Dual Blood Glucose Monitor and Insulin Pump for Type 1 Diabetics

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Background and Introduction of Type 1 Diabetes Mellitus:

Type 1 diabetes mellitus (T1DM) is a disease in which the β cells are destroyed by the immune system so they cannot produce insulin or properly regulate the blood glucose in the body [1][2]. This causes hyperglycemia and diabetic ketoacidosis. Hyperglycemia is when there is an excess of glucose in the blood that is not properly metabolized and diabetic ketoacidosis is when the body begins to digest the fat stored in the body because it cannot properly digest carbohydrates [2]. Diabetic ketoacidosis leads to a buildup of ketones–byproducts of fat metabolism–which, in high levels, are toxic.

The symptoms of T1DM include polyuria (excess urination) and polydipsia (abnormally great thirst) [1]. There is also typically extreme weight loss associated with T1DM. This is because the body can't properly digest the carbohydrates consumed meaning it cannot obtain energy from food. Since it cannot get the energy needed from carbohydrates, it turns to the fat reservoir stored in the body for energy [2]. Metabolizing fat creates the energy but also creates byproducts named ketones which are toxic in large quantities and after they build up in the system, they can damage crucial organs.

Extreme blood sugar levels can be very damaging to many organs in the body including the eyes, the kidneys, and the heart [1]. The longer the blood sugar is dangerously higher, the more damage the organs endure. The ideal preprandial blood glucose level for a diabetic is between 80 to 130 mg/dL and a postprandial level of less than 180 mg/dL [1]. Regularly going above 180 mg/dL staying above 180 mg/dL is when the adverse effects start manifesting. A common vital for diabetics to keep track of their hemoglobin A_{1C}. An ideal level for this to be at is below 7% [1]. A_{1C} is a measure of the average blood sugar levels over the past couple of months. A higher A_{1C} indicates that the blood sugar has been elevated for an extended period of time and therefore is causing organ damage.

Studies have shown that T1DM can be divided into three distinct stages [3]. The disease progresses through these stages at different rates depending on the patient and can usually be predicted fairly accurately. The first stage is indicated by the presence of at least two islet autoantibodies while the blood sugar still remains at a normal level [3]. This stage occurs before symptoms of the disease set in. The second stage also involves the presence of two or more islet autoantibodies but differs from the first stage because the blood sugar is no longer normal or stable [3]. This stage may present mild symptoms but usually is also asymptomatic. The third stage is when the typical expected symptoms start appearing including polyuria, polydipsia, weight loss, diabetic ketoacidosis, etc. [3]. The disease does not progress any more from this stage so this is where lifelong management becomes essential.

The length of each stage can vary drastically, but there have been statistics collected regarding the probable length of each. The risk of the disease progressing to the second and third step in the lifetime of the patient is close to 100% meaning that eventually, almost all diabetics will progress to the final stage. When in the first stage, the risk that the disease will progress to the second stage in the next five years is 44% and the risk of progression in the next ten years is 70%. When in the second stage, the risk of the disease progressing to the third stage is 75% in the next five years.

T1DM makes up only 5% to 10% of total diabetes cases [2]. The general population has a risk of about 0.4% of developing T1DM but those with familial history of the disease have an increased risk [1]. Siblings of someone with T1DM have a 6% to 7% of also developing it. Having a parent with T1DM also increases the risk of developing T1DM and fathers are more likely to pass it on than mothers are.

The Current Standard of Care for Type 1 Diabetes Mellitus and Its Limitations:

Unlike Type 2 diabetes, Type 1 diabetes allows the body to utilize insulin as it would normally if produced by the body. This means that synthetic insulin can be administered to replace the effects of the insulin that healthy β-cells produce naturally. This is helpful in the treatment of the disease because it provides a way to lower blood sugar and help mitigate some of the symptoms experienced due to hyperglycemia. Standard methods for delivering insulin include multiple daily injections (MDI) and continuous subcutaneous insulin infusion (CSII) [5].

While MDI was the standard treatment for a while, it required frequent injections, which can become cumbersome and painful, especially when self-administered. This limitation is what prompted the development of CSII more than 40 years ago [4]. CSII offers a more precise and flexible insulin secretion pattern, which can more accurately mimic the body's natural insulin tendencies [4].

The purpose of the CSII device was to imitate the insulin delivery patterns in healthy individuals [4]. There are two types of injections from CSII devices: basals and boluses. Basal injections are slow and constant injections from the device administered 24 hours a day [4]. These are administered subcutaneously using a cannula implanted in the skin [4]. Bolus injections are manually activated insulin doses that counteract the increased blood sugar following a meal [4]. These are used in tandem to, to the best of their abilities, copy the natural patterns of the body. These devices are extremely helpful for this purpose and to minimize the number of injections one has to administer to themself.

Although CSII devices reduce the frequency of injections required, they still have their drawbacks. The site where the CSII device is administered must be changed every 2 to 3 days to minimize infection and ensure the efficacy of the insulin stored within these devices. Another risk of these devices is the thermal degradation of the insulin stored inside, which begins to break down at temperatures exceeding 30°C [5]. The human body temperature is higher than 30°C, so if the insulin is exposed to the body for extended periods of time, it begins to degrade.

Blood glucose level monitoring remains a crucial aspect of the management of T1DM. There are two ways to test blood sugar: finger prick tests and continuous glucose monitors (CGMs). Finger pricks are not a realistic option for testing glucose levels because drawing blood every time a test is needed is not maintainable and would become increasingly painful. Finger pricks also only provide data when tested, which does not allow for trend identification or early detection of a blood sugar spike [1].

CGMs are very convenient and useful for diabetics because they provide real-time glucose readings and are able to alert if blood sugar levels are nearing dangerous territory [1]. Even though CGMs are much more convenient than finger pricks, they are not without their flaws. CGMs have to be replaced about every 10 to 14 days, and occasionally the sensor dislodges, making it useless until replaced [1]. The adhesive used for these can also cause skin irritation, especially for those with sensitive skin [2].

The advancements in the field of T1DM treatment have led to improved disease management and easier treatment, but there is still definitely room for improvement. These devices, while much better for quality of life than the traditional manual tests and injections, do present their own set of problems. Managing two separate devices requires frequent replacements, which can lead to patient fatigue and skin irritation [4].

Innovation for the Treatment of Type 1 Diabetes Mellitus:

As of right now, CSII devices need to be replaced every 2-3 days and CGM sensors need to be replaced every 10-14 days [1][4]. The combination of these two tasks creates a frequent alternation of arms for both of these devices which can be increasingly frustrating for a diabetic as they have to continuously change their medical devices out [9]. Something that would solve this is a combined device that incorporates technology from CSII devices and CGM devices to both dispense insulin and monitor blood sugar. The device would also only need to be changed every 4-5 days instead of the 2-3 that is currently necessary for the CSII device [6].

The goal of designing a device that combines the CGM and CSII function is to minimize the patient discomfort and reduce the frequency that replacement is necessary. The device would have a cannula on one side that delivers the insulin into the fat of wherever the device is placed and on the other side of the device it would have a thin filament inserted subcutaneously to monitor glucose levels in the interstitial fluid [6]. They would be separated by the entire length of the device in order to minimize the interference with one another. The CGM circuitry would be positioned closest to the skin for accurate glucose sensing, while the insulin reservoir and delivery mechanism would be housed above it to optimize space and maintain thermal insulation of the insulin by limiting the insulin's exposure to body heat [5].

The two functions would be integrated into a single mobile application on a mobile device. This device would be able to use the two functions separately and also to monitor the blood sugar levels and administer insulin if necessary. This would minimize the effort that the user would have to put into maintaining a steady blood sugar level. If the device sensed that the blood sugar was rising too far, it would increase the rate that the basal insulin is delivered and if the device sensed that the blood sugar was falling too low, it would decrease the rate at which the basal insulin is delivered. The device would utilize the wireless data transmission already present in both devices separately to communicate directly from the mobile device.

The CSII functionality would update the blood sugar reading once every five minutes in order to not run the power supply out too quickly but also to have real time accurate readings. If for some reason, the device is not able to read the blood sugar or update the device at one of the intervals, it will notify the user.

The device would include numerous safety features in order to ensure the health and wellbeing of the patients using it. The device would have a manual override option on the mobile application in case there is a sensor malfunction and the device is not appropriately delivering insulin.

Before this device would enter the market, many preclinical trials and human studies would have to be conducted to assess the biocompatibility of the device and the administration mechanism [8]. These trials would also test the very functionality of the device like the reliability of the insulin delivery system and the accuracy of the blood sugar sensor. A possible future development is a closed loop between the two devices [7]. It would omit the need for the user to administer insulin at all and would automatically regulate the blood sugar of the wearer. If this device were successfully developed, the integrated system would revolutionize the T1DM treatment and management and significantly reduce patient burden.

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