Journal of Diabetes Science and Technology
Volume 3, Issue 6, November 2009

ORIGINAL ARTICLES

Display of Glucose Distributions by Date, Time of Day, and Day of Week: New and Improved Methods

David Rodbard, M.D.

Abstract

Objective:

There is a need for improved methods for display of glucose distributions to facilitate comparisons by date, time of day, day of the week, and other variables for data obtained using self-monitoring of blood glucose (SMBG) and continuous glucose monitoring (CGM).

Method:

Stacked bar charts are utilized for multiple ranges of glucose values, e.g., very low, low, borderline low, target range, borderline high, high, and very high. Glucose ranges for these categories can be defined by the user, e.g., <40, 40–70, 71–80, 81–140, 141–180, 181–250, and 251–400 mg/dl. Glucose distributions can be displayed by time of day, in relation to meals, by date, or by day of week. The graphic display can be generated using general purpose spreadsheet software such as Microsoft Excel or with special purpose software.

Result:

Stacked bar charts are extremely compact and effective. They facilitate comparison of multiple days, multiple time segments within a day, preprandial and postprandial glucose levels, days of the week, treatment periods, patients, and groups of patients. They are superior to use of pie charts in terms of compactness and in their ability to facilitate comparisons using multiple criteria and multiple subsets of the data. One can identify episodes of hypoglycemia and hyperglycemia and can display standard errors of estimates of percentages. Interpretation of these graphs is readily learned and requires minimal training.

Conclusion:

Use of stacked bar charts is generally superior to use of pie charts for display of glucose distributions and can potentially facilitate the analysis and interpretation of SMBG and CGM data.

J Diabetes Sci Technol 2009;3(6):1388-1394

Author Affiliation: Biomedical Informatics Consultants, LLC, Potomac, Maryland

Abbreviations: (CGM) continuous glucose monitoring, (SMBG) self-monitoring of blood glucose

Keywords: continuous glucose monitoring, hyperglycemia, hypoglycemia, medical informatics, self-monitoring of blood glucose, statistical analysis, type 1 diabetes, type 2 diabetes

Corresponding Author: David Rodbard, M.D., Biomedical Informatics Consultants, LLC, 10113 Bentcross Drive, Potomac, MD 20854-4721; email address drodbard@comcast.net

Introduction

Self-monitoring of blood glucose (SMBG) and continuous glucose monitoring (CGM) can generate massive amounts of data. Clinicians must analyze and interpret these massive datasets within a few minutes or even seconds to identify the frequency, severity, and timing of hypoglycemic and hyperglycemic episodes by date, time of day, and day of the week. Pie charts[1] are one of the most popular methods for display of glucose distributions. Histograms and cumulative frequency distributions are used much less often. However, when one is presented with multiple "pie charts" representing glucose distributions for multiple time slots throughout the day, it is difficult to make the numerous comparisons needed to evaluate how the frequency of hypoglycemia or hyperglycemia varies in relation to meals. Similar problems arise when evaluating glucose distributions by day of the week or when comparing the pie charts from different periods in time (ranges of dates) to assess the effect of introduction of a new treatment regimen or other intervention. These problems are compounded by the fact that software for generation of pie charts from different manufacturers of glucose meters, CGM sensors, and insulin pumps use different ranges for categories of glucose, different color-coding, different symbols, different statistics, and different formats for presentation of the data. The present study describes new options for display of glucose distributions.

Methods

A pie chart shows the percentages assigned to each of several categories as a fraction of a complete circle (360 degrees). A stacked bar chart shows the cumulative percentages assigned to each of several categories as a percentage of a linear column or bar (vertical or horizontal). (The term "stacked bar chart" is used as inclusive of either horizontal or vertical charts of this type.) Multiple stacked bar charts can be placed adjacent to one another, contiguous, or with any desired degree of spacing. A wide range of glucose data were examined from patients with type 1 and type 2 diabetes on multiple forms of therapy as obtained using SMBG and CGM. Synthetic data was also generated for assessment of the new approaches. A number of alternative graphic methods were evaluated. The procedure for generating these kinds of graphs is as follows: (1) the user must select the number of ordered categories for glucose and provide designations (names) for these categories, (2) the user must assign upper and lower limits to each of the categories and assign color coding for each (**Table 1**), and (3) the user then selects whether to analyze the glucose data by date, time of day, or day of the week and selects the ranges for dates and time segments. Analysis by time of day may be performed either in terms of "time slots," e.g., 1 h intervals, or in relationship to meals, e.g., before breakfast, after

Table 1.
Categories Corresponding to Glucose Ranges (mg/dl)[a]

Category	Glucose range		Color	Glucose range	
	Lower limit (mg/dl)	Upper limit (mg/dl)		Lower limit (mmol/liter)	Upper limit (mmol/liter)
Very very low		39	dark blue		2.17
Very low	40	60	blue	2.22	3.33
Low	61	70	sky blue	3.39	3.89
Borderline low	71	80	aquamarine	3.94	4.44
Target range	81	140	green	4.50	7.78
Borderline high	141	180	light orange	7.83	10.00
High	181	250	orange	10.06	13.89
Very high	251	400	red	13.94	22.22
Very very high	401		pink	22.28	

[a] The number of categories, lower and upper limits for each category, and color coding can all be selected by the user. The values shown here differ somewhat from the case used as an illustration in the abstract.

breakfast, before lunch, after lunch, before dinner, after dinner, bedtime, or overnight (3 AM). For analyses involving a continuous variable (date or time of day), the user can select the parameters used for smoothing of the data.

Results

Conventional, Currently Available Methods

Figure 1 shows conventional displays of glucose that are representative of those commonly utilized,[2–9] including (A) pie charts of the glucose distributions, (B) display of glucose by date, (C) histograms and cumulative frequency distributions, and (D) display of glucose by time of day, often called modal day, standard day, glucose profile, or ambulatory glucose profile (AGP). Using these figures, it can be difficult to make comparisons, e.g., to compare the percentages that are high or very high at different times of day, on different days of the week, or for different ranges of dates.

Analysis in Relation to Meals

Figure 1A shows the conventional method for display of the glucose distributions for the entire dataset by time of day in relation to meals. It can be difficult to evaluate

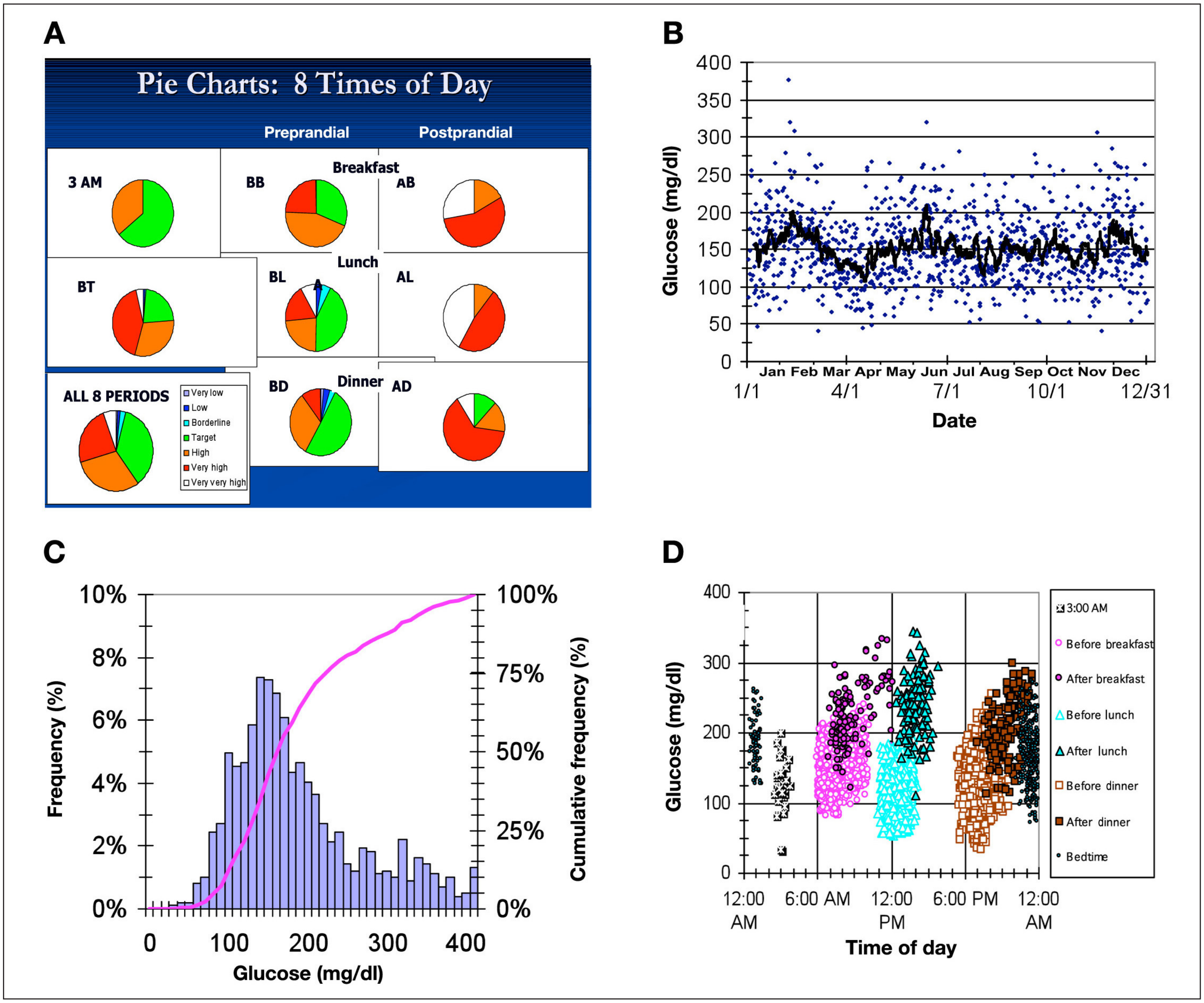

Figure 1. Conventional methods for display of glucose distributions. **(A)** Pie-charts showing the distribution of glucose values for an entire data set and for subsets corresponding to preprandial and postprandial values, bedtime and overnight. BB, before breakfast; AB, after breakfast; BL, before lunch; AL, after lunch; BD, before dinner; AD, after dinner; BT, bedtime. **(B)** Display of glucose by date. **(C)** Frequency histogram for glucose for all times of day (blue bar chart) and the corresponding cumulative frequency distribution (pink curve). **(D)** Display of glucose by time of day.[3–6,9] Overnight, black squares with superimposed white X; before breakfast, pink open circles; after breakfast, pink closed circles; before lunch, turquoise open triangles; after lunch, turquoise solid triangles; before dinner, brown open squares; after dinner, solid brown squares; bedtime, blue closed circles.

the relative importance of different types of problems for the subsets of the data being examined. One needs to compare the areas of the segments of the pie charts or the angle corresponding to each sector. Pie charts often result in considerable unused space between the several circular diagrams.

Analysis by Date

Figure 1B shows the conventional method for display of glucose data versus date; the glucose values and a smoothed trend line are shown. It is then left to the user to determine if and when there is a clinically important risk of hypoglycemia or hyperglycemia for various thresholds.

Frequency Histograms

Figure 1C shows a frequency histogram for glucose. Although nearly all commercially available software for analysis of SMBG and CGM data includes an option to provide this type of display, it is rarely used (unpublished observations). It is often difficult to appreciate the percentage of values below or above various thresholds. When histograms are superimposed, one often obtains a nearly undecipherable set of overlapping patterns. Use of a cumulative frequency distribution can be helpful[7] since it facilitates comparisons using any arbitrary threshold. Unfortunately, both physicians and patients are not generally comfortable with the use of this well-accepted and classical statistical method. As commonly implemented in the past, this method does not clearly identify the ranges of the glucose scale of greatest clinical interest.

Analysis by Time of Day

The modal day or glucose by time of day (**Figure 1D**) can help the viewer appreciate the times of day when hypoglycemia or hyperglycemia are of particular concern. However, it does not provide a precise numerical estimate of the risk of these events or how those risks depend on the arbitrary choice of the threshold defining hypoglycemia. One can construct the glucose profile by time of day separately for each of the days of the week to evaluate the stability of patterns over weekdays and weekends.[2–6,8–10]

New Methods: the Stacked Bar Chart

Figure 2 shows stacked bar charts displaying the glucose distribution in relationship to meals (**Figure 2A**), by time of day with time as a continuous variable (**Figure 2B**), by day of the week (**Figure 2C**), and by longitudinal date, again as a continuous variable (**Figure 2D**). The presentation is more compact than use of pie charts, so the space requirement is substantially reduced, permitting use of a larger display with better resolution.

Glucose Distribution in Relationship to Meals

Figure 2A displays the same data as **Figure 1A** but in a more compact format. Comparisons can be made using a linear (vertical) scale rather than an angular scale or comparison of areas as in **Figure 1A**. One can compare the frequency of very low values across the eight different times of day related to meals or the entire day. Similarly, one can compare the frequency of very low *and* low glucose values combined, by analysis of the border between low and target range. Similarly, one can compare the percentages of glucose values that are very high, or very high *and* high combined. One can obtain and display estimates of the precision of the percentages, i.e., the standard error of the percentages, using a standard formula based on the binomial distribution. [The standard error of a proportion (percentage) P is $se(P) = SQRT(P \times (100 - P)/N)$, where N is the number of observations. Although these data may be regarded as multinomial rather than binomial, the estimates based on the binomial distribution should be sufficient to estimate the approximate levels of uncertainty in the estimates of the proportions.] If one uses seven categories for glucose, then one will have six junctions between categories; each of these can be compared across the eight different times of day as utilized here, resulting in up to $6 \cdot (8 \cdot 7)/(1 \cdot 2) = 168$ possible comparisons. One can make each of these 168 comparisons within a few seconds by scanning one's eyes horizontally across **Figure 2A**.

Analysis by Time of Day as a Continuous Variable

A similar approach can be used when time of day is regarded as a continuous variable (**Figure 2B**). First, the range of dates for the data to be analyzed must be selected and as well as a window size for calculation of the percentages of glucose observations in each category (e.g., a 1 h sliding window, from 00:00–00:59, 00:05–01:05, through 23:00–23:59). The larger the number of observations, the smaller the window size that can be used without encountering excessive random sampling variability, which would be reflected in large standard errors of the percentages of glucose values in each category. In this example, 14 days of CGM data and a 1 h sliding time window are used, with glucose measured at 5 min intervals. The vertical bars corresponding to consecutive 1 h time windows are contiguous. To improve clarity, vertical lines between the bars are not shown.

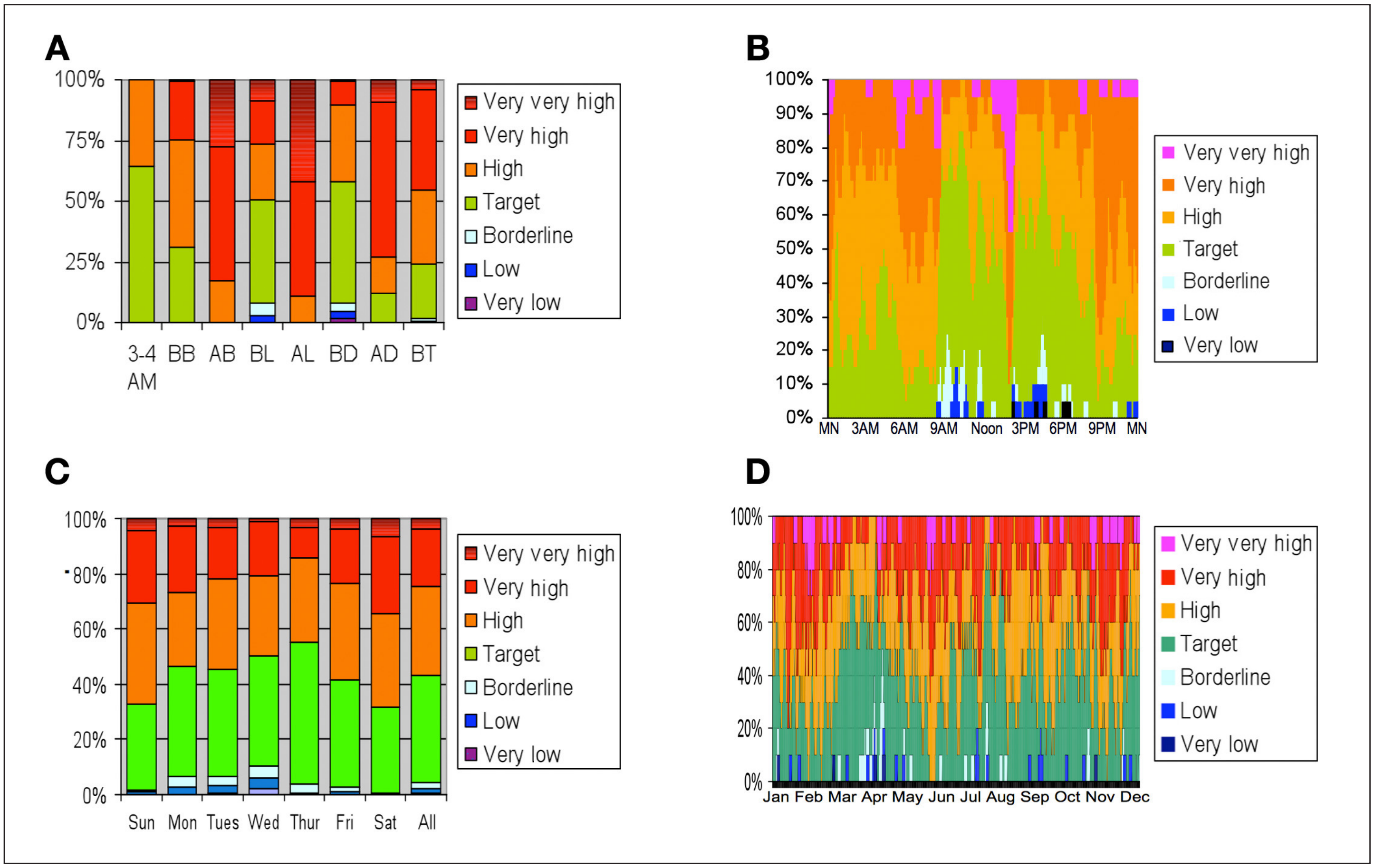

Figure 2. New methods for display of glucose distribution utilizing stacked bar charts with glucose ranges and color coding as shown in **Table 1**. **(A)** Glucose distribution in relationship to meals, bedtime, and overnight, using stacked bar charts for the same data as **Figure 1A**. BB, before breakfast; AB, after breakfast; BL, before lunch; AL, after lunch; BD, before dinner; AD, after dinner; BT, bedtime. **(B)** Glucose distributions as a function of time during the continuous 24 h period. Estimates of percentages of values within any specified glucose range are obtained for a 1 h sliding time window for glucose data accumulated over a 2-week period. **(C)** Glucose distributions for day of the week and all days combined. **(D)** Glucose distributions by date for a period of one year using time as a continuous variable as in Figure 2B. This facilitates the identification of periods where there were significant problems with hypoglycemia and hyperglycemia.

Analysis by Day of the Week

Use of a similar approach is proposed for display of glucose distributions by day of the week (**Figure 2C**). Once again, the display is more compact and more readily interpreted than multiple pie charts. Data can potentially be assimilated more quickly, easily, and accurately. If one is using seven categories for glucose, one will have six thresholds separating the categories. When combined with the seven days of the week and "all days" as an eighth category, one again has 168 possible comparisons. Each of these comparisons can be made with a quick scan of the graphic display.

Analysis by Date

A similar approach can be used for display of glucose distributions with respect to date. **Figure 2D** shows the distribution of glucose in seven categories by date for a period of one year. This can facilitate the identification of periods of time when there were problems with hypoglycemia and hyperglycemia or increased glycemic variability.

Options

Numerous variations of this approach are available. For example, one could construct an analysis by time of day as in **Figures 2A** or **2B** separately for each of the days of the week in order to characterize differences in circadian patterns for different days of the week. Alternatively, one could elect to show only selected categories, e.g., "very very low" and "very low," or "very very high" and "very high." In this manner, one can appreciate the range of dates, times of day, and days of the week that have significant problems with hypoglycemia or hyperglycemia. The user may select other combinations of categories, e.g., all categories between very very low and borderline low, or between borderline high and very

very high, or one might wish to redefine the thresholds separating each category **(Table 1)**. If one were interested only in hyperglycemia, one might display the percentages for high, very high, and very very high using a flat baseline of zero. Similarly, one might elect to display the percentage in target range on a flat baseline of zero.

Discussion

The methods described here are new and novel. Stacked bar charts have been used occasionally in the medical and scientific literature. For example, they have been used to illustrate the percentage of the total daily insulin dose allocated to basal as opposed to bolus insulin injections. They have also been used to show the relative importance of fasting and postprandial glucose values in determining hemoglobin A1c, in relationship to the hemoglobin A1c level itself.[10] However, to the author's knowledge, these graphs have not been used previously to display the distribution of glucose values as a series of clinically defined categories, e.g., from very very low to very very high. Hence, the types of graphs shown in **Figure 2** are believed to be new and novel. These types of displays appear to be superior to the types of graphs that have been used previously (**Figure 1**), because they convey clinically actionable information in a very efficient and compact manner. They facilitate the making of literally dozens of comparisons: one can quickly identify the times of day or the days of the week when there are the most severe problems with hypoglycemia or hyperglycemia, and one can compare and combine results from subsets of the data, e.g., preprandial versus postprandial (**Figure 2A**) or weekdays versus weekends (**Figure 2C**) more easily than when using pie charts (**Figure 1A**).

The present methods appear to be superior to use of pie charts, histograms, and cumulative frequency distributions by virtue of their compactness and their ability to facilitate analysis and interpretation. Individuals differ in their abilities to utilize graphic data as opposed to numerical data or information conveyed in the form of text. A variety of methods and options will continue to be popular for the analysis and interpretation of SMBG and CGM data. Many clinicians will continue to prefer the display of the "raw" data as in **Figures 1B** and **1D**.

When describing another new approach to display of glucose data, it was noted that there is a need for conducting studies to evaluate the preferences of users, based on monitoring of empirical usage when various methods are easily accessible, and based on cognitive laboratory studies to ascertain the effectiveness of various methods of display. Cognitive laboratory studies should be performed for different types of users, after various amounts of training, with multiple case studies presented for varying periods of time. Randomization and crossover designs are needed to correct for the effects of learning occurring during the course of the study.[11]

Conclusions

New and novel methods have been developed for display of glucose disttributions as applied to data from SMBG and CGM. This is the first use of stacked bar charts for a series of clinically defined categories or ranges of glucose. This approach can be used to describe the glucose distributions by date, time of day, relationship to meals, day of the week, or various combinations of these factors. This approach can be used when the time scale is viewed as discrete, e.g., intervals when the patient was receiving different forms of treatment, multiple time segments during the day (**Figure 2A**), or days of the week (**Figure 2C**). These methods can also be used when time is regarded as a continuous variable, e.g., the 24 h day (**Figure 2B**) or longitudinal date (**Figure 2D**).

These methods are simple both conceptually and computationally. They can be implemented using readily available and familiar software such as spreadsheets, and are easily and rapidly learned and applied. These methods produce graphic displays that are often easier to use and interpret than the conventional methods.

References:

1. Berger M, Jaffe ML, Devine P, Rodbard D. Computer programs to assist the physician in the analysis of self-monitored blood glucose data. Proc Annu Symp Comput Appl Med Care. 1988;9:52–7.
2. Pernick NL, Rodbard D. Personal computer programs to assist with self-monitoring of blood glucose and self-adjustment of insulin dosage. Diabetes Care. 1986;9(1):61–9.
3. Mazze RS, Lucido D, Langer O, Hartmann K, Rodbard D. Ambulatory glucose profile: representation of verified self-monitored blood glucose data. Diabetes Care. 1987;10(1):111–7.
4. Rodbard D. Potential role of computers in clinical investigation and management of diabetes mellitus. Diabetes Care. 1988;11 Suppl 1:54–61.
5. Rodbard D, Berger M, Pernick N. Computer, networking, and information systems to facilitate delivery of health care to patients with diabetes. In: Baba S, Kaneko T, eds. Diabetes 1994, Proceedings of the 15th International Diabetes Federation Congress, Kobe, 6-11 November 1994. New York: Elsevier; 1995, 800–3.

6. Rodbard D. Optimizing display, analysis, interpretation and utility of self-monitoring of blood glucose (SMBG) data for management of patients with diabetes. J Diabetes Sci Technol. 2007;1(1):62–71.

7. Juvenile Diabetes Research Foundation Continuous Glucose Monitoring Study Group, Tamborlane WV, Beck RW, Bode BW, Buckingham B, Chase HP, Clemons R, Fiallo-Scharer R, Fox LA, Gilliam LK, Hirsch IB, Huang ES, Kollman C, Kowalski AJ, Laffel L, Lawrence JM, Lee J, Mauras N, O'Grady M, Ruedy KJ, Tansey M, Tsalikian E, Weinzimer S, Wilson DM, Wolpert H, Wysocki T, Xing D. Continuous glucose monitoring and intensive treatment of type 1 diabetes. New Engl J Med. 2008;359(14):1464–76.

8. Rodbard D. A new approach to display of self-monitoring of blood glucose (SMBG) data. J Diabetes Sci Technol. 2009;3(5):1121–70.

9. Mazze RS, Strock E, Wesley D, Borgman S, Morgan B, Bergenstal R, Cuddihy R. Characterizing glucose exposure for individuals with normal glucose tolerance using continuous glucose monitoring and ambulatory glucose profile analysis. Diabetes Technol Ther. 2008;10(3):149–59.

10. Monnier L, Lapinski H, Colette C. Contributions of fasting and postprandial plasma glucose increments to the overall diurnal hyperglycemia of type 2 diabetic patients: variations with increasing levels of HbA(1c). Diabetes Care. 2003;26(3):881–5.

11. Rodbard D. A semilogarithmic scale for glucose provides a balanced view of hyperglycemia and hypoglycemia. J Diabetes Sci Technol. 2009;3(6):1395-1401.