Can J Diabetes 43 (2019) 27–33

Contents lists available at ScienceDirect

Canadian Journal of Diabetes

journal homepage: www.canadianjournalofdiabetes.com

Original Research

Perceptions by Adult Patients With Type 1 and 2 Diabetes of Current and Advanced Technologies of Blood Glucose Monitoring: A Prospective Study

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Key Messages

- Self-monitoring of blood glucose by patients with diabetes achieves optimal glucose control and reduces complications.
- Advanced blood glucose monitoring technologies, such as wristbands, contact lenses, earlobe sensors, saliva analyzers and tattoos, can improve adherence to glucose monitoring.
- Patient factors, such as gender, age and ethnicity, influence device selection.

A R T I C L E I N F O

Article history:
Received 23 November 2017
Accepted 8 February 2018

Keywords:
complications
diabetes mellitus
monitoring
patient factors
technology

Mots clés :
complications
diabète sucré
surveillance
facteurs du patient
technologie

A B S T R A C T

Objective: Intensive self-monitoring of blood glucose levels by patients with diabetes achieves optimal glucose control, hence reducing the likelihood of complications.
Methods: This is a prospective, cross-sectional study targeting adults with diabetes through community pharmacies and patient groups in Central and West London over a period of 10 weeks.
Results: In all, 195 adults with diabetes were included in the analysis of the results. When monitoring adherence was examined, 43.4% (n=33/76) of participants with type 1 diabetes reported that their health care professionals had asked them to monitor their blood glucose levels between 3 and 4 times per day; however, 10% of this group was not following their health-care professionals' directions. Participants with type 2 diabetes were asked the same question; 42.9% (n=51/119) were asked to monitor their blood glucose between 3 and 4 times a day, but only 2.5% (n=3/119) were following their health-care professionals' directions. When questioned about their reasons for poor adherence, the cohort indicated that it was due to the painful (29.2%, n=57/195), uncomfortable (33.8%, n=66/195) or inconvenient (36.9%, n=72/195) nature of testing. In addition, 75.3% (n=147/195) of the participants expressed their desire for a noninvasive monitoring device, and 74.3% (n=145/195) said they would be satisfied to use one of the preselected advanced technologies to monitor their blood glucose levels.
Conclusions: The favoured advanced technology, selected by 49.7% (n=97/195) of participants, was the wristband. Statistical significance was seen between the type of diabetes and the device selected; patients with type 1 diabetes preferred contact lenses ($p<0.05$) and tattoos ($p<0.0001$), whereas participants with type 2 diabetes preferred earlobe sensors ($p<0.0001$) and saliva analyzers ($p<0.0001$). Participants' gender, age and ethnicity also influenced device selection.

R É S U M É

Objectifs : Chez les patients diabétiques, l'auto-surveillance des concentrations de la glycémie leur permet d'atteindre une régulation optimale de leur glycémie et, par conséquent, de réduire les risques de complications.
Méthodes : Il s'agit d'une étude transversale prospective d'une durée de 10 semaines sur les adultes diabétiques des pharmacies communautaires et des groupes de patients de Central London et de West London.

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https://doi.org/10.1016/j.jcjd.2018.02.005

Résultats : En tout, 195 adultes diabétiques faisaient partie de l'analyse des résultats. Lorsque nous avons examiné l'observance de la surveillance glycémique, 43,4 % (n=33/76 des participants atteints de diabète de type 1 rapportaient que leur professionnel de la santé leur avait demandé de surveiller les concentrations de leur glycémie entre 3 et 4 fois par jour. Toutefois, 10 % de ce groupe n'ont pas suivi les directives de leur professionnel de la santé. Les participants atteints du diabète de type 2 se sont fait poser la même question; 42,9 % (n=51/119) se sont fait demander de surveiller leur glycémie entre 3 et 4 fois par jour, mais seulement 2,5 % (n=3/119) ont suivi les directives de leur professionnel de la santé. Lorsque nous leur avons demandé les raisons de leur faible observance, la cohorte a mentionné l'aspect douloureux (29,2 %, n=57/195), gênant (33,8 %, n=66/195) ou non pratique du test (36,9 %, n=72/195). De plus, 75,3 % (n=147/195) des participants ont exprimé qu'ils souhaitaient utiliser une méthode qui permet de déterminer de manière non effractive la glycémie, et (n=145/195) ont dit qu'ils seraient contents d'utiliser l'une des technologies avancées présélectionnées pour surveiller les concentrations de leur glycémie.
Conclusions : La technologie avancée privilégiée et choisie par 49,7 % (n=97/195) des participants était le bracelet. Nous avons observé une signification statistique entre le type de diabète et la méthode choisie : les patients atteints du diabète de type 1 préféraient les lentilles de contact (p<0,05) et les tatouages (p<0,0001), alors que les participants atteints du diabète de type 2 préféraient les capteurs fixés aux lobes des oreilles (p<0,0001) et les analyseurs de salive (p<0,0001). Le sexe, l'âge et l'origine ethnique des participants influençaient également le choix de la méthode.

Introduction

Diabetes mellitus is described by the World Health Organization as a global epidemic, with 422 million adults currently living with this chronic condition (1). It is anticipated that this number will rise steeply to 552 million adults by 2030 (1). In the United Kingdom (UK), diabetes mellitus costs the National Health Service £10 billion per annum, with 80% of this figure allocated to treating complications associated with the condition (2).

Individuals with diabetes can experience acute and chronic complications as a result of the condition. Acute complications of diabetes include episodes of hyperglycemia and hypoglycemia, when blood glucose levels rise above 10 mmol/L or decrease below 4 mmol/L, respectively (3). Chronic complications experienced by patients with diabetes range from heart attacks and strokes to retinopathy, renal failure, neuropathy and lower-limb amputations (4). To minimize the likelihood of complications, patients are encouraged to self-monitor their blood glucose levels in order to achieve optimum control (5). This advice has been supported by the findings from many studies that have explored the relationship between blood glucose control and the incidence of complications related to diabetes. Research conducted by Martin et al (6) investigated whether there was a relationship between self-monitoring of blood glucose (SMBG) and disease-related morbidity and mortality, concluding that SMBG was associated with a reduction in complications stemming from diabetes. In addition, the results from a 20-year, multicentre study conducted by Stratton et al (7) showed that complications associated with type 2 diabetes could be significantly reduced by improving blood glucose control.

Type 1 diabetes results from the autoimmune destruction of insulin-producing pancreatic beta cells (8), whereas type 2 diabetes occurs due to an alteration in the balance between insulin sensitivity and insulin secretion (9). At present, the National Institute of Clinical Excellence (NICE) recommends that patients with type 1 diabetes should monitor their blood glucose levels at least 4 times per day and should aim for glycated hemoglobin (A1C) levels below 48 mmol/mol (6.5%) (10). For patients with type 2 diabetes, NICE specifies an A1C target between 48 mmol/mol (6.5%) and 53 mmol/mol (7.0%), although recent monitoring guidelines have changed (10). The target for those with type 2 diabetes varies depending on individuals' management plans and whether the patients take antihyperglycemic agents, which may potentiate hypoglycemia. Research by Mindera et al (11) revealed that when participants with type 1 diabetes (n=150) increased the number of SMBG tests per day, it resulted in A1C level reduction. Their research showed that participants who practiced SMBG ≤4 times per day reported a reduction of –0.19% in A1C levels with each additional SMBG performed (p<0.001). Similarly, a study conducted by Zieglar et al (12) revealed that patients who monitored ≤5 times a day experienced a –0.2% decrease in A1C levels (p<0.001) with each additional measurement of SMBG performed. Despite these findings and recommendations and the emphasis put on self-monitoring by healthcare professionals in the UK, research by Wagner et al (13) has shown that the level of nonadherence by patients with diabetes remains high, concluding that less invasive SMBG technologies could enhance monitoring adherence.

Over the past 4 decades there has been a transition from measuring glucose concentrations using urine samples to the development of SMBG meters (14) and reagent strip systems (14). More than 60 glucose monitoring devices/strips are available in the UK, but only a few are offered through the National Health Service. As the metres have evolved, they have become smaller, more varied in design and more advanced in their data management and connectivity functions (14). To address some of the issues associated with SMBG adherence, several advanced technologies are currently undergoing development. For this research, 6 advanced SMBG technologies were selected, including contact lens sensors that measure ocular glucose concentrations (15), smart tattoos that change colour accordingly (16) and wristbands that function via reverse iontophoresis (17). In addition to the aforementioned technologies, saliva glucose analyzers (18), skin sensors (19) and earlobe sensors, which detect glucose concentrations via ultrasound (20), were also chosen.

This study aimed to investigate the perceptions of patients with diabetes of current and advanced blood glucose monitoring technologies in addition to exploring patients' expectations in relation to future SMBG devices.

Methods

A prospective, cross-sectional, descriptive study was undertaken in Central and West London, UK. These areas were selected because London has an ethnically diverse population, and 475,000 people are currently living with diabetes (21). A questionnaire was designated as the data-collection tool for this study. It was designed to investigate participants' perceptions of current and advanced blood glucose monitoring devices in addition to investigating factors that influence device acceptability. The questionnaires were anonymously distributed in community pharmacies and to groups of patients with diabetes in Central and West London. Each participant was supplied with a copy of the questionnaire, a participant information sheet and an additional printed sheet containing information regarding 6 preselected advanced technology devices. The participants returned the questionnaires upon completion; however, they were able to retain the information sheets for future reference.

The questionnaire was composed of a mixture of open-ended and closed-ended questions, producing a total of 27 questions, which were separated into the following 6 subsections: health perceptions (including several questions about diabetes complications), health-care professionals, monitoring/past, monitoring/present, new technologies and demographics. Our questions about monitoring frequency were adapted from questions previously used by Barnard et al (22). One of the questions in the health-care professional section utilized a 5-point Likert scale to assess participants' perceptions of and attitudes toward their health-care professionals. Similarly, there was another question that utilized a 5-point Likert scale in the new technologies section. In the latter, participants were asked to rate a number of potential design features for future blood glucose monitoring technology. There were also 2 questions within the monitoring/present section that utilized a 10-point Likert scale to ask participants to describe how happy they were with their current blood glucose levels and current monitoring methods. By using Likert-scale questions, participants were able to select the most appropriate option that aligned with their opinions. An open-ended question was used to ask the patients whether they would use the new monitoring devices if available on the market and why they felt the new technology would be better than the current methods available. Also, participants were asked to identify any additional features they would like to see in a glucose monitoring device. Participants were not asked to provide any identifiable information.

Prior to commencing this research, a pilot study was conducted that involved 14 participants with diabetes. This sample size equated to 5% of our required sample size for the main study, and it had a ratio reflective of type 1 and type 2 diabetes. Participants were selected at random to participate in the pilot study, and their input was used for face and content validation of the questionnaire. Findings from the pilot study suggested that the survey structure was highly welcomed, and no adjustments were necessary. To minimize study bias, individuals who participated in the pilot study were excluded from the main study.

To determine the sample size required for this study, a power calculation was carried out. Based on the prevalence of diabetes of 475,000 across London, the minimum sample size at 90% confidence interval (CI) and 5% margin of error was 271. With a prevalence of 10% of type 1 diabetes and 90% of type 2 diabetes in the UK, at least 27 patients with type 1 diabetes had to be be recruited (23), and at least 244 patients type 2 diabetes had to be recruited to achieve a CI of 90%.

The inclusion criteria required participants to have diabetes, to have monitored their glucose levels previously, to be 18 years of age or older and to be able to speak and understand English in order to provide consent. Participants were excluded if they were younger than 18 years of age, did not monitor their blood glucose levels, were unable to understand written or spoken English, had cognitive impairment or were unwilling to participate. Participants were supplied with an information sheet that clearly explained that their consent would be implied if they were to complete the approved questionnaire; however, participants were informed that they could withdraw from the study at any point. In addition, patients were provided with an information sheet about the monitoring device that was written in lay terms and described how to use the device, how the device works in terms of monitoring glucose and whether it was a continuous or noncontinuous glucose monitoring device. Participants were advised to speak to the pharmacist or the researcher or to contact the research team if they had any further queries.

The study was conducted over a 10-week period from January 2015 to March 2015. The completed questionnaires were collected immediately if the researcher was present or were left at the community pharmacies to be collected at the end of the data-collection period. All collected questionnaires were checked for meeting the inclusion criteria before analysis. The collected data were tabulated and analyzed using Microsoft (Redmond, Washington, United States) Excel. A chi-square inferential test was used to identify correlations between demographics and the responses provided. The level of statistical significance was set at $p<0.05$. The questionnaire was approved by the Faculty of Science, Engineering and Computing Ethics Committee at Kingston University.

Results

A total of 377 questionnaires were distributed, and 211 were returned. However, 16 were excluded because 4 participants did not have diabetes and 12 never monitored their glucose levels, so they did not fit the inclusion criteria. Consequently, a 51.7% (195/377) response rate was achieved. The demographic details of the cohort are presented in Table 1. Although the sample size is under-representative of type 2 diabetes, it is over-representative of type 1 diabetes; 76 patients with type 1 diabetes were recruited.

Incidence of diabetes complications

This study identified that 42.1% (n=82/195) of the cohort had experienced complications resulting from diabetes. The following conditions were defined in the questionnaire as complications: retinopathy, nephropathy, neuropathy, cardiovascular conditions and limb amputations. In addition, the results showed that 28.2% (n=55/195) of the cohort who had suffered from complications had lived with diabetes for more than 10 years (Figure 1). These findings demonstrate a positive correlation between time elapsed since diagnosis and the incidence of complications ($r=0.9$).

Participants were asked about their blood glucose control and their experiences of hyperglycemic episodes (blood glucose levels of 10 mmol/L or higher) to determine whether complications were associated with poor control. Irrespective of diabetes type, all participants reported A1C values higher than those recommended by NICE. The results showed that 87.6% (n=171/195) of the cohort had experienced hyperglycemic episodes. In addition, the results also showed that increased frequencies of hyperglycemic events were associated with poor diabetes control ($r=0.9$).

Frequency of blood glucose monitoring

The cohort members were asked how often they had been told to monitor their blood glucose levels, and these data were compared to their current monitoring frequencies, enabling participants' adherence to be assessed. The data showed that 43.4% (n=33/76) of participants with type 1 diabetes were asked by their health-care team to monitor their blood glucose levels between 3 and 4

Table 1
Demographics of eligible study participants

Parameter	Type 1 diabetes	Type 2 diabetes
Diabetes type %	38.9 (n=76)	61.1 (n=119)
Modal age range	>60 years	>60 years
Gender (male/female) %	56.6 (n=43) / 43.4 (n=33)	63.8 (n=76) / 36.1 (n=43)
Ethnicity (White/Black/Asian/other/prefer not to say) %	35.5/5.3/47.4/7.9/3.9	26.9/5.0/41.2/25.2/1.7

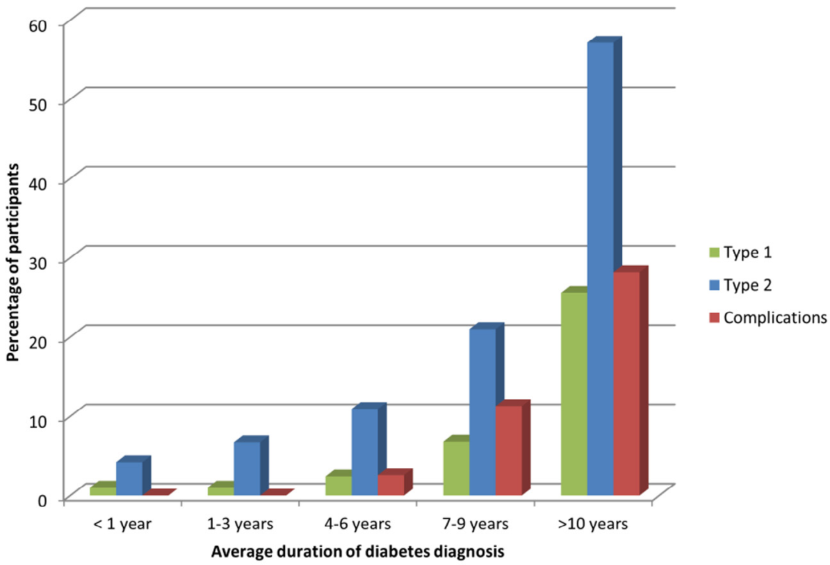

Figure 1. The number of diabetes complications and average duration of diagnosis in the study's population (n=195).

times a day. However, a tenth of those did not follow this recommendation; only 34.2% of the participants indicated that they followed their recommended monitoring regimen. On the other hand, 42.9% (n=51/119) of participants with type 2 diabetes were asked to monitor their glucose levels between 3 and 4 times per day, and only 2.5% (n=3/119) were following this monitoring guidance. For participants with type 2 diabetes, increasing the recommended number of glucose monitoring times per day was associated with a significant decline in adherence.

Current technology usage and perceptions

When the participants were asked about their current methods of monitoring glucose levels, 77.8% (n=158/195) reported using a finger-prick test; 6.6% (n=13/195) measured glucose levels using urine samples, and 2.0% (n=4/195) used a continuous blood glucose monitor (Figure 2A).

Using a Likert scale (0 to 10), participants were asked to ascribe a quantitative value to their level of satisfaction with their current blood glucose monitoring equipment. A value of 0 was given by participants who were unhappy with their current equipment, while a value of 10 was given by participants who were very happy with their current equipment. Overall, 60.0% (n=117/195) of participants rated their satisfaction level as ≤5, showing that a significant number of the cohort were dissatisfied with the technology being used. Reasons given for the ratings provided were that the monitoring device was uncomfortable (33.8% [n=66/195]); inconvenient (36.9% [n=72/195]); or painful (29.2% [n=57/195]) (Figure 2B).

Desired features of future blood glucose monitoring technology

The cohort was asked to rate a number of potential design features for future blood glucose monitoring technology by using a Likert scale, with 1 being the lowest and 5 being the highest rating, depending upon the perceived level of importance. The preferred choice, reported by 49.2% (n=96/195) of the participants, was the easy-to-use design feature; 49.2% (n=96/195) required the technology to be painless, thus improving the overall comfort level. The cohort ascribed low values to several design features, including style (41.0%) and voice control (33.8%), suggesting that these features were perceived as being less important when considering the future design of blood glucose monitoring technologies. More than three-quarters (75.3%) of the participants provided details about their desire for noninvasive monitoring technologies. In addition, more than one-half the participants (52.8%) preferred noncontinuous glucose monitoring in comparison to CGM. The results showed a statistical significance ($p<0.0001$) between the type of monitoring preference and the daily frequency of diabetes testing; hence, those who tested more frequently preferred CGM.

Perceptions of advanced blood glucose monitoring technology

Participants were shown 6 potential blood glucose monitoring devices; 74.3% (n=145/195) of the cohort said they would be happy using the new devices, which may be released in the near future. Overall, 49.7% (n=97/195) of participants preferred the wristband option (Figure 3A). There was no statistical significance ($p>0.05$) between the selection of wristbands and type of diabetes. However, there was statistical significance between type of diabetes and other device preferences. Participants with type 1 diabetes preferred contact lenses ($p<0.05$) and tattoos ($p<0.0001$), whereas participants with type 2 diabetes showed a statistically significant preference for earlobe sensors ($p<0.0001$) and saliva analyzers ($p<0.0001$).

The study considered whether gender had an impact on device selection (Figure 3B). Males showed a statistically significant preference for the wristband ($p<0.05$). However, females showed a statistically significant preference for contact lenses ($p<0.01$) and tattoos ($p<0.001$).

Additionally, the influence of age on device selection was investigated. The results in Figure 3C, show that tattoos were the preferred device choice for 47.2% (n=17/36) of participants younger than 30 years of age. However, tattoos were not selected by any participant older than 30 years of age. Participants' preference for saliva analyzers varied across the age groups; 53.7% (n=29/54) of participants between 50 and 59 years of age selected this device as their first choice, whereas saliva analyzers were not selected by any participant between 21 and 29 years of age. When considering participants who were 60 years of age or older, 73.8% (n=65/88) preferred the wristband option (Figure 3C).

A difference in device selection according to participants' ethnicities was also observed (Figure 3D). All ethnic groups selected earlobe sensors; however, this device was particularly popular among

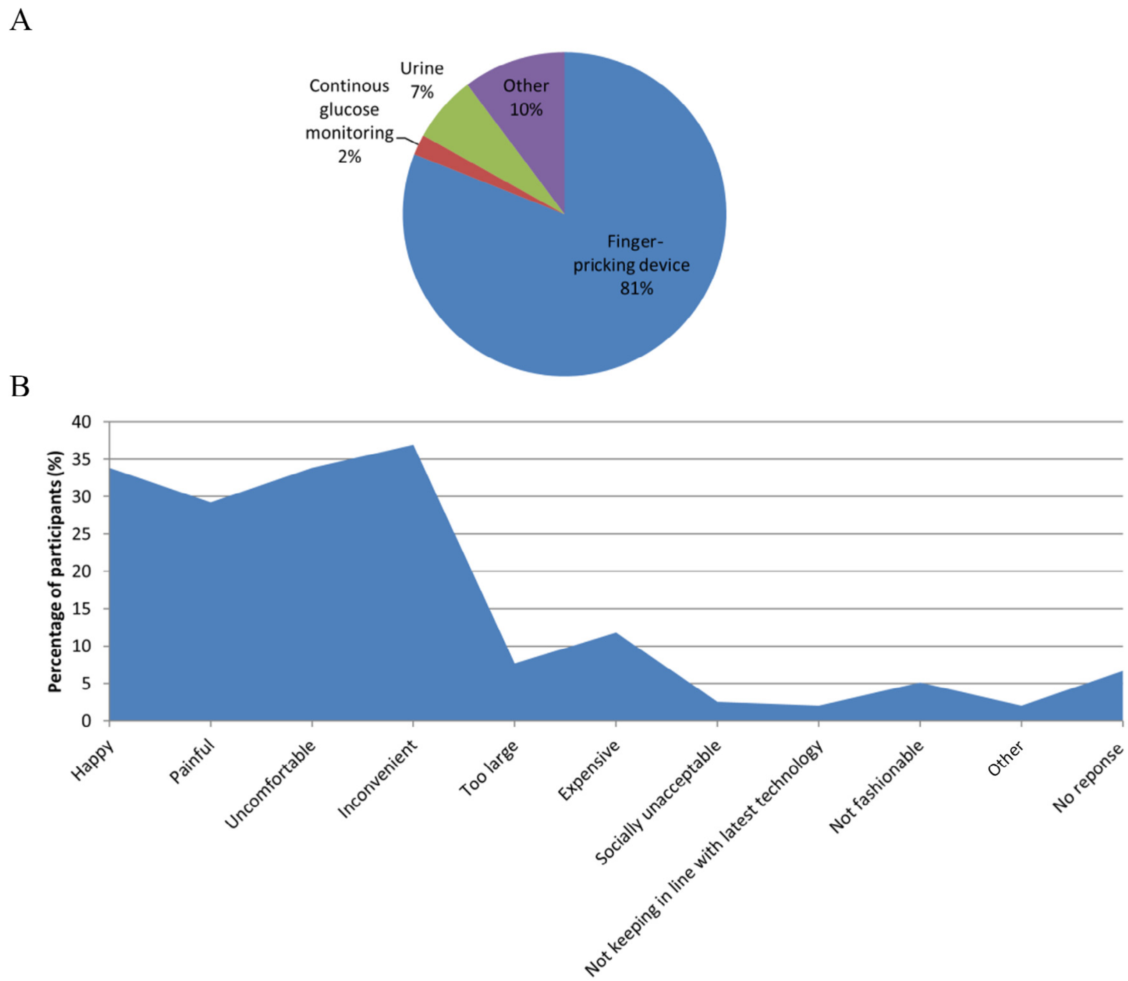

Figure 2. Current methods used to monitor glucose levels by participants (A) and their perceptions of the selected glucose-monitoring techniques (B) (n=195).

black participants. Interestingly, smart tattoos, saliva analyzers and skin sensors were selected by all ethnicities except black participants.

Discussion

It is widely recognized that elevated blood glucose levels, poor monitoring adherence and extensive disease duration are all contributory factors to the development of the complications of diabetes. This study has identified that all participants, irrespective of their diabetes type, failed to achieve A1C values within the target range, as specified by NICE, and 42.1% of participants experienced complications.

In this study, participants were asked about the recommended frequency of blood glucose level monitoring and to compare it to their actual monitoring frequency. This enabled participant adherence to be assessed. There was a noticeably lower participant adherence level compared to that recommended by health-care teams. Nonadherence to monitoring can lead to disease related to complications. The research conducted by Martin et al (6) investigated the incidence of disease-related complications and mortality in people with diabetes. Their findings showed that the incidence of complications was lower in the group who regularly monitored their blood glucose levels in comparison to the group who failed to monitor. Rodríguez-Gutiérrez (24) acknowledged the wealth of evidence surrounding blood glucose monitoring in diabetes; however, the study also reported discordance in the literature surrounding frequent monitoring and the reduction in complications of diabetes. Further research into the association between frequent monitoring and complications of diabetes is required.

This study aimed to investigate the perceptions by patients with diabetes of current and advanced blood glucose monitoring technologies. When participants were questioned about the reasons for their poor adherence to monitoring, most of the cohort was relatively dissatisfied with their current monitoring technologies, citing their reasons for dissatisfaction as pain, inconvenience and discomfort. These findings have been supported by qualitative research conducted by Ong et al (25), which recognized that the uptake of self-monitoring is low in many countries, and they reported that the factors influencing uptake include the pain, inconvenience and complexity of currently available SMBG equipment.

Self-monitoring is an integral part of diabetes management, and it is necessary for achieving optimum blood glucose control. However, a review by Benjamin (26) recognized that the true potential of blood glucose monitoring has not yet been reached, thus providing support for new, innovative technologies to improve monitoring adherence. This study differentiates itself from previous research by asking participants about their attitudes toward and perceptions of advanced technologies while considering the factors that may influence their choices when selecting a monitoring device. When questioned, almost three-quarters of the cohort were prepared to try a less invasive advanced technology to monitor their blood glucose levels. These findings are supported by research conducted by Wagner et al (13), which showed that more than

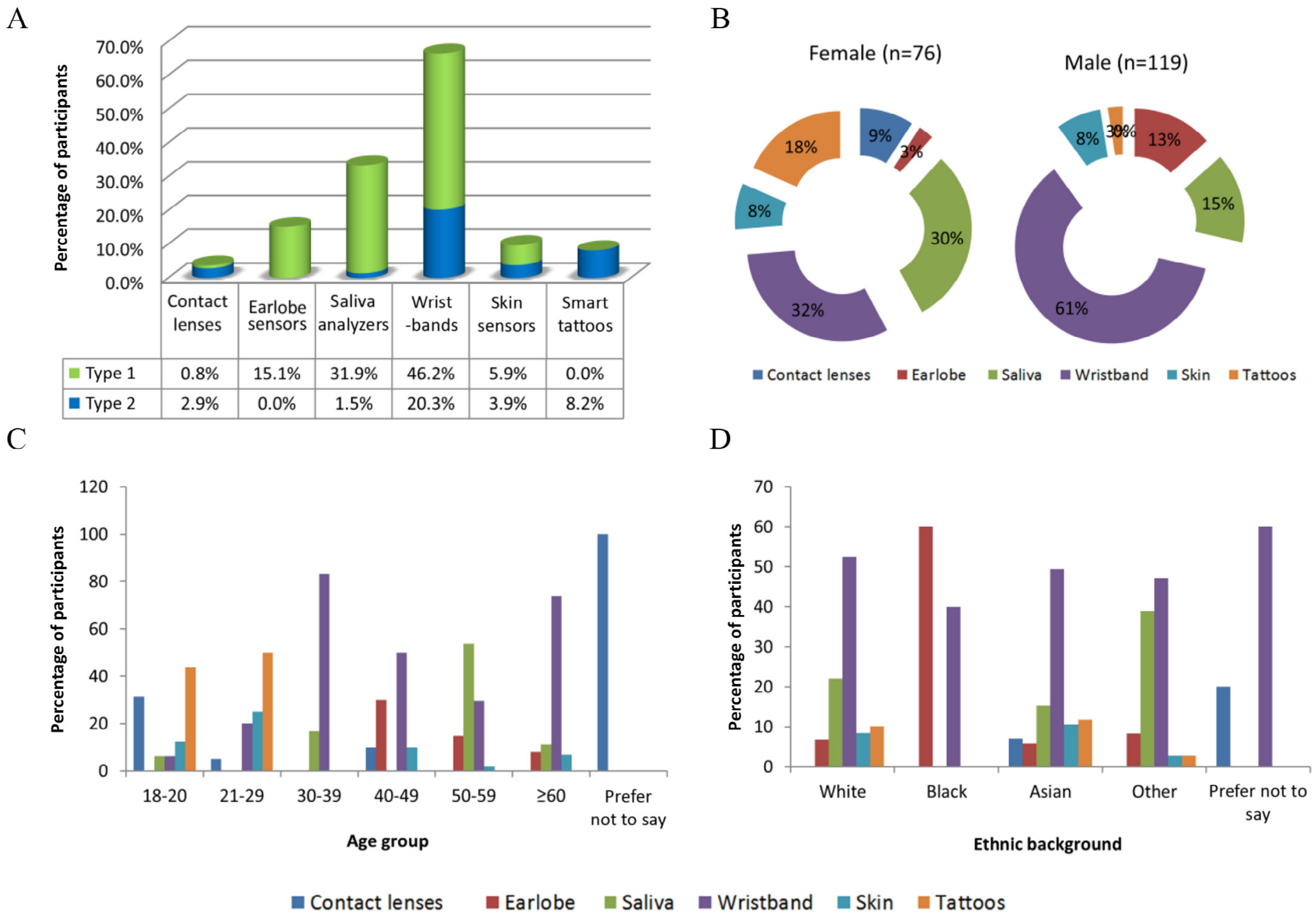

Figure 3. Patients' preferred choice of advanced glucose monitoring technologies (A) and patients' choice of the selected monitoring devices by gender (B), age group (C) and ethnicity (D) (n=195).

two-thirds of their study's participants reported avoiding blood glucose monitoring because of the invasive nature of testing. It was also reported that invasive technology was associated with increased levels of anxiety and suggested that this was another serious barrier to self-monitoring of blood glucose levels (13). The psychological impact of SMBG is beyond the scope of this study; however, the number of noncompliant participants was similar in both studies.

Participants were asked about desired design features for advanced technology devices. They said that an easy-to-use, pain-free and comfortable product was most important to them, whereas design features such as style and voice control were considered less important. This study aimed to investigate which factors influenced the acceptability of advanced technology devices. Prior to commencing this study, we selected 6 advanced technologies that have been proposed for future development. More than three-quarters of the participants were prepared to try an advanced technology monitoring device. The preferred device, selected by 49.7% of participants, was the wristband. There was no statistical significance between the selection of wristbands and type of diabetes. However, there was statistical significance between the type of diabetes and other device preferences. Participants with type 1 diabetes preferred contact lenses and smart tattoos, whereas participants with type 2 diabetes preferred earlobe sensors and saliva analyzers. Looking closely at the participants with type 1 diabetes who opted for tattoos, we found that all the participants were younger than 29 years of age, and 82.3% of them were female (n=14/17).

The results from this study also show that gender can influence the acceptability of advanced technology devices. Statistical significance was detected between males and their preference for the wristbands, whereas females showed a statistical significance in their preference for contact lenses and smart tattoos. The results fall in line with the previous findings by Kelvin et al (27), who surveyed 1,850 people between 12 and 55 years of age. It was concluded that young, highly educated females tend to wear contact lenses more often for cosmetic reasons. Tattoos are perceived by females as a body art; nonetheless, previous studies did not report any significant difference between gender and the prevalence of tattoos (28,29).

Furthermore, the influence of age and ethnicity on device acceptability was also investigated. The results showed that participants under 30 years of age preferred smart tattoos, whereas participants who were 60 years of age or older preferred wristbands. Participants' preference for the other devices varied across the age ranges, with saliva analyzers being the most popular type of monitoring device in participants between 50 and 59 years of age. When considering the influence of ethnicity on device selection, earlobe sensors were the most popular choice by black participants, whereas smart tattoos, saliva analyzers and skin sensors were selected by all ethnicities apart from black participants. Thus, this study shows that patients with diabetes are open to trying new monitoring devices and that patients' demographics will affect their selection of future glucose monitoring devices.

This study has some limitations. First, the sample size for this study was relatively small, and participants were selected from an urban community in Greater London, which may limit the generalizability of our results. Also, participants' choices of monitoring devices may have been influenced by confounding factors; however, we were not able to account for confounding factors in our statistical analysis. Further work with a larger sample size is required to enable a clear conclusion concerning variables influencing monitoring device preference.

Conclusions

This research, despite the small sample size, has provided a remarkable insight into patients' perceptions of advanced technologies for blood glucose monitoring. The results showed that a significant proportion of participants would be willing to try an advanced technology to monitor their blood glucose levels. Additionally, this research has also identified patient factors, such as type of diabetes, gender, age and ethnicity, that may be influential in device selection. For instance, participants with type 1 diabetes preferred contact lenses and tattoos, whereas participants with type 2 diabetes opted for earlobe sensors and saliva analyzers. The results from this study could be used to inform the future design and manufacturing of monitoring devices.

These initial findings call for further research to be conducted in order to identify other factors that may influence the acceptability of advanced technology devices. This research considered 6 different advanced technology devices, so further work should consider alternative monitoring devices.

Author Disclosures

Conflicts of interest: None.

Author Contributions

RK and AE conceived and designed the study; NA-T collected the results; NA-T and NS analyzed the data; NS, RK and AE wrote the manuscript.

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