C4G BLIS: Health Care Delivery via Iterative Collaborative Design in Resource-constrained Settings

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ABSTRACT

Health care delivery in resource-constrained settings presents many challenges, including highly diverse workflows, lack of standardization in data collection and reporting, and scarcity along many dimensions such as infrastructure, income and education. Many attempts to introduce state-of-the-art standardized systems for electronic record keeping have met with limited success in these settings. We present the design, implementation and evaluation of C4G BLIS, a system that tracks patients, laboratory samples, test results, and generates customized reports and trends for patients, physicians and health officials. The system was designed and deployed based on two major principles: (1) an Iterative Cooperative Design (ICD) methodology (2) immediate and continuous benefits for day-to-day users of the system. C4G BLIS is currently in use in many large hospital laboratories in Africa, and we report on the experience and results from these deployments, including improved turn-around times, reduced error rates and user satisfaction.

CCS Concepts

•Human-centered computing → HCI design and evaluation methods; •Applied computing → Health care information systems; •Information systems → *Database design and models;*

Keywords

Developing nations, Hospital Laboratory, Health Care, ICTD, Customizable, Zero-training

1. INTRODUCTION

Health care delivery in sub-Saharan Africa remains an important and formidable challenge today. Doctors, clinics and access to treatment for infectious diseases and other conditions are in short supply [6]. This shortage is exacerbated by the lack of infrastructure and the diversity in medical practices [7]. Almost all of the over 1500 hospital laboratories in this region record activity only on paper-based logbooks, leading to high error rates, significant clerical overheads and virtually no access to patient histories or aggregate trends [8]. How can a computerized laboratory information system help in such environments? What should its design be so as to serve these functions without imposing an additional burden on laboratory staff? How can it be evaluated?

Addressing these questions resulted in the development of the Computing-for-Good Basic Laboratory Information System (C4G BLIS), an open-source system developed by the C4G initiative at Georgia Tech, in collaboration with the CDC, Laboratory staff across Africa, MoH personnel in participating countries and local NGOs. The system has been in continuous deployment since May 2010 and has expanded from its initial deployment in 3 hospitals in Cameroon to dozens of hospitals, in Uganda, Tanzania, Ghana, DRC, Kenya and Cameroon.

Our central finding is the following: In resource-constrained settings, *Iterative Collaborative Design* (ICD) [23] along with *continuous benefits to end users* can result in effective and sustainable systems for health care delivery.

The collaborative nature of the development cycle allows the needs of many different regions and various resource constraints to be taken into account without assuming the stakeholders are proficient with computers. These findings are based on 6 years of design, deployment and maintenance, the results of a 6-month pilot evaluation conducted in 3 hospital laboratories, a broader survey conducted in 2012, and continuous feedback from stakeholders. We also provide a qualitative analysis of the effectiveness of the system, lessons learned and the prospects for future sustainability.

1.1 Problem and background

Clinical laboratories perform the following functions: They register patients, collect and register specimens from patients, schedule tests, record test results and report outcomes to patients and doctors; they also keep track of equipment and supplies and maintain billing information. It is vital to report results correctly and keep the *turnaround time* from the registration of the patient to the reporting of

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System	Power?	Infrastructure?	Cost?	Diversity?	Technical Proficiency?
Bika LIMS[11]	**partial** manual backups	**yes** web-based	**free**	**partial** multilingual	**yes** nonfree training
StarLIMS[12]	**partial** manual backups	**yes** intranet use	**no** ~$8000 to ~$18,000[16]	**yes** multilingual, customizable	**yes** nonfree training
OpenMRS[13]	**no** recommend power backup	**yes** intranet use	**free**	**yes** multilingual, customizable [17]	**no** training suggested
OpenELIS[14]	**partial** paper system backup	**yes** intranet use	**free**	**partial** English/ French	**yes** onsite training [18]
GNU Health [19]	**partial** manual backups	**yes** intranet use	**free**	**partial** multilingual	**yes** 3rd party training [15]
C4G BLIS	**no** backup UPS units	**minimal** wireless router	**free**	**yes** extreme customizability	**no** zero-training interface

Table 1: Analysis of existing LIMS systems

the outcome as brief as possible [4]. Needless to say, errors in recording or reporting test results can lead to incorrect diagnoses and serious complications. The purpose of a laboratory information system is to help improve the accuracy and efficiency of the laboratory; the latter is key to scaling up capacity. Besides turnaround time, efficiency is also reflected in the time taken to look up a patient's history in the lab, i.e., previous test results.

1.2 Challenges of resource-constrained settings

Record-keeping. The resource-constrained settings motivating this work are clinical laboratories in sub-Saharan Africa, where most record-keeping is paper-based. In a typical laboratory, there are separate logbooks for registering patients, specimens, test results, and a paper report is prepared for the patient and/or doctor. Each section of the laboratory (haematology, chemistry, TB, HIV etc.) often has its own register. Thus, record-keeping imposes a significant clerical burden on laboratory technicians and administrators and magnifies the chance of errors in transcription.
Power supply is intermittent in many regions with a need to resort to back-up power (if available) for several hours a day [9].
Computing infrastructure is limited in many ways. Most laboratories currently do not have internet access or computers. When available, internet access is slow and unreliable.
Variability in lab practices. Tests conducted in laboratories vary from one lab to another, even within the same country. Measures used to record test results, terminology for various laboratory entities and interpretations of results vary as well. The actual workflow of a sample from collection to reporting can vary depending on the physical environment. As expected in a region with such great diversity, there are major variations in language and culture [6].
Cost. The development, licensing and maintenance costs usually associated with software development are typically too high for our target settings in the long run. Moreover, unexpected technical hurdles require on-site help and result in significantly higher consulting/travel charges. Thus, a commercial vendor has not been a viable option [2] [3].
Computing workforce. There is a shortage of lab technicians with IT experience, and a general shortage of IT developers. Laboratory staff, who typically have degrees in Biology, Chemistry or Pharmacy, have limited experience with computers and have not previously used an LIS [10].

2. RELATED WORK

Laboratory information management systems are the norm in developed countries. Following are some of the notable existing LIMS efforts that influence some of the functionality and development process of C4G BLIS:
Bika LIMS - A CMS-based LIMS being used in South Africa, primarily in the chemical analysis industry [11].
StarLIMS - A commercial web-based LIMS that places a significant focus on interfacing with laboratory equipment directly, as well as emphasizing the traceability of a sample collected in the laboratory [12].
OpenMRS - Open-source LIMS whose development cycle places a heavy emphasis on collaboration [16][40].
OpenELIS - A free, open-source LIMS which places an emphasis on being adaptable to a variety of different existing record systems [14].
GNU Health - Free health and hospital management system that focuses on providing laboratory management to underdeveloped areas and facilitating care to the underprivileged [15][41].

These systems address the traceability of samples/ tests/ patients and other challenges in developing regions, adaptability to various existing systems, and fostering collaborative development of the system [4]. Although these systems and others offer solutions for the needs of laboratories, there are several shortcomings they commonly demonstrate[summarized in table 1]. Most commonly these shortcomings are related to a failure in implementation or post-implementation of the LIMS. These failures can be attributed to poor or rushed training of technicians, as well as inadequate access to the LIMS in daily use. The implementation itself can also be flawed; if a system is not properly installed/configured, it will be more prone to failure in day to day usage [1]. Another problem that many of these systems failed to incorporate is the vast variability of labs in Africa, and the brittleness of a "one-size fits all" approach that forces labs to change their workflow or terminology overnight.

A common shortcoming is the lack of a mechanism whereby the users of the system (technicians, administrators, and clerical personnel) can provide feedback to the developers. Enabling the users to request needed features, call attention to bugs, and provide other feedback on the usefulness of the LIMS enables the developers to create a system that is more relevant to the laboratories, and prevents them from spending time on unnecessary or unwanted changes [1]. In addition to this, there are also environmental factors that limit the effectiveness of many past solutions. As mentioned in Section 1.2, there are several resource constraints that influence the effectiveness of a LIMS in a particular region. Most notable of these are power and internet connectivity, but there are other shortcomings of infrastructure that harm the effectiveness of some solutions.

Besides LIMS', there are also many Hospital Information Management Systems (HIMS) that are mainly used for the purpose of electronic record keeping. Some examples are DHIMSII [26] and HAMS [27]. These are more adopted in certain regions in Africa than LIMS'.

3. THE EVOLUTION OF C4G BLIS

3.1 Design principles

Our goal was a laboratory information system to support laboratory functions without imposing new burdens. Over time, and in collaboration with users and stakeholders, we arrived at the following design principles:

1. Robustness to limited infrastructure. To handle frequent power cuts, laboratories procured additional UPS units. The system itself does not rely on the internet for any of its operation. A simple local wireless network was set up with a single locally available router.

2. Simple, minimal user interface that does not assume prior experience with computers (but does assume familiarity of users with lab functions). Our goal here was zero training for a workforce that was laboratory-trained but possibly lacking experience with computers.

3. Flexible database that allows fields to be added and modified as labs evolve. The fields used for registering patients, specimen, tests and results vary widely across laboratories, and change over time even within the same lab. C4G BLIS handles this diversity and transition smoothly.

4. Fully configurable and customizable workflow that lets the lab administrator determine form and functionality while keeping all actions accountable. The user interface was made configurable to the labs workflow so that any user already working in the lab needed no extra training to start using C4G BLIS

5. Patient confidentiality and system reliability, especially in retaining data and in matching test results with patients. Many aspects of medical records are confidential, especially with the high prevalence of chronic diseases. C4G BLIS allows lab managers to choose security levels of users, so that technicians entering results cannot view patient names, reports can be generated without names etc. The system maintains a backup of all database operations so that the entire database can be reconstructed if needed.

6. Respect for stakeholders' time and feedback, recognizing that they are making the most of available resources, and providing them continuous benefits without duplication of work. An initial challenge was to avoid "double" work for lab staff when they started using C4G BLIS, i.e., entering data in both the system and in paper records. To do this, we included the option of a daily log and a weekly log, so that the lab could print this report and file it with their physical records.

7. Collaborative development environment with substantial local participation. This aspect of the overall system took a few years to get started. While local participation in the *design* of the system was crucial and substantial from the beginning, it is only in the past two years, that local developers have joined the progamming effort and created new modules within C4G BLIS that are in use in multiple sites. Part of the reason could be the scarcity of experienced local programmers, an aspect that is gradually improving.

8. Immediate and continuous benefits for day-to-day users of the system. System users (lab staff, managers, clinicians) must feel the system adds value to their daily operation. To this end, we (a) responded as quickly as possible to feedback on the interface, usually within 24 hours (b) added new features after consulting with our implementing partners, always in a configurable way (c) respected and enabled current methods in daily use, without trying to enforce standardization or other changes.

In addition to laboratory staff in participating countries, we worked in close collaboration with the International Laboratory Branch of the Centers for Disease Control and their local personnel, a group whose core mission includes strengthening laboratory practices in PEPFAR countries and whose global experience played an essential role in our design, development, deployment and evaluation.

3.2 Design

The design principles of the previous section formed the basis of our design methodology for C4G BLIS, and lead to a continuously evolving system in terms of both extensions and improvements based on user feedback. We used the following cycle: implement current design, solicit further feedback, update design. We refer to this paradigm as Iterative Collaborative Design (ICD). The ultimate aim was to ensure immediate and continuous benefits for the users after each release.

The starting point was a rudimentary system in 2009 that was able to register patients, samples and test results, and generate reports. It was based on surveys administered in 12 laboratories across Africa, from Cameroon, Ghana, Botswana, Tanzania, Uganda and Nigeria. Early choices included: Open-source for cost reasons; Windows OS, since it is the prevalent platform across all our target regions; mySQL + PhP for the database and interface, since we wanted a browser interface and access on a local wireless network.

Over the subsequent year, we received feedback by email from staff in these laboratories and from visits to participating laboratories by CDC personnel. To collect feedback, we asked lab users to perform a set of tasks, record their anticipated difficulty (pre-task) and experienced difficulty (post-task), and any specific comments they might have. An observer would only intervene if the lab user was unable to proceed for some reason. Following this, we had an oral feedback session. In the first year, these evaluations and interviews were conducted for us by CDC personnel, senior staff in participating laboratories, and Global Health Systems Solutions (an NGO). We now discuss the major design aspects.

3.2.1 Database Schema

In the design of databases, there is a tradeoff between efficiency and flexibility, i.e., specialized fixed tables to make queries and updates to the database as efficient as possi-

1. What tests are handled in your laboratory?
2. What samples are handled in your laboratory?
3. What specific machines are used in your laboratory? Please list details about the machine and the tests for which they are used.
4. How is the output of the machine recorded? What format? Please send sample outputs for each machine and test.
5. How would you describe the internet connectivity in your laboratory?
6. Does your laboratory currently have computers? If yes, how many, what type (desktop, laptop, etc) and what are they primarily being used for?
7. What are the monthly averages for the number of patients and number of tests samples handled by the laboratory?
8. How are test results and reports sent back to the originator (Doctors, patients, health centers)?
9. Are test results or Summary results reported to regional or national headquarters?

Figure 1: Questionnaire for the survey conducted prior to pilot implementation

ble vs a single table structure ("entity, attribute, value") to which it is easy to add new fields but might not scale well. C4G BLIS handles a large amount of data and this was always anticipated; on the other hand, the fields used for registration, measures used to record tests etc. vary considerably and future requirements cannot fully be anticipated. In other words, besides data such as user credentials, patient information, test results etc., there is also the need to store data for customizable entities such as user-defined specimen and test catalogs. We use a hybrid schema, by viewing the database as three separate logical parts. The first set has tables to store data for patient information, tests etc. and assign a unique integer ID to every tuple. A second set of tables that stores data for each custom field (that users can choose to create) along with its field id. The third set of tables has information about all custom fields. Figure 2 illustrates this for patient fields.

3.2.2 User interface

C4G BLIS has a minimal user interface designed on the principle of unobtrusive expansion. We use JQuery and Ajax for updating sections of page on user-triggered events to display requested information. This technique has also been helpful in designing a clean and responsive user interface that prevents delays in information retrieval from affecting the user.

Configurability of language and terminology.. The need for C4G BLIS to support multiple languages and varying terminology for lab procedures even within the same country and linguistic region was apparent from our initial surveys

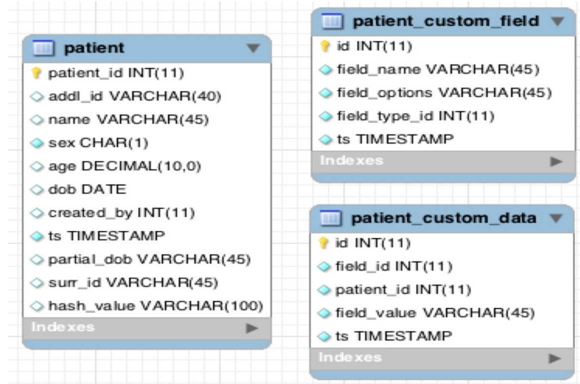


Figure 2: DB schema for patient information

and discussions. We decided to support current practice as best as possible rather than attempt to standardize. If and when labs or countries choose to standardize practices or terminology, the system would enable this. Thus, one of the key configuration features in C4G BLIS is the ability to choose the base language and to modify the user interface text and messages locally. All strings displayed on the system's front end are coded as a set of name-value pairs and stored in the database. This allows us to provide the user with an option to switch language (via a button provided in the footer of the system). Currently C4G BLIS provides the options for English and French and with our design, adding more languages is a simple, user-driven process.

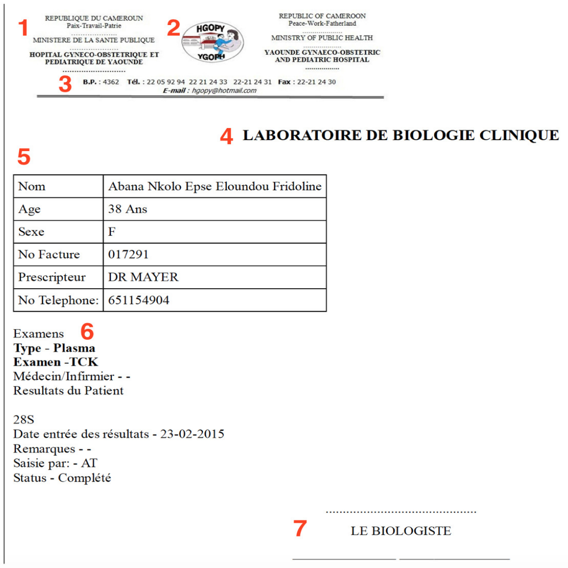
Configurable user help.. An integral feature of C4G BLIS is the provision of page-specific tips for the users in the top-right section of the screen. These concise tips serve as an aid to the user to learn what that specific page provides and how to use it. The actual text that appears in the tips boxes can be modified by an admin user. In addition to this, users are also provided with a comprehensive user manual that is accessible from within the system.

3.2.3 Customizable workflow

C4G BLIS is designed to be configurable by the lab admin to align its operation and available features with lab's current practices and to modify the configuration as lab practices evolve. Labs can define the tests they conduct in terms of their name, measures, specimen compatibility, target turn-around time etc. thus creating a test catalog as per their practice. They can also create custom worksheets, for specific types of tests.

Optional components.. Some features are incorporated into the system as either optional or core, based on their relative importance to the goals of the system and their priority to the users. C4G BLIS provides the ability to enable/disable features. This can be accomplished by the lab administrator without the risk of losing any data associated with features.

Results Interpretation.. Upon request from participating labs, we included the ability to specify text-based interpretations for user-defined values or ranges of test measures. Thus, when patient reports are generated, the specified in-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4 **LABORATOIRE DE BIOLOGIE CLINIQUE**

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Examens 6
Type - Plasma
Examen -TCK
Médecin/Infirmier - -
Resultats du Patient

28S
Date entrée des résultats - 23-02-2015
Remarques - -
Saisie par: - AT
Status - Complété

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Figure 3: Snapshot of a customizable report rendered in french

terpretation of results can be included in the report. For example, in case of a test measures with numerical values, the user can set the result interpretation field as "positive" if the value of the measure is higher than a pre-set threshold.

Reports.. C4G BLIS started out with a set of basic reports including patient reports and daily usage logs, the latter to avoid having to create paper records. As the system evolved, we added more reports on the basis of demand and user feedback. It now has a wide variety of reports capable of displaying information such as prevalence rates, infection data, turnaround time, user statistics and doctor statistics. We note that some of these reports including the one displaying doctor statistics were not conceived by us, but were only included after receiving requests from users. Such reports have played an integral part in the acceptance and sustainability of C4G BLIS, again highlighting the role the users play in the design and development.

An essential feature of reports is that they are highly customizable. One issue we faced after the initial deployment is that both staff and patients were more comfortable with the hospital logo and signatures of the supervising staff member(s) included on patient reports. So there is the option to upload the laboratory's logo as part of the configuration, and have it appear on patient reports. Also configurable is the choice of fields displayed as well as the headers and footers of the reports. Figure 3 shows a sample report in french with its customizable components labeled in red.

Some hospitals also store paper based reports in addition to the electronic reports in C4G BLIS. In such cases, it would typically be a burden on the users as they have to enter the same data twice. However, C4G BLIS makes this efficient for the users by allowing them to print or export reports and provides support for formats such as Microsoft Word (.doc) and PDF. The system also has a feature to export the daily log and print the same.

3.2.4 Reliability.

Backup.. C4G BLIS deals with sensitive medical records and has a feature for generating a backup of the current data. The backup feature exports the database to an SQL file that can be later imported to restore the database. Users have the option to create an encrypted or an anonymized database. These options protect patient confidentiality. Backups have been used both to see nationwide aggregate data and trends and to debug problems faced by users.

Patient-result matching.. It is critical for labs to correctly match test results with patients. To ensure this, C4G BLIS adds a background mechanism for cross-checking results. This is done by computing a hash for every patient based on their name, gender and age, and appending this to each of their test results in the database. Thus when the results are retrieved for generating a patient report, the hash value can be checked for consistency.

3.2.5 Interoperability

Instrumentation Module.. The latest release of C4G BLIS (v3.0) allows external instruments to be plugged into the system in order to push/pull patient tests data/results. Currently, the system supports 12 instruments with the facility to add new instruments or update configurations of existing instruments from the UI.

Integration with local HIMS systems.. Version v3.0 of C4G BLIS also supports integration with local HIMS systems and provides the ability to pull reports for view from the C4G BLIS UI. Currently, DHIMSII [26] by Ghana has been added to the system and is in use.

3.2.6 Wireless connectivity.

C4G BLIS has been designed in such a way that it is easily accessible over a local area network where multiple computers can be connected through a wireless router. The system is installed on one machine which acts as the server and makes C4G BLIS available to all other systems via a web browser by going to the server machine's IP appended with a predefined port number.

3.2.7 Other significant features

Director interface.. Version 2.0 was a major release for C4G BLIS that introduced a module for country directors. This interface allows a country director to create configurations for setting up C4G BLIS for new labs. The country director interface also provides a feature for importing data from multiple labs and viewing aggregate reports, thus obtaining a regional or national view.

Billing.. As part of v2.3, we introduced billing in C4G BLIS. This was a feature requested by many of the labs as a critical need for them. Initially higher-level administrators were wary of including this feature. In the end it was included as an optional feature. It can generate invoices for patients automatically, and the costs of tests can be configured.

Inventory management.. Similar to the billing feature, an inventory management module was also added after requests for the same by multiple labs. This feature is now being widely used by many laboratories as reflected in our evaluation.

Barcodes module.. With the help of a generic barcode reader, this feature enables C4G BLIS to generate and recognize barcodes for quickly identifying and searching for patients, specimens and inventory items. In contrast to the billing and inventory feature, the barcode support was conceived by us; it has been welcomed by lab staff and is thus being extended across other C4G BLIS functions.

4. C4G BLIS INSTALLATION AND MAINTENANCE.

The first version of C4G BLIS was deployed in the Buea Regional Hospital Laboratory in Buea, Cameroon on 1st May, 2010. It has been in continuous operation in this laboratory since then. It was subsequently deployed (in 2010) in two other labs in Cameroon, in Bamenda Regional Hospital and Laquintinie Hospital, Douala. In 2011, the system was deployed in 3 labs in Uganda and 3 labs in Tanzania. In the following year, it was deployed in 12 labs in Ghana and in 2013, C4G BLIS was deployed in 2 labs in DRC. In the last two years, it has expanded further and is also being used in many labs in Kenya. Since its initial deployment, C4G BLIS has undergone over 70 updates, with frequency of updates starting at roughly once every two weeks but now down to once in 4 to 6 months.

4.1 Installation

Our focus was to make both initial deployment and application of subsequent updates to the system as simple and user-friendly as possible. We believe this to be an important factor in not only promoting the initial adoption of C4G BLIS by medical laboratories but also in avoiding the need for extensive support for applying system updates on client machines. C4G BLIS runs on any laptop or desktop without any special installation procedure. It is ready to run as soon as it is downloaded [24] clicking the BLIS.exe executable. On startup C4G BLIS can set up its runtime requirements including the web server (Apache) and the database (MySQL) server. Making the system accessible over a local area network is also a simple task. A user just needs to download the system on one machine that is connected to the network followed by clicking on "Setup Network" link provided in C4G BLIS interface. This machine then acts as the server making the system accessible to all machines connected to the network via a web browser. In the labs where C4G BLIS is currently deployed, multiple computers are used in different sections of the lab and connected by a wireless router.

4.2 Updates

Internet connectivity poses a challenge to propagate system updates to users. Our update procedure allows the lab administrators to download the update from any location that has internet connectivity, often their residence or a cybercafe, and bring it to the labs on a storage device to apply the update. The update procedure has evolved from manual updating of code from a zipped version of updated source code to an automated process that applies the update on client systems with minimal user intervention. This was an important step towards making C4G BLIS more sustainable

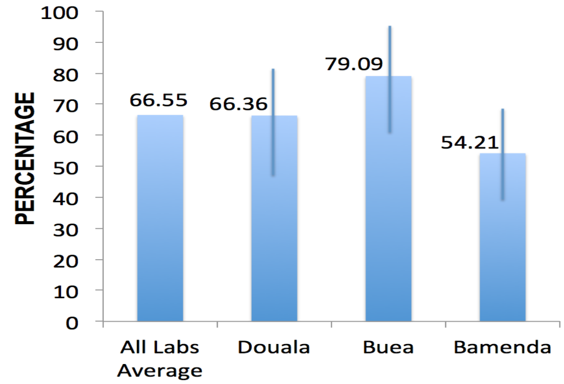

Figure 4: Average error reduction rate.

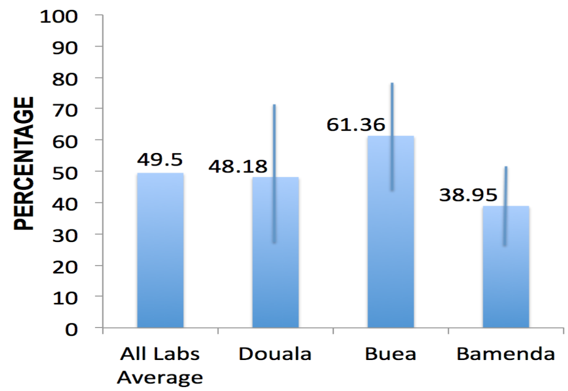

Figure 5: Average workload reduction.

and sensitive to user constraints. The procedure has evolved to a point that is capable of handling both database and code updates in a robust and unified streamlined process of both preparing and applying the update making it easier and less error-prone.

4.3 Backward compatibility

All versions of C4G BLIS from v2.9 are backward compatible which means that the update packages can be applied to any previous version, not just the immediate previous version. This is to minimize the effort for labs that may have missed an update and wish to install the latest version. With each update, we also provide a complete installation package for new users.

5. EVALUATION

The primary purpose of our evaluations was to determine the impact and effectiveness of C4G BLIS in its target environments. Based on all the feedback prior to deployment and our design principles, we hypothesized that

1. Labs with C4G BLIS will be able to handle more patients, specimens and tests.
2. They will have fewer errors.
3. Users in these labs will not feel an additional burden.

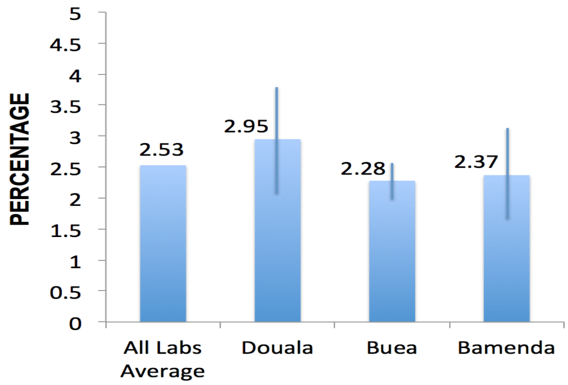

Figure 6: Average user ratings after completion of study.

5.1 Results from evaluations conducted by GHSS

To assess the effectiveness of C4G BLIS in improving the efficiency and performance of laboratory activities, we conducted a series of qualitative and quantitative evaluations. Our sources for these evaluations include:

1. Results from pilot evaluation from Sept 2010 to Oct 2010 (Cameroon).
2. Results from a year-long evaluation from April 2011 to April 2012 (Cameroon).
3. Analysis of anonymized laboratory data from 5 labs (3 in Cameroon, 2 in Ghana).
4. User survey conducted in April 2013 in 7 labs.

We present the results below. Before the system was expanded in Cameroon and deployed in other countries, a pilot study was performed to evaluate the usefulness of C4G BLIS at the time, and determine what problems it may have been facing. This study was performed by Global Health Systems Solutions (GHSS) staff. The 6-week study in Cameroon had the goal of achieving the following:

1. Setup software and train users.
2. Provide technical support as situations arise.
3. Send daily feedback to Georgia Tech to report inadequacies or bugs in the system.

In addition to these high-level goals, there were specific objectives that the team hoped to achieve. The metrics for these objectives were data capture rate, error reduction, workload reduction, and user rating. The data capture rate in the 3 labs in Cameroon went up from 37.7% to 96.6%, i.e., by the end of the study less than 3.4% of data was entered manually. On average, errors made in laboratories in Cameroon went down by 66%(Figure 4). Error reduction was measured in terms of number of entry errors, invalidated results, reports sent back to laboratory for verification, and complaints by clinicians and patients. The average workload reduction was found to be nearly 50%(Figure 5). Workload was measured using patient registration time, result entry time, result search time, time to calculate infection rates, time to generate reports and some additional tasks. Laboratories also reported reduced registration times from an average of 52 seconds pre-BLIS to 27 seconds with C4G BLIS. The reduced times initially meant significant daily savings, and gradually lead to labs serving more patients and a larger volume of tests.

Voluntary user ratings indicated that the personnel did not feel that C4G BLIS imposed an undue burden on their performance, and did not impede workflow. This was administered as the following optional question with responses based on Likert's scale [25], whenever a user logged out of the system. An average user rating of 2.53 was measured, indicating user satisfaction (Figure 6).

How would you rate this experience with C4G BLIS?
1. Highly satisfactory
2. Somewhat satisfactory
3. Neither satisfactory or unsatisfactory
4. Unsatisfactory
5. Highly unsatisfactory

In addition to these metrics, GHSS personnel reported that user adaptation and performance was high, even among those who had no prior experience with an electronic management system.

5.2 Analysis of laboratory data backups

In order to get precise statistics on usage of C4G BLIS we obtained the (anonymized) database backups for a set of labs in Cameroon and Ghana. On the basis of this data we wanted to study the impact of C4G BLIS on the volume of patients served and tests conducted. Thus we counted the number of patients registered and the number of tests conducted on a weekly basis, before the installation of C4G BLIS and 2-6 months after its installation (the system was installed at different times in the labs in Cameroon and in Ghana). We hypothesized that these two statistics should increase during the initial period of deploying C4G BLIS. In a span of few months as the lab fully adopts C4G BLIS and the users become comfortable with the system the volume of patients served and tests conducted approaches a relatively steady value. We note that these are the complete data, not a sample. The plots below show the number of new patients served. Figures 7 and 8 show the trend for the number of patients registered per week starting from the very beginning when the C4G BLIS was installed in the respective labs. All the three curves show a similarity in case of the number of patient registrations in the initial weeks of adopting C4G BLIS. There is an increase in the number in the first few weeks which later stabilizes as time passes (there are gaps in data in the chart due to a few factors out of our control, e.g., in Buea, timestamps were not added with patient registrations till mid-2012). We found similar results for the number of tests conducted per week.

5.3 User Surveys

A survey in the form of a questionnaire was conducted in April 2013 to assess the user experience and the extent of impact and usage of C4G BLIS in the various labs. It consisted of 11 questions divided into two sections. The first section consisted of 8 questions, required to be answered by all users, aimed at obtaining user opinion for gauging the impact of C4G BLIS on the individual labs as well as for evaluating their overall experience and satisfaction with the system. The next section consisted of a set of 3 questions, applicable to only the lab administrators, requesting estimates of quantitative data about their lab operations. We received 42 responses from 7 laboratories in Cameroon and Ghana. The respondents included lab staff operating at different levels and designations, namely, deputy directors, lab administrators, biomedical scientists, department heads, lab technicians, secretaries and receptionists. Lab administrators were also asked to provide the estimates of the weekly number of patients and tests conducted in their labs, as well as number of errors discovered, both pre-C4G BLIS and post-C4G BLIS. We report on these first. The increase in the number of patients the labs serve after implementing

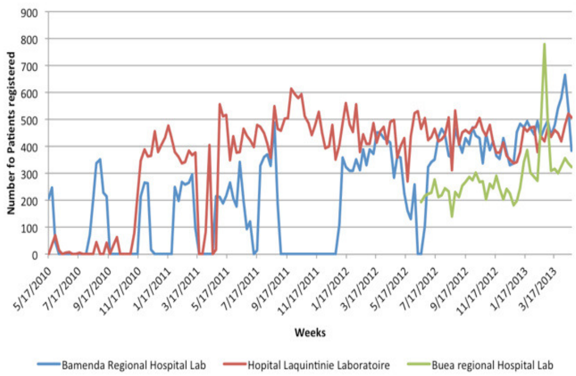

Figure 7: Number of patients registered per week (Cameroon Labs)

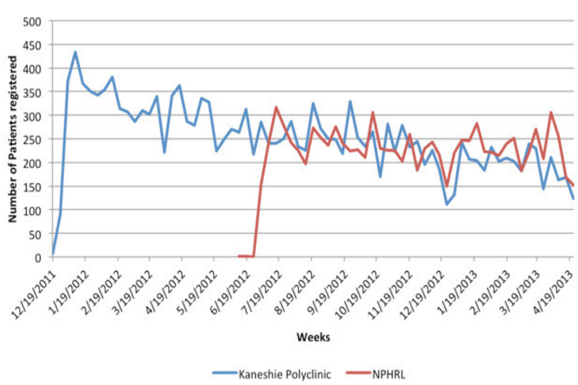

Figure 8: Number of patients registered per week (Ghana Labs)

Laboratory	Patients Served / Week Before C4G BLIS	Patients Served / Week After C4G BLIS	Increase (%)
Bamenda	420	550	23.64
Buea	420	560	25
Kaneshie	70	85	17.65
Koforidua	130	140	7.14
NPHR	30	35	14.29
Saltpond	75	90	16.67

Table 2: Increase in the number of patients the labs serve after implementing C4G BLIS

Laboratory	Tests Conducted/Week Before C4G BLIS	Tests Conducted/Week After C4G BLIS	Increase (%)
Bamenda	1250	1500	16.67
Kaneshie	130	150	13.33
Koforidua	650	750	13.33
NPHR	50	60	16.67
Saltpond	140	185	24.32

Table 3: Increase in the number of tests conducted per week after implementing C4G BLIS

Laboratory	Errors Before C4G BLIS	Errors After C4G BLIS	Error Reduction (%)
Bamenda	8	2	75
Buea	3	1	66.67
Kaneshie	4	0	100
Koforidua	10	2	80
NPHR	3	0	100
Saltpond	5	1	80

Table 4: Reduction in errors after implementing C4G BLIS

C4G BLIS ranged from 7.14% to 25%(Table 2). The number of tests conducted per week by these labs also increased by significant amounts ranging from 13.33% for Kaneshie Polyclinic and Kofridua Regional Hospital Lab to 24.32% for Saltpond Municipal Hospital Lab(Table 3). There was a significant decrease in the number of errors found after implementing C4G BLIS. The reduction in errors ranges from 66% to 100%. Considering the immense importance of correctness of results in a medical laboratory we feel these numbers to be very significant in improving the overall quality of the service provided by the labs(Table 4). The majority of the errors both before and after adding C4G BLIS were classified as 'transcription errors', although most of Bamenda's errors were classified as duplicate entries before C4G BLIS and spelling or data capture errors after implementation. These results indicate a clear improvement in all three measures used. We now turn to the responses for the wider survey. Responses were based on the Likert scale.

Q1. How has C4G BLIS impacted your laboratory's workflow?
Q2. How has C4G BLIS affected your workload?
Q3. How has C4G BLIS impacted the speed of patient registration?
Q4. How has C4G BLIS impacted the accuracy and correctness of test results?
(Response options: 1. Significant improvement 2. Minor improvement 3. No improvement 4. Minor degradation 5. Significant degradation.)
Q5. How would you rate your overall level of satisfaction with using C4G BLIS? (1. Highly satisfied 2.Moderately satisfied 3. Neither satisfied nor unsatisfied 4. Moderately unsatisfied 5. Highly unsatisfied)
Q6. How inclined are you to recommend C4G BLIS to other labs? (1. Highly likely 2. Somewhat likely 3. Neither likely nor unlikely 4. Somewhat unlikely 5. Highly unlikely)
Q7. Which features of C4G BLIS do you use most frequently?
Q8. Which features of C4G BLIS are most useful to you?

As evidenced in table 5, most of the responses were '1' or '2' indicating a high level of satisfaction/improvement with C4G BLIS and a noticeable contribution to the efficiency of the laboratory workflow. From these results, it can be inferred that lab staff feel that C4G BLIS has had a significant positive impact on their workflow, reduced their workload, improved the speed of patient registration and accuracy of test results and report. We note that 100% of respondents were highly satisfied or moderately satisfied with the system and 88% were highly likely to recommend the system to other users (with the remaining 12% being somewhat likely to do so).

Besides this, we also received a report from I-Tech Kenya that adopted C4G BLIS in 17 laboratories starting in 2014. Lab technicians from these labs reported that the system is user friendly and easy to use as it mimics the lab workflow. The users also noted that C4G BLIS has decreased the turn-around-times (TAT) of laboratory results making it easier to track patient specimen within the lab. The users pointed out that the system is beneficial in encouraging accountability among users, as all activities undertaken in the lab are traced back to the user and logged into the system. C4G BLIS has enabled lab users to more easily determine the workload at each laboratory department, making it easier for lab managers to assign duties.

The survey results and the feedback from different labs indicate a substantial improvement in the performance of each of the labs that adopted C4G BLIS. It is important to observe that the volume of patients served and tests conducted has increased appreciably without compromising the quality of service. Indeed the quality of service can be observed to have been improved considerably as measured by the improvement in accuracy of lab records and provision of additional services such as printed patient reports made possible by C4G BLIS.

6. DISCUSSION

In resource-constrained environments, a major challenge is the lack of well-specified requirements for system design. In many cases, it is difficult for designers, developers or stakeholders to foresee what the solution would be. Iterative collaborative design (ICD) is well-suited for such scenarios.

Adopting laboratory information systems has run into many difficulties in developing regions. Systems that work well in developed regions assume the availability of infrastructure and resources and are thus a mismatch. They also impose expectations and constraints on user behavior and workflow (e.g., by insisting on standardization), making them untenable in laboratories where workflows have adapted to suit local circumstances. Perhaps the most important design decision made for C4G BLIS based on user feedback was to make it ultra-configurable and customizable by individual laboratories. The results of our evaluations provide strong evidence that this design choice has been effective. The main novelty of this work is that the system designed, implemented and evaluated actually works over a long period of time (5+ years of continual use).

An automated system with up-to-date data offers access to aggregate trends and patterns that can be valuable information for health care implementation and policy. In Figure 9, we see the infection prevalence for two diseases over a 1-year period in one of the labs.

Is C4G BLIS sustainable? There is clearly a need for such a solution in hundreds of labs where an effective LIS would be vital to strengthening laboratory operations and efficiency. The first 3 deployments of C4G BLIS have been running continuously for over 5 years, with 100% of patients now recorded on the system. The number and variety of current deployments across 6 countries suggest that it can address laboratory needs across sub-Saharan Africa. After less than a month of the initial deployment in Buea, Cameroon, we got this message:

From Elive Ngale reporting on 8/25/2010, near the conclusion of the 1-month trial:
"A very important remark from Buea, is the fact that they are already closing earlier because the BLIS is facilitating easy registration and delivery of results."

What then are the main factors for the success so far, and for its long-term sustainability? Our experience suggests 4 major factors.

1. Collaborative design and development, involving all

Question	Average Response	1		2		3		4		5	
Q1	1.059	37	88%	5	12%	0	0%	0	0%	0	0%
Q2	1.882	20	48%	16	38%	2	5%	3	7%	1	2%
Q3	1.529	25	60%	16	38%	1	2%	0	0%	0	0%
Q4	1.882	31	74%	10	24%	1	2%	0	0%	0	0%
Q5	1.294	23	55%	19	45%	0	0%	0	0%	0	0%
Q6	1.588	37	88%	5	12%	0	0%	0	0%	0	0%

Table 5: User survey response.

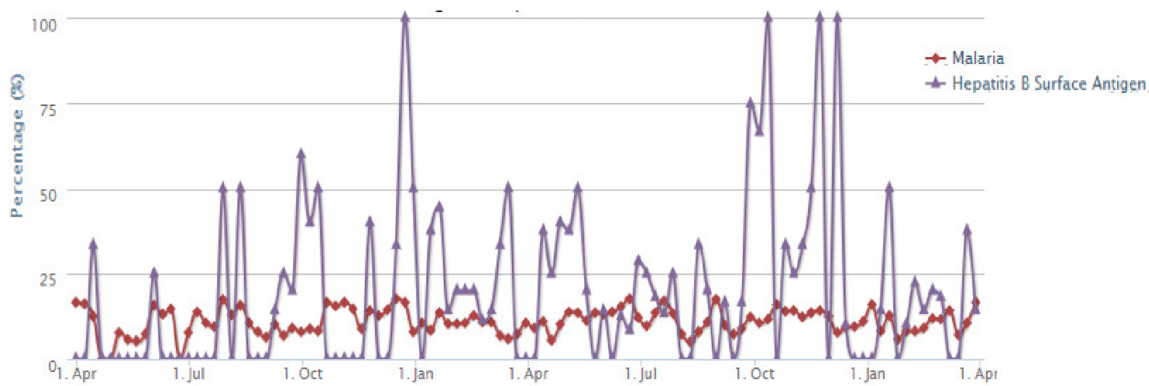

Figure 9: Prevalence rate April 1, 2011 to April 1, 2013 at Buea Regional Hospital Lab, Cameroon

the major stakeholders throughout the process. This began initially with feedback on early versions and was strengthened by quick responses, incorporating desired features and other changes. C4G BLIS is built iteratively, with each iteration coming directly as a reaction to current user feedback and needs; not with study groups or focus groups, but actual users. The user population has now a subpopulation of experts on configuration, installation and collecting feedback, and very recently local developers! Over the past year, developers from Kenya and Ghana have contributed towards the instrument interface module and integration of local HIMS systems with C4G BLIS. While ICD has much in common with both user-centric design and agile programming, there is more to it.

2. C4G BLIS provided continuous benefits to its users from day 1. This was done by providing one or more features with each update to relieve workloads (e.g., by generating customized patient reports), and by ensuring that work does not have to be duplicated (daily logs can be printed, thus avoiding the use of logbooks). In addition, we tried to respond as quickly as possible to requests for new features as labs evolved to using more technology (e.g., the use of barcode readers and direct instrument interfaces).

3. Flexible and configurable design, which ensured that even when new features were added, each laboratory could decide whether to use it, and in what form. Thus, a lab never had to change its practice abruptly, rather it could adapt over time based on its resources and policy. Labs did not even have to standardize their terminology — while a standard was available, each lab could use the configurable language option to avoid confusion up front.

4. Financial sustainability. Even though the system is free with no royalties or licensing fees attached, installation/support/maintenance all have costs as do computers, printers, wireless routers, barcode readers, printing paper/labels etc. Our initial expectation was that these costs would be borne by hospitals, both public and private, when the benefits of the system to patients and doctors became apparent. In reality, something much more direct and effective happened. Across Africa, the practice is to charge a (small) fee for every test conducted. The lab is a major source of revenue for the hospital, bringing in typically 25% or more of the total revenue of the hospital. With C4G BLIS in place, the volume of tests that labs were able to conduct went up significantly meaning the labs were generating significantly more revenue (by 34.5% on average in the 3 Cameroon labs!). Indeed, the hospital administrators had no hesitation in providing additional computers and taking care of associated costs from local budgets. The remaining challenge is to move to a state where the costs of supporting organizations are paid locally without relying on funding from the CDC or other global organizations.

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