A novel approach to ICU data visualization and communication integration

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Abstract
The intensive care unit (ICU) is a highly complex environment that houses critically ill patients requiring constant monitoring and care, as well as vast amounts of time-oriented data disseminated through a range of health information technologies (HIT), e.g., bedside and clinical decision support systems. Studies show the occurrence of medical mishaps due to diagnostic errors, impacting patient safety in spite of advances in HIT. Available visual representations of data, although time-oriented and multivariate, lack contextual information for communication among the ICU intensivists. We present a medical data visualization system (MIVA) that delivers multivariate data via a visualization display. The system organizes data into controllable time resolutions, providing contextual knowledge and communication tools at point-of-care. When comparing MIVA to paper charts, findings from two studies suggest that MIVA enabled significantly greater speed and accuracy during an in-lab experiment, while participants also noted its potential to significantly impact decision-support.

Introduction
The healthcare domain is one of the most data-rich environments at point-of-care, where physicians and other medical practitioners retrieve, organize, and interpret critical data from multiple sources that are both technological (e.g., bedside devices, electronic medical records) and non-technological (e.g., paper charts, handwritten notes). Of all clinical domains, the intensive care unit (ICU) remains a uniquely complex setting that generates a large flow of patient data. The ICU holds critically ill patients who have significant organ dysfunction, limited physiological reserve, and require constant monitoring and support. In this setting of overwhelming volumes of data coupled with alarm fatigue, ICU practitioners (intensivists) can have difficulties with making rapid and accurate evaluations of what might be seen.

Clinical errors related to diagnostic error and errors of omission, such as inaction, delayed action, or incorrect action may occur in spite of advances in clinical decision support (CDS) systems and smart bedside devices. Human factors studies demonstrate that 80% of HIT “user error” is attributed to cognitive overload in incorrect use or user error in analyzing medical data. Further findings suggest that 91% of all medical mishaps are due to communication breakdown, inefficient team collaboration, and decision-making. Communication, including face-to-face interaction, is often interrupted and of poor quality. This leads to inefficiencies and potential error in the ICU, where rapid and accurate communication is essential for delivering safe patient care.

Despite the existence of modern medical diagnostic technologies, many ICUs continue to depend on analog systems (such as paper charts) to display and record patient data. Moreover, the most current digital data visualization technology still use the same interface paradigms developed over two decades ago; often displaying too much or not enough data, giving intensivists limited control over what might be seen. In either case, intensivists are still left to navigate through a complex architecture of static patient data, while being burdened with collecting and maintaining relevant data in working memory, then integrating, through analysis of this data to arrive at a diagnostic outcome. In either case, whether through paper charting or modern electronic static data displays, user error can be attributed to inadequately designed system interfaces or interaction sequencing that directly impact cognitive load during medical diagnosis and general caregiving.

Studies have shown that when cognitive load increases, a deterioration of performance is observed in lower response times and greater errors in task performance. Conversely, studies show cognitive load reduction with using visualization versus paper charting. Although multitasking had previously been thought of as a high-level cognitive skill, researchers now acknowledge that it is an inefficient work method that contributes to cognitive overload. As a result, there is a need to design electronic tools that support adaptive processes. With the goal of reducing cognitive load and maximizing knowledge acquisition, effective data visualization strategies enable more efficient spatial reasoning, such as inferences of proximity, relatedness, and common destination.

Proposed System
Existing visualization systems assist intensivists in analyzing patient data for multiple parameters over time. However, such systems do not allow for an immediate recognition of vital sign trends and relationships between co-parameters, while presenting a comprehensive historical representation of other patient data such as lab work, med compliance reporting, x-rays, clinical notes, etc. Conversely, our team has envisioned a system that provides data visualization with other historical patient
data, while supporting communication and collaboration among ICU team members. The visualization system, referred to as the Medical Information Visualization Assistant (MIVA), was designed to assist in data analysis and decision-making in the ICU. MIVA delivers aggregated multivariate biometric data (bedside data, x-rays, labs, meds and clinical reports) via a visualization display that transforms data into temporal resolutions. The result is a spatial organization of multiple datasets that allows rapid analysis and interpretation of trends. MIVA was also designed to support decision-making and diagnosis by allowing a rapid recognition of essential changes to multiple and relational physiological data over a designated timeframe. Using selection menus, critical care team members control necessary data sources, time periods, and time resolutions to narrow down their problem list, diagnoses and final assessment of a patient’s condition in the context of a broad range of information.

In the current iteration of MIVA (Phase 3), visualization and communication technologies are combined to provide optimized human-computer interaction (HCI) during clinical workflow. It offers health care providers patient data that is intelligently filtered and presented in ways to enhance diagnosis and long-term health care management. The design of MIVA was iterative and spans over three phases from 2006 to 2013 (Figure 1).

Figure 1. Three phases of the MIVA interface from 2006 to 2013.

In Phase 1, the design of a static (non-interactive) prototype took as an initial model the visualization research of Edward Tufte. The work also included the examination of several ICU bedside devices in the context of complex data delivery. Leading up to the completion of Phase 1, the interface (i.e., the longitudinal data control tool) went through 8 iterations (See Figure 2, Left: A-H). This phase included informal participatory focus groups with medical faculty from the Indiana University School of Medicine regarding placement of data points, size of numeric information, and general location of biomedical, time, and numeric data. Findings from study 1 (outlined below) informed the Phase 2 development of a dynamic prototype using Flash Action-Script. Two key contributions to this phase included: 1) the application of a “time scrubber tool” to control longitudinal data, allowing the user to identify a specific point in time while obtaining readings for all intersecting points at the Y axis (See Figure 2. Middle) and 2) the dataset tool from which clinicians drag-n-drop the needed dataset parameter into the primary visualization display (Figure 2, Right: A-C).

Figure 2. Tool development: (L) longitudinal data control (Phase 1), (M) time scrubber, and (R) drag-n-drop datasets.

Informed by study 2 (outlined below), Phase 3 included the communications tools and refinement of icon tray with clinical notes and other longitudinal data related to patient interventions. Also, at the conclusion of study 2, a heuristic inspection was conducted to determine MIVA’s degree of the usability. Three information technology professionals (from Indianapolis) examined the MIVA dynamic prototype. The inspection findings suggested no catastrophic errors, but rather that the interface and interaction design of MIVA was well conceived. However, several lower priority improvements were recommended to improve MIVA’s usability, e.g.,: (1) the Minutes/Current Data and Date/Time labels must be clarified, (2)
the background window of each notation should match the color of that notation’s icon, (3) the background of the current data box should be red if any of the data are out of range, and (4) a pop-up legend should be created, explaining the types of icons. Changes were made immediately or put on the list of items to fix during the next development iteration.

**Empirical User Studies**

In **Study 1** we compared ICU charts and static MIVA interface prototypes. A convenient sample of 16 participants (physicians/nurses) from the medical population of the Indiana University, School of Medicine and School of Nursing, and the Regenstrief Institute were recruited. The control group (paper charts: Figure 3) and experimental group (MIVA static prototypes, Figure 1, Phase 1) consisted of eight participants each. All the participants received the same clinical scenario with eight multiple-choice questions. Participants responded with answers extracted from their analysis of either the paper charts or MIVA prototypes. The MIVA interface images were displayed sequentially (using MS PowerPoint). Experimental group participants walked through the presentation (one slide at a time) to ascertain the correct answer to the eight questions. Time-on-task and accuracy were measured for each question. Both control and experimental groups were provided a 3-5 minute priming session to understand the placement of data on the paper charts and MIVA interfaces. After completion of the tasks, all participants answered a post-test questionnaire.

Using SPSS (v17.0.2), the Mann-Whitney test identified the experimental group to be faster than the control group and significantly faster in answering two (of 8) questions: $U=7.0, p=.01, r=.66$; $U=7.5, p=.01, r=.64$. The Chi-squared test was used to identify a significant difference in accuracy between experimental and control groups for question one: $\chi^2 (1, 16)=6.35, p=.041$. (See Figure 4, Left). Also, the post-task questionnaire yielded favorable results (experimental group) with a mean score of 3.78 (Likert 1-5), further attributing to the acceptance of MIVA in supporting clinical decision-making.

**Figure 3.** ICU paper chart used in study 1 and 2.

**Figure 4.** Shows time-on-task measures for study 1 (Left) and study 2 (Right) between the control and experimental groups.

Before **Study 2** began, design revisions were instituted to MIVA based on the outcomes of Study 1, including making the prototype interactive. The prototype was then tested using the same clinical scenario and eight questions (from Study 1), with 12 participants. This included the control group (6) using medical paper charts and the experimental group (6) using interactive MIVA (2.0). Four data points were collected: 1) clinical decision-making accuracy, 2) time-on-task (in min.) usability, 3) context-of-use information through a post-test questionnaire, and 4) close-ended questions and open-ended interviews. For time-on-task, the control group (M=1.30, SD=.78) was found to be generally faster than the experimental group (M=1.53, SD=.87). Using SPSS (v21.0), an independent sample t-test showed no overall significance, the experimental group was found to perform significantly faster than the control group in answering two questions: $t(10)=3.11, p=.011, r=.70$; $t(10)=3.65, p=.004, r=.76$. The experimental group participants were faster in four of the five questions than the control group, to lesser degrees. The Chi-squared test identified an overall significant difference in accuracy between the experimental and control groups: $\chi^2 (1,12)=5.04, p=.03$. (See Figure 4, Right) Lastly, a summary of participant input from the post-test questionnaire and interviews identified MIVA as: a) providing added visualization points without the need to review paper charts, b) being consistent with clinical practice, c) providing an external representation of activities for clues about group coordination, and d) a solution to resolve conflicts about interpreting team activity. Findings from studies 1 and 2 were also averaged and the combined measures were compared. To do this, we used the Kruskal Wallis test which identified significant differences in the combined measure between paper charts, static charts of MIVA, and the interactive MIVA prototype ($\chi^2 (2,N=7)=12.85, p < .01$). See Figure 5.
Discussion and Conclusion
Notably, 75% of both the control and experimental group participants from study 2 agreed that current approaches to collecting and presenting ICU critical care data are not sufficient for supporting accurate diagnoses. Participants from studies 1 and 2 noted that MIVA provided a unique contextual analysis of real-time ICU experiences, with a rich social matrix of human activity. Further, there was considerable concurrence that MIVA showed promise to significantly impact decision-support and improve clinical workflow effectiveness. In sum, our findings demonstrate the value of MIVA to facilitate diagnostics for intensivists thereby improving their capability to interpret and interact with patient data. Limitations of studies 1 and 2 suggest that small sample sizes and use of a single clinical scenario may have jeopardized a more comprehensive assessment of the MIVA prototype in an in-lab setting. As such, our next study should adjust accordingly. Also, based on the above two studies, forthcoming research will identify with greater specificity the sources of HCI error related to ICU clinical workflow, leveraging these findings to advance the design of the next generation of MIVA that utilizes the power of wearable technology (e.g., Google Glass) and other ubiquitous computing devices that have the potential to support knowledge sharing and reduce cognitive load, as well as provide portable, hands-free communication and glanceable interaction with patient data at point-of-care.

As future work, we believe that MIVA will both advance research in the area of portable and hands-free biomedical diagnostics, as well as research in the area of knowledge sharing. However, to do so we hold that without a comprehensive understanding of ICU workflow and the context in which critical care occurs, it is improbable that systemic factors that lead to errors will be adequately understood. Therefore, next steps are imperative to better understand the underlying mechanisms of error from which innovative HIT/CDS systems can be designed to improve ICU care delivery. Hence, MIVA’s ability to support teamwork with communication tools for collaborative decision-support and distributed clinical intelligence are inevitable. Through CDS systems like MIVA, clinical communities will leverage mutual knowledge sharing and problem-solving, and group diagnostic reflection to better predict adverse events, planning courses of action, and diagnosing patients at point of care.

References