HYPOalert: Designing Mobile Technology for Hypoglycemic Detection and Monitoring—Based on Human Breath

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ABSTRACT

Hypoglycemia (HYPO) is characterized by low blood glucose (BG)—leading to complications such as sweating, weakness, passing-out, coma, and even death. Effective HYPO management is required to avoid complications and to increase quality of life. Recently, a noninvasive smart breathing sensor was developed for detection of HYPO in human breath (HYPOalert). The device has the ability to deliver data (via Bluetooth) to a mobile application—with the intent to support Type 1 and 2 diabetics with the self-management of their hypoglycemia. This paper presents the first two (prototype) design iterations of research and testing of HYPOalert. Twelve Type 1 and 2 diabetics were interviewed to deduce user requirements and to understand their perception and level of interest in the proposed mobile system. Outcomes informed a human-centered design process of the interactive prototype, currently under final testing. Results were positive—showing that users were very interested in HYPOalert's use of visualization, as well as its HYPO monitoring and alert system that supports diabetes patients' healthy lifestyle management.

Author Keywords

Hypoglycemia; Diabetes, Breathing sensor; Mobile health; Interface; Data visualization

ACM Classification Keywords

H: Information Systems→H.5: INFORMATION INTERFACES AND PRESENTATION (e.g., HCI)→H.5.2: User Interfaces

INTRODUCTION

In 2012, the American Diabetes Association stated that one-tenth of all health care dollars were spent on costs directly attributable to diabetes. The total cost—$245 billion. More importantly, over half of these costs were directly or indirectly resulting from poor maintenance of blood glucose (BG) levels [3]. Diabetes has two classifications with accompanying medical conditions—depending upon the glucose level. Type 1 diabetes (T1D) is characterized by deficient insulin production and requires external insulin administration every day, and Type 2 diabetes (T2D) is an outcome of the body's ineffective usage of insulin [6]. The direct healthcare costs per-person for Type 1 diabetes (T1D) are 50% higher than for Type 2 diabetes (T2D) [1]. According to recent data, there are more than 970K people living in the US who have T1D, with projections that by 2050, more than half of these will be children. Diabetes mellitus is a chronic disease caused by the body's insufficient production of insulin. As a hormone, insulin regulates BG levels, thus diabetics take insulin as an external medication to regulate BG levels [2].

Managing diabetes requires tight control of BG levels, where too high BG results in hyperglycemia (HYPER) and causes long-term complications. Conversely, low BG results in hypoglycemia (HYPO, i.e., BG levels of <70 mg/dL) [4] and can cause short-term complications including unconsciousness, permanent brain loss, or even death. HYPO, common in T1D, is most dangerous for infants, young children [16], elderly [10], and those who have impaired awareness for HYPO [8]. In addition, the fear of HYPO causes many patients to err towards HYPER and lead passive life-styles, including decisions not to engage in healthy exercise [5] and not driving [14].

Of the mHealth diabetes devices and applications (apps) on the market, there are four basic ways of glucose monitoring: skin prick, saliva, urine, and continuous glucose monitoring systems. The most used methods for detecting HYPO are invasive and rely on analyzing glucose levels in blood (through finger-stick) or interstitial fluids (continuous glucose monitors, CGMs) [9]. However, CGMs often under-report HYPO [7] or display a significant time lag before indicating HYPO [11]. A recent study showed CGMs may not significantly improve glycemic control in children with T1D [12]. Each method has its own limitations related to invasiveness, expense, and availability. There is, however, a method that has shown considerable promise is trained canines—diabetes alert dogs (DADs), that act as an early warning system by alerting patients without any noticeable symptoms of HYPO [15] [16].

As noted, research has demonstrated that DADs can smell the metabolic by-products of HYPO even before it registers on a glucose-based detection device, prompting patients to check their BG levels and take action before they suffer a HYPO episode. This early detection is due to the ability of DADs to smell volatile organic compounds (VOCs) from breath caused by metabolic changes that lead to HYPO, not by smelling glucose itself. Preliminary studies indicate patients with DADs have improved glycemic control and improved quality of life with fewer complications and lower healthcare costs. However, there are long wait-lists and many costs associated with training and maintaining DADs. As such, we believe an accurate, affordable, and non-invasive device can be designed to detect (through human breath) these metabolic changes. The smart sensor system will mimic the DAD's ability to detect HYPO from VOCs in breath—thus being a technological breakthrough in hypoglycemic detection, while decreasing costs of care, decreasing morbidity and mortality, and transforming the health and well-being of patients with diabetes.

PROPOSED RESEARCH

In response to these challenges, we are in the final phase of designing and developing a noninvasive connected mobile health system for T1D and T2D patients—that includes a canine-inspired, smart nanosensor (breathing device) technology that connects via Bluetooth with a mobile application. We tentatively refer to the system as: HYPOalert. The app has the capability of 24/7 (HIPAA compliant) determination of HYPO, while providing early warning alerts detecting chemical changes in human breath. Incorporated into a smart device, the sensor system will communicate health data to caregivers, collect data for health management, and integrate with other diabetes management devices. See Figure 1.
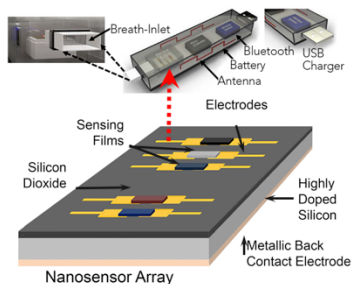

Figure 1. Illustrates the nanosensor array and de-vice configuration with breath-inlet, antenna, battery, Bluetooth, and charger.

Thus far, the research team has collected and analyzed human breath samples using gas chromatography/mass spectrometry—creating signature VOC breath profiles that correlate to HYPO. Second, the design, fabrication and testing of the nanosensor array and breathing smart sensor device will allow patients to obtain a registered response—arising from any detected metabolic change during a transient condition leading to HYPO. Each sensor on the

array will respond to one or more of the identified VOCs. The sensor array will be equipped with computational resources and wireless data transmission-communication modules. Data will be transmitted via Bluetooth and mobile devices (e.g., smartphone)—alerting patients or caregivers (between doctor-recommended blood glucose measurement intervals) that the patient may be trending toward HYPO and needs to test BG levels or take immediate corrective action.

The focus of this paper (and subsequent presentation) will review the design and testing of the first two prototype iterations of the mobile app—that will accompany the forthcoming smart breath device system.

DESIGN ITERATION—PHASE 1
Design Iteration Process

Based on a preliminary review of existing diabetes products and mobile applications, we developed a series of exploratory static/rapid interfaces for inspection by diabetes patients. As outlined, the primary purpose of HYPOalert is to warn patients of an approaching or existing state of HYPO. For this reason, the initial interfaces reflect this primary functional aspect. Figure 2 illustrates the first conceptual iteration of HYPOalert. Based on this iteration of interfaces, we performed a user requirements study—focusing on understanding user needs through questionnaire, semi-structured interviews, and a preliminary review of the first iteration of the mobile app interface design. Findings provided design requirements and the users' overall perception and interest in a breath smart sensor app for supporting HYPO monitoring.

Figure 2. First iteration of the HYPOalert static interfaces. First interface displays the app splash-page. All remaining interfaces indicate the patient's name and reading date/time. Interfaces 2-4: (1) Three color-coded visualization areas: Green=NORMAL, Yellow=APPROACHING (or Caution), and Red=HYPO, and (2) Hourly indication of breathing times and their location on the HYPO visualization scale. Interface 4 displays the patient's weekly breathing summary, broken down in percentages.

Method—User Requirements and Design Testing

Participants: We recruited 12 participants with T1D (60%) and 8 with T2D (40%), n=20. Recruitment including paper flyers circulated across the University of Illinois at Chicago (UIC) campus and email to all UIC staff and students. All

participated receive an Amazon $10 eGift for their participation. Inclusion criteria included: volunteer's age must be above 18 years, must speak fluent English and all vulnerable populations are omitted.

Interview, Questionnaire and Rapid Prototype Review: Participants received eight open-ended interviews and 13 multiple-choice survey questions. At the conclusion of the questionnaire, participants were shown the first iteration of the mobile app interface designs, with follow-up questions related to benefits, functionality, and overall appeal. Data analysis of the 13 questions consisted of means and standard deviations (SD)—converting integer values using Excel 2010. The histogram values of each question were graphically displayed as bar plots and pie charts.

Findings

Questionnaire: Regarding the method for tracking BG levels, 65% participants use the skin prick, 30% used both continuous glucose monitoring and skin prick, and 5% used urine testing. Regarding HYPO management, 35% of participants had sugar intake at random hours, 25% make use of health apps to track glucose levels by measuring food intake and physical exercise, while only one participant uses noninvasive glucose tracking. Only three participants use a combination of all three methods for managing HYPO levels. Only 20% of participants did not use any method to track their HYPO levels.

Regarding satisfaction with their current monitoring system, only 10% of participants were pleased, 45% participants are somewhat satisfied, and 40% are not satisfied with their current BG measuring method and devices. A total of 85% of participants expressed their interest to use the proposed HYPOalert noninvasive breathing sensor over their current HYPO management devices. Regarding the extent of use of a breathing sensor, 70% wished to use the device more than 20 times a day, if available today—while only 20% expressed that they would only use it only once a day to manage their HYPO condition.

Regarding BG data display types, 40% of participants wanted to see their data visualized with alerts, rather than a color-coded visualization—while 45% wished to see the data visualization color-coded (with numbers, color coding data, and line/bar plots)—similar to the HYPOalert app. And 15% expressed an interest in visualizing their BG data with bar or line plots only. Regarding sharing their data with others, 95% stated their interest in including their family, while 90% wanted to include a way to share their HYPO data with their primary provider.

All participants (100%) were interested in using the HYPOalert app, with its data visualization system—stating that it would help advance their understanding and management of a HYPO condition. All participants (100%) were slightly to strongly in agreement that the proposed

HYPOalert system (sensor and app) would positively impact their daily lifestyle practices.

Open-Ended Interview: Outcomes of our interviews showed the frequency of both severe HYPO and mild HYPO episodes among the participants. We found that the occurrence of mild HYPO episodes (5.1±7.3 times per week) is approximately 10-fold higher than the severe HYPO episodes (2.1±2.3 times per month). The average participants monitoring of Blood Glucose (BG) levels was 2.8±2.9 times per day—while BG monitoring still varied from patient to patient, e.g., one T1D participant monitors BG levels 10 times a day whereas four participants check their BG randomly throughout the week.

About 80% of participants use BG measuring devices to specifically manage their hypoglycemia. Although, most of participants use traditional or advanced BG monitoring devices, the adoption of mHealth apps is very poor, i.e., 75% of participants do not use any type of mobile app that links their BG results from the device to their smartphone. The remaining 25% use *GoMeal*, *Dexom*, *OneDrop*, or other apps to review BG data from their monitoring devices.

Regarding HYPO data visualization, the majority of participants (70%) recommended that the device save the breathing sensor data through a log option (up to six months), with the ability to visualize the data at any point in time according to glucose levels, mg/dL and trends. In addition, three participants expressed their interest to include an option for food intake data whereas one participant suggested we include insulin dosage option and alerts when HYPO occurs. Two patients would like to include predictions or causes of HYPO.

DESIGN ITERATION—PHASE 2
Product Review

To better understand the advancements of other mHealth diabetes products, we conducted an audit of two FDA approved mobile products that include both a BG measuring device, with data transmission capabilities (via Bluetooth or directly) to a smartphone app. Our assessment included the Dario and iHealth wireless blood glucose monitoring systems. After registering online, our team tested and assessed the products for two weeks; including daily blood samples. We then de-constructed and built an interface/system information architecture flow-chart, followed by a comparative analysis of the two products using the same criteria.

Briefly, both apps offer innovative solutions that improves patient satisfaction by enabling them to manage health more efficiently. Patients can set thresholds for normal and danger glucose levels, personalized goals, medication reminders, diet, and exercise plans. They can also log their blood sugar level manually/using the device as often as they want, follow their progress visually, and export results as an Excel, PDF, or CSV file to their healthcare provider or family members using e-mail, text, or via shared access in social media.

At the same time, our findings showed there was a lack of consistency in color codes to display some of the HYPO BG reading levels, creating some confusion in interpreting the results. For example, although iHealth had a well-designed interface and visualization system, the color coding system was difficult to distinguish. While Dario provides access to most options with an inside hamburger menu, iHealth features/commands can be assessed directly from the interface as icons, text or a combination of both. Unlike Dario, iHealth requires Bluetooth connection, and does not support the visually impaired. However, Dario supports adding emergency contacts and uses GPS to locate the patient when blood glucose levels reach a dangerous range.

Design Process

Findings from the first iteration and the review of the two BG monitoring systems informed our design of the interactive prototype (Figure 3) of phase two. Usability testing using the interactive prototype (on an iPhone 7 Plus) is currently on the way—consisting of three parts: (1) a scenario task-based time-on-task study, (2) a post-test questionnaire, and (3) a post-test interview.
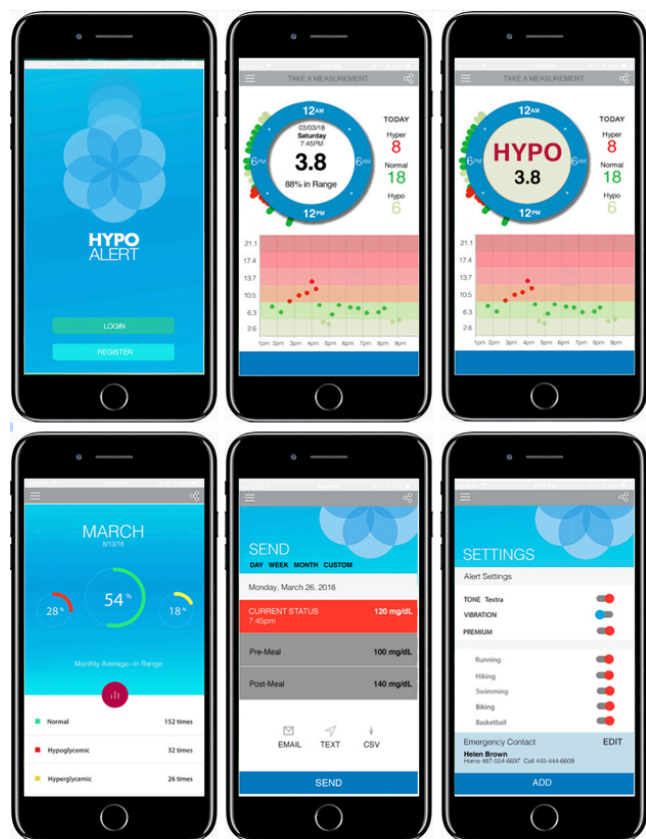

Figure 3: Illustrates the HYPOalert interactive interfaces that focus on data monitoring using several temporal systems, the alert system, along with reminders, settings, and summary reports.

CONCLUSIONS

Hypoglycemia can be a life-threating condition, of which regular metabolic monitoring is critical. This paper reported on a two-iteration design process of a mobile app (HYPOalert) that will accompany a new noninvasive smart sensor that detects HYPO by human breath for Type 1 and 2 diabetics. After our first design iteration, we interviewed users regarding the system (with static prototypes). Findings suggest a strong reception of HYPOalert. Participants agreed that the proposed system will have a positive impact on managing their HYPO. We then conducted the evaluation of two FDA approved mHealth BG monitoring systems to compare/assess product features. Our comparative analysis was used to inform/enhance the prototype design of the second iteration. Lessons learned have guided our understanding that—Data visualizations should offer a summary of individual BG level readings/trends, with customizable timeframes and a standardized color coding system that accompanies the actual values displayed. We've confirmed that customizing BG thresholds for normal and danger levels is required to enable HYPO alerts and for patients to define their own BG management plan. Finally, a usability study that observes for ease of use and functionality is currently on the way. Study findings will provide significant insight for the third design iteration of product development, followed by a clinical trials.

REFERENCES

1. Alberti KGMM, Zimmet PZ: Definition, diagnosis and classification of diabetes mellitus and its complications Part 1: diagnosis and classification of diabetes mellitus Provisional Report of a WHO Consultation. *Diab Med* 1998;15:539–553.

2. American Diabetes Association, Classification and diagnosis of diabetes mellitus and other categories of glucose intolerance. Diabetes 1979;28:1039–1057.

3. American Diabetes Association, Economic costs of diabetes in the U.S. in 2012. Diabetes Care. 36, 1033-1046 (2013).

4. Bergenstal, R. M., Ahmann, A. J., Bailey, T., Beck, R. W., Bissen, J., Buckingham, B., et al. Recommendations for standardizing glucose reporting and analysis to optimize clinical decision making in diabetes: The ambulatory glucose profile (AGP). *Diabetes Technol. Ther. 15*, 198–211 (2013).

5. Brazeau, A.-S., Rabasa-Lhoret, R., Strychar, I., and Mircescu, H. Barriers to physical activity among patients with type 1 diabetes. *Diabetes Care 31,* 2108–2109 (2008).

6. Dall, T. M., Mann, S. E., Zhang, Y., Quick, W. W., Seifert, R. F., Martin, J., et al. Distinguishing the economic costs associated with type 1 and 2 diabetes. *Pop. Health Mng. 12,* 103–110 (2009).

7. Davey, R. J., Stevens, K., Jones, T. W., and Fournier, P. A. The effect of short-term use of the Guardian RT continuous glucose monitoring system on fear of hypoglycaemia in patients with type 1 diabetes mellitus. *Prim. Care Diabetes 6,* 35–39 (2012).

8. Elliott, J., and Heller, S. Hypoglycaemia unawareness. Pract. *Diabetes Int. 28*, 227–232 (2011).

9. Maia, F. F. R., and Araújo, L. R. Efficacy of continuous glucose monitoring system (CGMS) to detect postprandial hyperglycemia and unrecognized hypoglycemia in type 1 diabetic patients. *Diabetes Res. Clin. Pract. 75*, 30–34 (2007).

10. Munshi, M. N., Segal, A. R., Suhl, E., Staum, E., Desrochers, L., Sternthal, A., et al. Frequent hypoglycemia among elderly patients with poor glycemic control. *Arch. Intern. Med. 171,* 362–364 (2011).

11. Oliver, N. S., Toumazou, C., Cass, A. E. G., and Johnston, D. G. Glucose sensors: A review of current and emerging technology. *Diabet. Med. 26*, 197–210 (2009).

12. Rachmiel, M., Landau, Z., Boaz, M., Mazor Aronovitch, K., Loewenthal, N., Ben-Ami, M., et al. The use of continuous glucose monitoring systems in a pediatric population with type 1 diabetes mellitus in real-life settings: The AWeSoMe Study Group experience. *Acta Diabetol.* (2014).

13. Rooney, N. J., Morant, S., and Guest, C. Investigation into the value of trained glycaemia alert dogs to clients with type I diabetes. *PLoS ONE 8,* e69921 (2013).

14. Stork, A. D. M., van Haeften, T. W., and Veneman, T. F. The decision not to drive during hypoglycemia in patients with type 1 and type 2 diabetes according to hypoglycemia awareness. *Diabetes Care 30*, 2822–2826 (2007).

15. Wells, D. L., Lawson, S. W., and Siriwardena, A. N. Canine responses to hypoglycemia in patients with type 1 diabetes. J. *Altern. Complement. Med. 14,* 1235–1241 (2008).

16. Wintergerst, K. A., Buckingham, B., Gandrud, L., Wong, B. J., Kache, S., and Wilson, D. M. Association of hypoglycemia, hyperglycemia, and glucose variability with morbidity and death in the pediatric intensive care unit. *Pediatrics 118,* 173–179 (2006).