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An open source tool to compute measures of inpatient glycemic control: translating from healthcare analytics research to clinical quality improvement

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ABSTRACT

Objectives: The objective of this study is to facilitate monitoring of the quality of inpatient glycemic control by providing an open-source tool to compute glucometrics. To allay regulatory and privacy concerns, the tool is usable locally; no data are uploaded to the internet.

Materials and Methods: We extended code, initially developed for healthcare analytics research, to serve the clinical need for quality monitoring of diabetes. We built an application, with a graphical interface, which can be run locally without any internet connection.

Results: We verified that our code produced results identical to prior work in glucometrics. We extended the prior work by including additional metrics and by providing user customizability. The software has been used at an academic healthcare institution.

Conclusion: We successfully translated code used for research methods into an open source, user-friendly tool which hospitals may use to expedite quality measure computation for the management of inpatients with diabetes.

Key words: hospital, glycemic control, quality improvement, blood glucose monitoring, hypoglycemia, diabetes mellitus

INTRODUCTION

Inpatient glycemic management is a key part of care of hospitalized patients with diabetes mellitus (DM). An association of poor clinical outcomes (including death) with hypoglycemia and hyperglycemia has been demonstrated.[1–7] Despite that, inpatient glycemic control remains suboptimal with occurrence of hypoglycemia and hyperglycemia. Inpatient hyperglycemia and hypoglycemia events can be decreased through quality improvement programs.[8–10]

Glycemic control guidelines and strategies may differ from hospital to hospital. However, a key part of any inpatient diabetes qual-

LAY SUMMARY

Glucometrics is a set of measures designed to assess whether the blood glucose of patients with diabetes are effectively managed. However, it is difficult to incorporate glucometrics into routine operations in hospitals and healthcare institutes, because to compute glucometrics requires consolidation of datasets from multiple sources and extensive data manipulation, which are challenging without dedicated manpower with specific professional skills. Various software tools are currently available for generating glucometrics, but they are paid proprietary tools, and some of them pose potential data security issues by requiring data to be uploaded to a third-party server. To fill in this gap, we created an open-source tool with a user-friendly graphical interface, named QcDM Project, that allows users to: (1) consolidate and manipulate the data via a point-and-click approach, (2) compute commonly used glucometrics measures, and (3) generate the results into a report for subsequent use. After installation, our tool is able to run on a standalone workstation without the need for internet connection, minimizing the risk of data leakage. The source code of our tool is available on GitHub under a flexible open-source license, allowing professionals to modify and extend it for wider applications, e.g., integration into the electronic health records system for automated routine monitoring.

ity control program is regular surveillance for adverse events such as hypoglycemia and hyperglycemia. This allows programs to assess effectiveness of interventions and to detect increases in adverse events in a timely manner. Monitoring requires compiling and analyzing blood glucose (BG) results and generating regular, periodic reports of glucometrics, measures of inpatient glycemic control.[11] This evaluation involves multiple calculations, and often, different parties. Manual evaluation is inefficient and prone to human errors. Hospitals may engage vendors to construct bespoke programs; yet these can become costly, especially when changes are needed.[12–15]

Given these factors, a number of software solutions have been created to assist monitoring. These tools, while useful, do have shortcomings; some require use of a proprietary point of care BG system.[16] Others require hospital medical data to be uploaded to the cloud[2,17] for analysis. While the tools themselves are commendable, such issues may prevent the use of these solutions in some institutions. In this paper, we present a solution for glucometrics monitor-

ing which overcomes these issues. We initially developed this code for research projects in healthcare analytics.[9,10,18] During interactions with clinical staff at our institution, we became aware of operational needs and seized the opportunity to practice translational research.

To improve the efficiency of the whole glucometrics reporting process and overcome the identified shortcomings in other tools, we developed an open source, graphical user interface (GUI) that is available under the MIT license. This allows users to generate their own routine report and shorten the feedback process through process automation. It empowers healthcare staff to scale up monitoring efforts and achieve American Diabetes Association monitoring recommendations at a unit or ward level[19] with minimal additional effort.

We developed this tool from R code adapted from related diabetes research projects. The open source R language is widely used in healthcare analytics.[20] This approach gives savvy users the flexibility to easily modify and extend the code's capabilities based on the
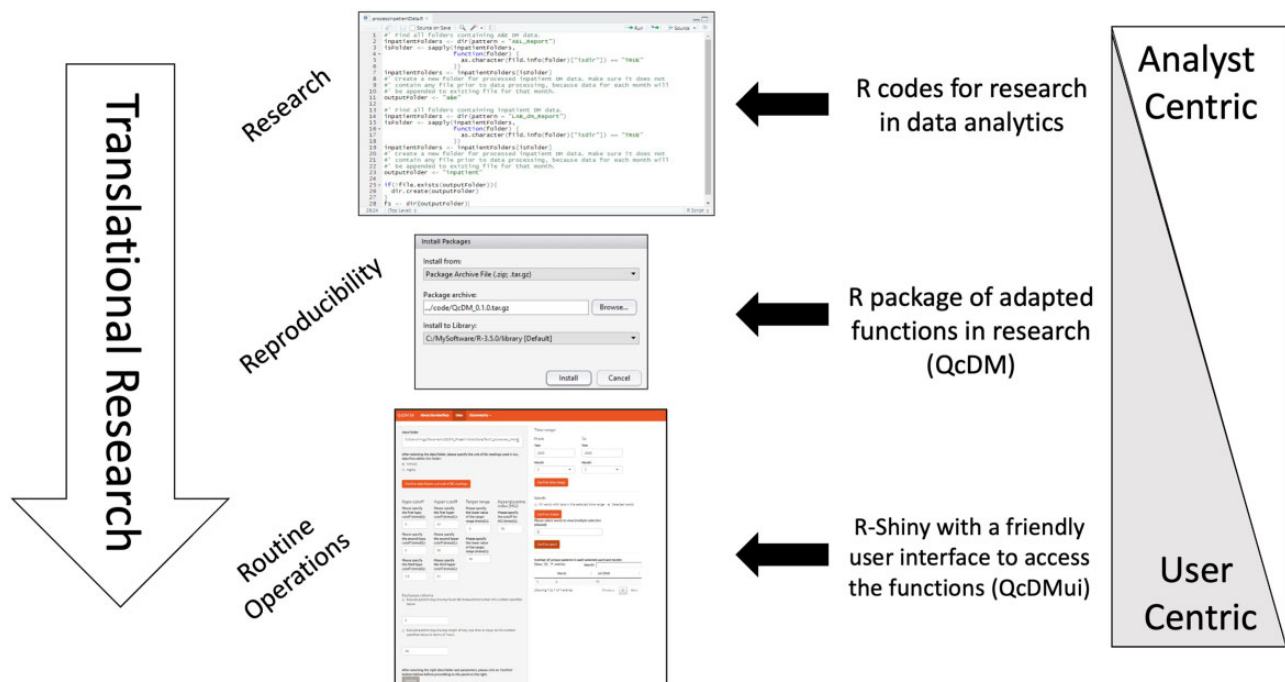

Figure 1. Quality care for diabetes mellitus (QcDM) project timeline.

Table 1. Glucometrics definitions in quality care for diabetes mellitus (QcDM)

Glucometrics	Patient-sample (pt-sample)	Patient-day (pt-day)	Patient-stay (pt-stay)
Glycemic control			
Percentage of hyperglycemia[a]	$\dfrac{\text{pt-samples with hyperglycemia}}{\text{pt-samples}}$	$\dfrac{\text{pt-days with hyperglycemia}}{\text{pt-days}}$	$\dfrac{\text{pt-stays with hyperglycemia}}{\text{pt-stays}}$
Hyperglycemia index[29b] (HGI)	NA	NA	HGI of glucose readings from a pt-stay
Percentage of glucose in desired range[c]	$\dfrac{\text{pt-samples in range}}{\text{pt-samples}}$	$\dfrac{\text{pt-day means in range}}{\text{pt-days}}$	$\dfrac{\text{pt-stay means in range}}{\text{pt-stays}}$
Mean glucose	Mean of glucose readings from a pt-sample	Mean of glucose readings from a pt-day	Mean of glucose readings from a pt-stay
Average of mean glucose from pt-days within a pt-stay	NA	NA	Average of means of glucose readings from pt-days within a pt-stay
Hypoglycemia			
Percentage of hypoglycemia[d]	$\dfrac{\text{pt-samples with hypoglycaemia}}{\text{pt-samples}}$	$\dfrac{\text{pt-days with hypoglycaemia}}{\text{pt-days}}$	$\dfrac{\text{pt-stays with hypoglycaemia}}{\text{pt-stays}}$
Percentage of recurrent hypoglycemia[e]	NA	NA	$\dfrac{\text{pt-stay with 2 or more days having hypoglycaemia}}{\text{pt-stays}}$
Glycemic variability			
Standard deviation (SD)	NA	SD of glucose readings from a pt-day	SD of glucose readings from a pt-stay
J-index[33f]	NA	J-index of glucose readings from a pt-day	J-index of glucose readings from a pt-stay

aHyperglycemia corresponds to blood glucose (BG) readings that are more than 14 mmol/L (or 252 mg/dL), 20 mmol/L (or 360 mg/dL), or 24 mmol/L (or 432 mg/dL) and these cut-offs are customizable in QcDMui.

bHyperglycemia index is computed where the cut-off for hyperglycemia is 14 mmol/L (or 252 mg/dL), and these cut-offs are customizable.

cDesired range corresponds to blood glucose readings that are between 4 mmol/L (or 72 mg/dL) and 10 mmol/L (or 180 mg/dL), and these cut-offs are customizable.

dHypoglycemia corresponds to BG readings that are less than 4 mmol/L (or 72 mg/dL), 3 mmol/L (or 54 mg/dL) or 2.5 mmol/L (or 45 mg/dL) and these cut-offs are customizable.

eRecurrent hypoglycemia corresponds to 2 or more BG readings that are less than 4 mmol/L (or 72 mg/dL), and this cut-off is customizable via the first user-specified cut-off for hypoglycemia.

fJ-index is computed as a factor of the square of the sum of mean and SD, which is 0.324 when unit is mmol/L and 0.001 when unit is mg/dL and these cut-offs are also customizable.

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Figure 2. Quality care for diabetes mellitus (QcDM) graphical interface.

needs of the organization. Our R library, or package, **Q**uality **c**are for **D**iabetes **M**ellitus (QcDM), was developed as a prototype module for potential integration with electronic medical records systems. However, it has the flexibility to be deployed in either centralized (server) or decentralized (client only) use cases enabling its use in care settings of various scale. The graphical interface of QcDM (QcDMui) was developed with the R-Shiny package.[21]

The aim of the QcDMui tool is to enable healthcare staff to conduct glycemic monitoring with routinely collected electronic medical records in a flexible and approachable manner via an easy to use interface. The tool allows users to specify cut-off values used to define hyperglycemia and hypoglycemia. It can process glucose results in mg/dL or mmol/L, and users are required to specify the unit associated with the data file(s). QcDMui can be adapted to work with data from numerous sources or formats with minimal cost or effort as long as 4 data fields are present in the data. To illustrate this feature, we provide a GUI that allows users to adapt their datasets to the required format. Note that these tools do not require the internet to operate; instead, all input and output data can be kept on a work-station or local server where they are installed. All patient data are kept within the institution, an approach that removes potential legal or organizational restrictions on the use of the tool.

MATERIALS AND METHODS

During research projects in healthcare analytics,[9,10,18,22–26] we developed and applied novel analytical approaches to inpatient diabetic data. During the course of this interdisciplinary research, interactions with physicians made us aware of their need for a software tool for routine monitoring of glucometrics. This prompted us to translate our research-oriented R codes into a form that could support the needs of clinical quality monitoring.

We realized that an important aspect of the translation process was to lower the barrier of entry to using the R code. The first step was to generalize code into functions and consolidate these into an R package, which we called QcDM. The package would facilitate the reproducibility of data analysis and provide the foundation for
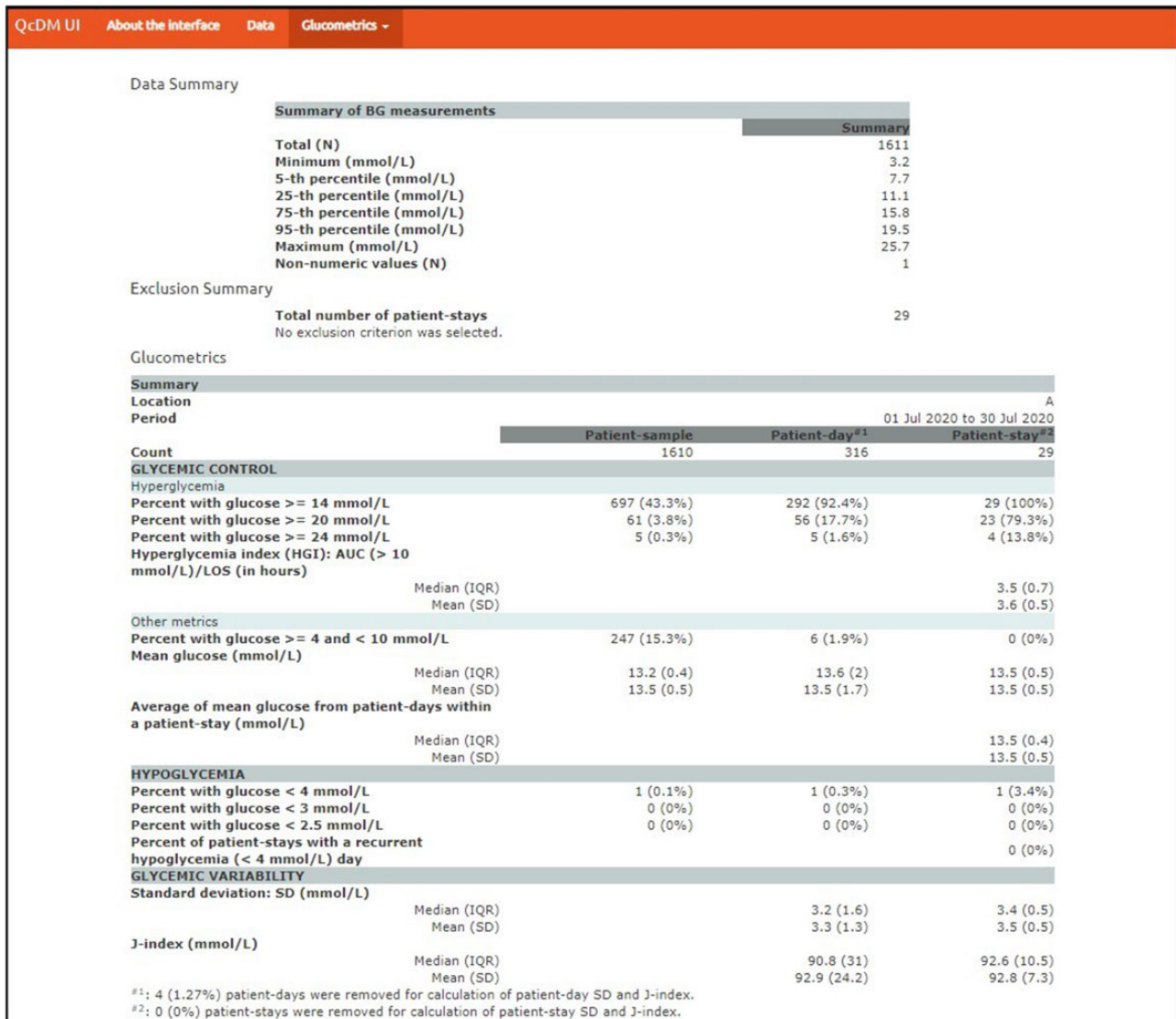
Data Summary

Summary of BG measurements	Summary
Total (N)	1611
Minimum (mmol/L)	3.2
5-th percentile (mmol/L)	7.7
25-th percentile (mmol/L)	11.1
75-th percentile (mmol/L)	15.8
95-th percentile (mmol/L)	19.5
Maximum (mmol/L)	25.7
Non-numeric values (N)	1

Exclusion Summary

Total number of patient-stays	29
No exclusion criterion was selected.	

Glucometrics

Summary			
Location			A
Period			01 Jul 2020 to 30 Jul 2020
	Patient-sample	Patient-day[#1]	Patient-stay[#2]
Count	1610	316	29
GLYCEMIC CONTROL			
Hyperglycemia			
Percent with glucose >= 14 mmol/L	697 (43.3%)	292 (92.4%)	29 (100%)
Percent with glucose >= 20 mmol/L	61 (3.8%)	56 (17.7%)	23 (79.3%)
Percent with glucose >= 24 mmol/L	5 (0.3%)	5 (1.6%)	4 (13.8%)
Hyperglycemia index (HGI): AUC (> 10 mmol/L)/LOS (in hours)			
Median (IQR)			3.5 (0.7)
Mean (SD)			3.6 (0.5)
Other metrics			
Percent with glucose >= 4 and < 10 mmol/L	247 (15.3%)	6 (1.9%)	0 (0%)
Mean glucose (mmol/L)			
Median (IQR)	13.2 (0.4)	13.6 (2)	13.5 (0.5)
Mean (SD)	13.5 (0.5)	13.5 (1.7)	13.5 (0.5)
Average of mean glucose from patient-days within a patient-stay (mmol/L)			
Median (IQR)			13.5 (0.4)
Mean (SD)			13.5 (0.5)
HYPOGLYCEMIA			
Percent with glucose < 4 mmol/L	1 (0.1%)	1 (0.3%)	1 (3.4%)
Percent with glucose < 3 mmol/L	0 (0%)	0 (0%)	0 (0%)
Percent with glucose < 2.5 mmol/L	0 (0%)	0 (0%)	0 (0%)
Percent of patient-stays with a recurrent hypoglycemia (< 4 mmol/L) day			0 (0%)
GLYCEMIC VARIABILITY			
Standard deviation: SD (mmol/L)			
Median (IQR)		3.2 (1.6)	3.4 (0.5)
Mean (SD)		3.3 (1.3)	3.5 (0.5)
J-index (mmol/L)			
Median (IQR)		90.8 (31)	92.6 (10.5)
Mean (SD)		92.9 (24.2)	92.8 (7.3)

[#1]: 4 (1.27%) patient-days were removed for calculation of patient-day SD and J-index.
[#2]: 0 (0%) patient-stays were removed for calculation of patient-stay SD and J-index.

Figure 3. Summary of data quality and glucometrics.

the subsequent development of a user-friendly interface. We then built a GUI tool for healthcare staff using the R-Shiny framework; we called this QcDMui. We obtained feedback from users to improve usability. Figure 1 shows the development process.

At the institution where QcDM was developed, staff use a standard glucometer, Accu-Chek Inform (Roche Diagnostics, Indianapolis, IN, USA). Only point-of-care, capillary BG values are used for glucometrics. Data are imported into the GUI tool via comma separated values (csv) file(s) with 4 data fields: (1) name of the patient-care unit (or ward) for which glucometrics will be computed, (2) identifier for the patient-encounter, (3) date and time of the BG results, and (4) the BG result, which must be exclusively in either mg/dL or mmol/L and the unit is specified when using the QcDMui. Due to differences in the glucometers and reporting conventions across institutions, BG data files can have a variety of columns or fields. To facilitate a flexible, convenient and less error-prone workflow, we developed an easy-to-use data adaptor called QcDMconverter. It allows users to specify the 4 required fields from any tabular data saved as comma, tab or semicolon separated version files and based on the specifications made, it generates the data

file into the required format for import into QcDMui (see the user manual for detailed usage, available from: https://github.com/nyilin/QcDM_Project/blob/main/QcDM_Project_User_Manual.pdf).

After importing the BG data, the QcDMui graphical tool uses the QcDM package to generate glucometrics according to the requirements of an inpatient DM care program in Singapore that considered: (1) the needs of healthcare workers from participating institutions in Singapore, (2) the Yale glucometrics experience, and (3) the published studies on glucometrics for assessing glucose control.[17,27–33] The QcDM package consolidates the code for routine generation of glucometrics into 3 main functions: "FormatDate" to process the date-time stamp of BG readings, "GenEpisode" to correctly identify glucose monitoring episodes based on admission information in the input data, and "GenGluM" to compute commonly reported glucometrics measures. In the glucometrics literature, there are 3 units of analysis: patient-sample, patient-day, and patient-stay (see Table 1), which are reported by the tool because they provide information from different perspectives.[27] Users are given the option to implement 2 exclusion criteria prior to the generation of these glucometrics. They may: (1) exclude any patient-stay with fewer BG measurements than a pre-

specified number and (2) exclude any patient-stay where length of stay (inferred from the date and time of the earliest and latest BG test) is less than or equal to a pre-specified number of hours. Both exclusion criteria can be customized by the user.

RESULTS

To launch the QcDMui tool, a user needs to double click a file called "Launch QcDMui.RData," which will initially display a brief tutorial in the user interface. When the user clicks on the "Data" tab they will be asked to select a directory which contains the input BG data files and the eventual output generated by the tool. The user must create this parent folder, which also contains 3 child folders: "new_data", "processed_data" and "glucometrics_output". The user can place 1 or more BG files for concurrent processing in "new_data"; as the software processes the data, it will move these to "processed_data". The generated glucometrics output will be placed under "glucometrics_output" and will be organized by Ward, Year and then, Month. Data passed to the system should be 1 month per file and can contain any number of columns but must contain ADMISSION.ID (unique patient-encounter identifier), RESULT.DATE (date and time of the glucose reading), RESULT (glucose reading in mg/dL or mmol/L), and LOCATION (ward). This was the format of the BG data files in our research projects; the QcDMconverter was developed so that BG data files with other formats could be easily transformed, and the parent and child folders could be automatically generated with a user-friendly interface. Once the data are loaded into the tool, the GUI that allows a user to specify various cut-off values is displayed (see Figure 2).

Then the user is able to configure the tool with cut-off values for mild, moderate and severe hyperglycemia and hypoglycemia, as well as an upper and lower cut-offs for target range in mg/dL or mmol/L. This allows much flexibility to adapt glucometrics output for multiple institutions as cut-offs are customizable. The user may also specify exclusion criteria which excludes inpatient stays below a specified number of hours or with too few glucose readings. Once the user has chosen these values, they need to confirm their choices (see Figure 2, the GUI section with the grey background).

To generate a glucometrics report, the user must specify the period and the wards to be analyzed. Once the user confirms these specifications, a preview of the data matching the specifications is shown. The user may then click the "Glucometrics" tab to view the summarized results of glucometric readings as well as an exclusion summary and data quality indicators (see Figure 3).

The glucometrics report generated from this tool was validated against a published tool[17] by analyzing a test data set[34] provided by the authors of the published tool. By applying the same cut-off values and exclusion criterion (i.e., patient stays that have only 1 BG measurement were excluded) from the published tool to our tool, we were able to reproduce the number of patient-samples, patient-days and patient-stays, and the summary statistics concerning adverse events (i.e., hypoglycemia and hyperglycemia) and the target range of BG levels, reported in the glucometrics report generated by the published tool. Detailed parameter configuration of our tool when analyzing this test data and the resulting glucometrics report from both tools are available in a supplementary material (available from: https://github.com/nyilin/QcDM_Project/blob/main/Supplementary_material.pdf).

DISCUSSION

Glucometrics, a set of measures for monitoring the quality of glycemic management in inpatients with DM, was proposed more than a

decade ago, but its uptake in healthcare institutions has been limited by the lack of an easy-to-access software to handle the extensive data consolidation and manipulation. This paper presents an open-source tool for glucometrics calculation. We developed an R package that implements a variety of commonly used glucometrics measures, and subsequently developed 2 user-friendly GUIs that simplify the data processing and configuration steps, and automatically generate a report of consolidated glucometrics measures computed by the functions in the R package. The development of this software enabled translational research by taking research methods in healthcare analytics and successfully implementing them in a framework for routine operations in an academic healthcare setting. This demonstrates the essence of multidisciplinary work. The software has been used for regular glycemic monitoring within an academic healthcare institution to generate monthly, quarterly and yearly glycemic control reports. Using the same set of parameters as input, it has enabled the direct comparison of reports across different time points. These automated reports have also reduced the work of healthcare staff who are managing the glycemic program, allowing them more time in clinical work. By using masked identifiers and deploying the tool in a local, secured server or encrypted USB storage device, data privacy can also be ensured. The vendor agnosticism in the design of the tool resulted in a flexible architecture which may be extended through the use of other open-source R libraries.

Successful deployment of this software does require close cooperation between healthcare practitioners and information technology staff. Although the current software was specifically designed for a glycemic control program, this work can be easily adapted to other inpatient situations requiring routine glucometrics evaluations. For example, although we designed the software to work on point-of-care, capillary BG data, it can also be used directly to generate basic glucometrics from continuous glucose monitoring (CGM) data that conforms to the required data format. However, given the granularity of the CGM data, glucometrics specific to CGM data and the potential difference in the patient care settings,[35,36] future work should adapt and extend the tool for CGM data.

We developed the QcDM software to be run manually on a workstation using BG data extracts. Yet with moderate local technical effort, it can be automated and integrated with other electronic health records (EHR) reports. The QcDM package can be used with an R script to securely query a local database which contains the input data, extracted from warehouses via a scheduled SQL procedure. Once the QcDM script ingests these data and calculates glucometrics, the output can be displayed using R-Shiny or displayed on a local reporting server; a document link can be placed in the EHR. To facilitate more seamless integration, future work could consider leveraging Fast Healthcare Interoperability Resources for data exchange in the context of developing glucometrics as an electronic clinical quality measure .[37–39] The QcDM package could be adapted and called as a calculation system for expression logical model and clinical quality language documents.

CONCLUSION

We illustrate the development of a GUI reporting tool for inpatient glycemic control that facilitates both research and healthcare operations by transforming electronic medical data into actionable insights for healthcare staff.

CONFLICT OF INTEREST STATEMENT

None declared.

DATA AVAILABILITY

The software described in this paper is available as an open source tool distributed under the MIT license. More details on the software discussed in this paper and its source code can be found at: https://github.com/nyilin/QcDM_Project.

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