Cutting-Edge Anesthesia: Visualizing patient vital signs during surgery

Gabriel Erion
University of Washington
Seattle, WA
erion@uw.edu

Alex Okeson
University of Washington
Seattle, WA
amokeson@uw.edu

Jose Mario Pineda
University of Washington
Seattle, WA
mao223@uw.edu

ABSTRACT
Anesthesia equipment and monitor usage mistakes are cited as significant sources of error in the provision of major surgical care. However, no standardized guidelines exist for the efficient display of vitals information in the operating room. We attempted to help increase anesthesiologist performance in the operating room by creating a new, interactive interface that displays more data and uses interactive visualizations. We interviewed and observed two University of Washington anesthesiologists to learn current practices and determine advantages and deficits in the current system. We redesigned the anesthesiology operating room interface to include display customizability, trend visualization, exploration of historical vitals measurements, and calculation of vitals statistics not available in the existing vitals display. Our design aims to improve how quickly anesthesiologists can retrieve relevant information compared to the current interface.

Author Keywords
Anesthesia display; vital sign monitor

ACM Classification Keywords
J.3. Computer Applications: Life and Medical Sciences.

INTRODUCTION
Surgery is vital to health care, with approximately 230 million major surgical procedures (under general anesthesia) performed worldwide per year [1]. Proper anesthesia care is critical to positive surgical outcomes. Anesthesiologists are responsible for administering anesthetic medication, and monitoring and stably maintaining patient physiologic variables in a healthy range perioperatively. Close and careful monitoring of the patient and the anesthesia equipment (e.g. ventilators, blood pressure devices, etc.) is important in order to detect a patient's deviation from physiologic normal and to detect equipment malfunction—in order to correct these perturbations before the patient is injured or harmed. Despite these careful precautions, surgery and anesthesia are not without risk. Studies in the United States and Australia have shown that rates of perioperative death and major complications and injury from inpatient surgery can reach up to 0.8% and 17%, respectively [2,3]; these figures are most likely higher in developing countries [5]. More importantly, up to half of these deaths and injuries can be averted [2,3,4]. 1 to 2% of the closed claim lawsuits involving anesthesiologists and other anesthesia professionals (e.g. nurse anesthetists) are comprised of cases citing usage error and failure of anesthesia machines and their associated monitors. Surprisingly, usage error accounts for majority of these equipment-related litigations, up to 5-fold more than equipment failure [6,7]. Guidelines and standardized procedures have been adopted in order to attempt to reduce the number of preventable deaths associated with anesthesia care, including: equipment setup and verification of correct equipment functionality, scheduling and frequency of checkout procedures, and provider briefing pre and post-surgery [8,9,10,11]. However, no guidelines exist for how anesthesia monitors should display the measurements on the screen, a potential source of misuse. Decreasing equipment and monitor misuse, specifically through improving how physiological measurements are displayed, is a largely unexplored avenue for optimizing anesthesia care and increasing positive patient surgical outcomes. Thus, we attempted a redesign of the anesthesia vital sign monitor. We examined the particular model used ubiquitously in the University of Washington Medical Center (UWMC).

Motivation, design strategy, and related work
The American Society of Anesthesiologists (ASA) recommends the following equipment to monitor patient vitals, as a minimum: pulse oximeter, continuous electrocardiography, noninvasive blood pressure (NIBP) device, and a temperature monitor, meters for inspired O_2 and expired CO_2, and the associated malfunction or disconnect alarms [13]. However, no guidelines exist for how anesthesia monitors should display the measurements. Given this deficit, we targeted out design towards the vitals sign monitor that is used in most operating rooms in the United States, specifically the model used in the University of Washington hospital system (Figure 1). The left side of the screen shows real-time vital signs in 6 rows: EKG lead II, EKG lead V5, blood pressure cuff (NIBP), pulse oxygen (SpO_2), arterial pressure (ART), and temperature. Most measurements are shown as line plots over the past 10 seconds. Blood pressure cuff measurements are in tabular form because they are measured every 3 minutes, with 4 past measurements shown. This means that blood pressure is the only measurement for which any sort of history beyond 10 seconds is visible on the vitals display (along with pulse oxygen, which is also displayed in the table). An interesting

[1]All code, both for generating synthetic data and for implementing the visualization, is available on our Github repo https://github.com/cse512-18s.github.io/cutting-edge-anesthesia/

and ubiquitous design choice in displaying real-time vital signs is that the data do not scroll as more time points come in. Instead, the existing measurements are overwritten, with the current time point shown as a break in the line plot.

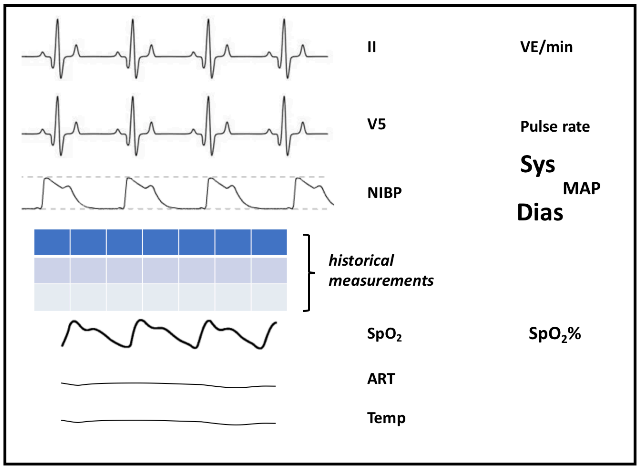

Figure 1. Diagram of the UWMC anesthesia vital sign monitor.

We identified areas for improvement through multiple interviews with practicing anesthesiologists. We contacted a UWMC anesthesiologist and had a broad unstructured discussion about the use of data displays in the operating room. Our initial conversations also covered the types of monitors in the OR (vital sign monitor, ventilation settings monitor, and medical record monitor), which led to our focus on vital signs. We next visited the operating room and spent several hours observing anesthesiologists (one attending and one chief resident) using data displays and asking questions about how the displays fit into their work.

Below is a comprehensive list of the **criticisms of existing vital sign displays** we noted during our discussions and surgical observations:

- Historical trends in vital signs are not easily seen (only the last 10 seconds displayed).
- Trends visualization (on a different monitor) does not allow the user to choose what variables and/or statistics to be tracked over time.
- Statistics of interest like ST elevation, QRS width, and cerebral perfusion pressure require user input to calculate and display, though they should be automatically calculable.
- Recording and re-accessing baseline characteristics of the patient for comparison is difficult.
- It could be useful to add a video function to see the patient's face (and airway) even when it's obscured during surgery (e.g. prone position surgery, patient's head is on the opposite side of the operating table from the anesthesiologist).
- Details about where certain measurements are made (location of temperature sensor, etc.) are not displayed.
- Some measurements (e.g. nerve conduction studies) are not displayed on any monitor because they are done by a different department.
- Many vital signs and statistics are shown as poorly differentiated plain text on the right side of the monitor, leading to a sense of clutter.
- The number of monitors used by anesthesiologists as well as how the values and plots are laid out on the screen vary greatly by procedure and by medical center even within the same city. For instance, in Seattle, the University of Washington Medical Center uses a completely different monitor, and in turn monitor layout, in comparison to Virginia Mason Medical Center. This difference requires anesthesiologists who often rotate between hospitals (e.g. resident physicians) to relearn how to use and display important physiological data.

From our surgical observations, we decided to keep the following **themes** in mind moving forward:

- Anesthesiologists interact with displays differently at different times. There exists time for interaction/customization before surgery. During the start of surgery and critical moments, time and attention is very scarce. There are then long quiet periods during surgery, and another intense period at the end. A good interface should allow users to use interactivity during free time (before surgery, middle of surgery) to prepare for busy moments (start of surgery, etc) -- for example, through customization of which data is displayed.
- Anesthesiologists spend most of their "screen time" periodically reviewing vital signs on the vitals monitor, looking at the screen when an alert sounds or doing paperwork on the medical record monitor.

These themes led to the following **Design Goals:**

- Provide a way to access a patient's entire vital sign history
- Use interactivity to allow users to specify and follow long-term trends and statistics computed from the raw data

METHODS

We started implementing our visualization by generating synthetic vitals data as CSV from an IPython notebook so as to avoid privacy and confidentiality concerns with displaying patient data (i.e. the data does not correspond to any real patient; physiological accuracy is limited to our best approximation). Our visualization app read in this CSV file as an array of timepoints, and did the real-time data display by slicing the array and using d3.timer to redraw the plot with the new time points that became available at each time step;

it could easily adapt to truly streaming data by setting future time points to “NaN” and updating them as new data comes in.

The initial core of the visualization was showing the patient’s entire vital sign history in a detailed line plot showing 15 seconds of each vital sign (EKG, CO2, etc) as well as a scrubbing bar inspired by the side bars in Sublime Text and VSCode that allowed the detail window to be moved throughout the entire course of surgery. This was implemented by using linked line plots with a brush on the zoomed-out plot, as in [14] and [15]. Because these data were so dense, showing a zoomed-out version on the scrubbing bar would be jumbled and uninformative, so instead we maximized data density by showing a relevant *second* vital sign for which longer-term trends would be of interest (Heart rate, respiratory rate, etc). Our scrolling interface is an intentional departure from the usual method of overwriting past vital signs within a fixed window, in order to naturally allow exploration of past data.

drawn from scratch and synced to display data at the same time point as all the others. Users can reset the plot and choose different variables at any time, representing our attempt to make detailed data on many variables available without cluttering the display. We attempted to further reduce clutter by removing buttons in favor of scrollbar functionality. For example, instead of using “snap to present” buttons we automatically snap to the present when the scroll bar is dragged beyond the current time (conversely, the window stops automatically scrolling to the right if the user selects a time point in the past). The final mode of interface customization is draggability, implemented using [16] to place each vital sign in its own draggable box so each user can lay out the signals in the way that is most useful to them.

RESULTS

We successfully incorporated the following features in our redesigned display (Figure 2):

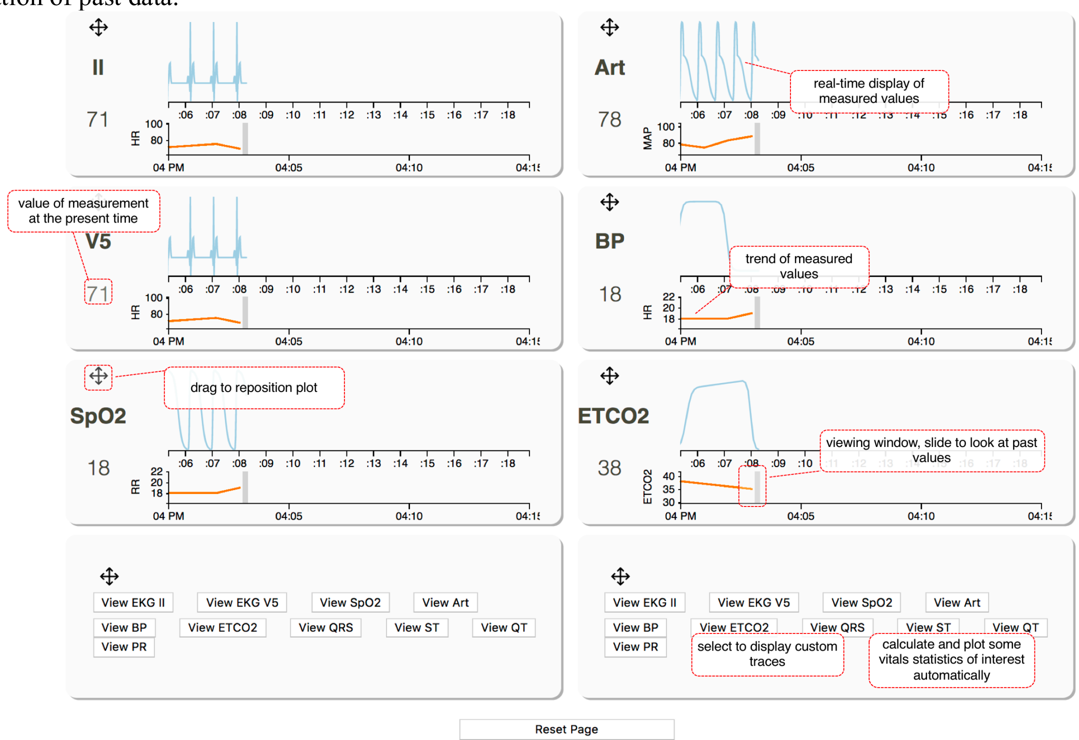

Figure 2. Cutting-Edge Anesthesia. Live anesthesia data-visualization interface, split into 6 standard vital signs and 2 customizable boxes. In each box the top line plot is a real-time vital sign tracing, while the bottom plot is an associated variable (i.e., EKG is paired with heart rate) plotted over the time-scale of the entire procedure. The left number is the current value of the associated variable updated minute by minute. The brush in the bottom plot can be scrubbed to scroll the top plot, and the boxes can be dragged to place related vital signs near each other. Any available vital sign or derived statistic can be plotted in the 2 customizable windows (a reset button allows changing the displayed data in custom boxes at any time).

We also addressed the large number of variables that must be available for viewing by using customization and details on demand. We made sure that the default view of our visualization displayed the 6 vital signs that are present on almost every such monitor, but also included 2 customizable boxes to display additional statistics like PR interval on demand. When a statistic is chosen, a new plot is

- **Real-time data visualization:** each real-time vitals tracing (blue) is updated every 3 seconds. The new, incoming, data does not overwrite the existing data. Rather, the entire waveform is scrolled to the left in order to make space for incoming data. Thus, the current time point is always the rightmost side of the tracing. We hope that scrolling the data every three seconds, rather than continuously scrolling, enhances anesthesiologists' ability to recognize important patterns (which could be difficult if data are constantly moving).

- **Display customizability:** each vitals tracing/plot is modular. That is, each plot can be ordered according to user preference by dragging. Two additional tracings are available to be added and customized if desired, positioned below as default. These plots could be duplicates of existing plots or could be other important vitals statistics not included in the existing UWMC monitors and/or will be otherwise manually calculated.
- **Trend visualization and historical data exploration:** each vitals tracing (blue) includes a relevant vitals statistic plotted over time (orange) (e.g. Art (arterial pressure) has MAP (mean arterial pressure) plotted below it). This allows visualization of trends associated with important vitals statistics. A sliding window designates the current time frame being visualized. This window can be dragged in order to examine the past data.
- **Layout redesign:** the real time values of the vitals measurements are still included (as in the existing design, see Figure 1). These numbers (unlabeled in the current hospital monitors) are now integrated within their respective vitals traces, rather than occupying their own separate sections. This also allowed us to utilize more space to cleanup the display.

An area where our visualization could help is illustrated by one anesthesiologist's anecdote about the difficulty of comparing a mid-surgery EKG tracing to a patient-specific baseline, such as the same patient's tracing at the start of surgery. The only way to do this with existing software is to save a screenshot of the tracing at the start of surgery; this screenshot can't be pinned to the display and must be manually re-displayed every time he wants to compare against it. In contrast, our visualization allows for quick, intuitive, accessible comparison against *any* past data with the scrubbing interface. In addition, our use of small multiples, draggability, and scrubbing would allow the anesthesiologist to place a copy of a specially-chosen baseline EKG segment next to the live feed. This allows instant comparison against a baseline, with no interaction necessary, as fast as the eyes can move, and could be much more useful than the existing system when time or attention is at a premium.

Another use case for the visualization is an anesthesiologist who wants to automatically display of metrics such as QRS and PR interval over time, for example to monitor for effects of toxicity or track progression of heart block. Current software requires anesthesiologists to manually enter into the computer the calculations desired, and is only able to view the most recent calculation. In our design, the statistics can be displayed in real-time and stored for all past time points. The time series of those calculations can be viewed using the customizable small multiples with a single click.

Finally, we addressed the anesthesiologists' concern about "clutter" regarding the cluster of unlabeled numbers on the right side of the existing screen. Our redesign has distributed these numbers into their relevant vitals tracing, which eliminates the need to memorize the position and identity of these numbers. Further, we preserved the vitals measurements IDs to label each tracing, consistent with what is used in the existing screen. This was done to minimize the amount of new learning a user needs to do when transitioning to our layout.

DISCUSSION

Our redesigned visualization was presented in an informal setting to several graduate students of the UW Computer Science and Engineering program, as well as other graduate students in the biological and life sciences. Each user was briefed on the limitations of the existing vital sign monitor, our design process and rationale, and instructions on how to use the redesigned monitor. We hope to gather physician input on the design in the near future, but interactions with these students also revealed several insights about our redesign. First, users were very satisfied with the drag-and-drop functionality and customizability of our monitor. Second, users were satisfied with the ability to have a simultaneous view of the real-time tracing and the past tracing. Third, some confusion regarding the scrubbing features were apparent. The method of "catch up to the live updates by scrubbing to the current time point or farther" was not immediately grasped by all users; and, users who tested our design expressed desire to be able to change the zoom width. Fourth, users seem to want the numbers corresponding to current time measurements of particular vitals to be larger and more apparent. Lastly, the use of our monitor was negatively hindered at later time points due to lag induced by redrawing 8 high-resolution lines with tens of thousands of points every 100ms. This slowdown may have made it more difficult to explore the various novel features introduced in our design for some users. The small group of test users expressed a great understanding and agreement regarding the importance of the design problem being addressed. From their feedback, we believe that that problems regarding customizability and trends visualization were successfully addressed. However, technical issues regarding the monitor performance have to be revisited.

FUTURE WORK

We plan present our display to the anesthesiologists involved in the initial user study and interview. Gathering physician input about the usability and limitations of our implementation will help us incorporate further design iterations into future, and conduct larger-scale user tests done by our research group. These tests will help us determine if our revised display and visualization of additional data improves physician information-retrieval time and better informs clinical decision-making, leading to better patient outcomes. In addition to addressing critiques received during the informal demo of this visualization, we aim to add new functionalities to the design: adding normal ranges for the different time series metrics which can be customized for an individual patient (e.g. normal blood pressure ranges differ between pediatric versus geriatric patients), adding alarms and alerts when vitals signs deviate from normal ranges, and using machine learning models we have developed to incorporate risk predictions and explanations for risk predictions for adverse future events [12].

ACKNOWLEDGMENTS

We would like to thank our anesthesiology collaborators Dr. Monica Vavilala and Dr. Nicholas Sirs for allowing us to observe them in the operating room at Harborview Medical Center. We also thank Devin Moore for coordinating the observership sessions.

REFERENCES

1. Thomas Weiser, et al. 2008. An estimation of the global volume of surgery: a modelling strategy based on available data. The Lancet. 372, 9633: 139-144.
2. AA Gawande, et al. 1999. The incidence and nature of surgical adverse events in Colorado and Utah in 1992. *Surgery*. 126:66-75
3. AK Kable, et al. 2002. Adverse events in surgical patients in Australia. *Int J Qual Health Care*. 14: 269-276.
4. DT Ubbink, et al. 2012. Registration of surgical adverse outcomes: a reliability study in a university hospital. *BMJ Open*. 2: e000891.
5. MK Yii and KJ Ng. 2002. Risk-adjusted surgical audit with the POSSUM scoring system in a developing country. *Br J Surg*. 89: 110-113.
6. RA Caplan, et al. 1997. Adverse anesthetic outcomes arising from gas delivery equipment: a closed claims analysis. *Anesthesiology*. 87: 741.
7. SP Mehta, et al. 2013. Patient injuries from anesthesia gas delivery equipment: a closed claims update. *Anesthesiology*. 119: 788.
8. Lorelei Lingard, et al. 2008. Evaluation of a Preoperative Checklist and Team Briefing Among Surgeons, Nurses, and Anesthesiologists to Reduce Failures in Communication. *Arch Surg*. 143, 1: 12-17.
9. K Mazzocco, et al. 2008. Surgical team behaviors and patient outcomes. *Am J Surg*.
10. World Alliance for Patient Safety. WHO guidelines for safe surgery. Geneva: World Health Organization. Retrieved May 30, 2018 from http://apps.who.int/iris/bitstream/handle/10665/44185/9789241598552_eng.pdf;jsessionid=F05BD92328997958639CB5CC44D08E0F?sequence=1.
11. Sub-Committee of ASA Committee on Equipment and Facilities. 2008. Recommendations for Pre-Anesthesia Checkout Procedures. Retrieved May 30, 2018 from http://www.asahq.org/resources/clinical-information/2008-asa-recommendations-for-pre-anesthesia-checkout.
12. Scott M. Lundberg, Bala Nair, Monica S. Vavilala, Mayumi Horibe, Michael J. Eisses, Trevor Adams, David E. Liston, Daniel King-Wai Low, Shu-Fang Newman, Jerry Kim, Su-In Lee. 2017. Explainable machine learning predictions to help anesthesiologists prevent hypoxemia during surgery. *bioRxiv*. doi: http://dx.doi.org/10.1101/206540
13. Committee of Origin: Standards and Practice Parameters. Standards for Basic Anesthetic Monitoring. Retrieved May 30, 2018 from https://www.asahq.org/~/media/Sites/ASAHQ/Files/Public/Resources/standards-guidelines/standards-for-basic-anesthetic-monitoring.pdf.
14. Mike Bostock, “Brush & Zoom”, Interactive Block graphic from https://bl.ocks.org/mbostock/34f08d5e11952a80609169b7917d4172
15. mcaule (Github user), *d3-timeseries*, Github repository from https://github.com/mcaule/d3-timeseries
16. RubaXa (Github user), *Sortable*, Github repository from https://github.com/RubaXa/Sortable