results. JMF took the lead in writing the manuscript. JRMR performed statistical regression analysis and reviewed statistical analysis. All authors provided critical feedback and helped shape the final manuscript.

Declarations

Competing interests
The authors declare no competing interests.

Additional information
Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-025-22666-z.

Correspondence and requests for materials should be addressed to J.M.-F.