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Validation of Prototype Continuous Real-Time Vital Signs Video Analytics Monitoring System "CCATT Viewer"

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University of Maryland School of Medicine

January 2018

Final Report
for September 2014 to November 2017

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14. ABSTRACT
We have developed an automated physiological data-organizing and information-summary system (Critical Care Air Transport Team (CCATT) viewer) to present aggregated information from multiple data sources, provide at-a-glance summaries of clinical data, and assist with prioritizing care for multiple patients in intensive care units (ICU). In the Maryland Shock Trauma Center, the viewer displays 230 beds (grouped into 14 clinical units) for up to 72 hours of continuous vital signs data with 1-minute temporal resolution. It visualizes vital signs that are routinely monitored for patients with shock, burns, trauma, traumatic brain injury, or respiratory failure. We conducted the prospective survey in our trauma center ICU. Over 60% of clinicians believe the viewer enhanced their understanding of their patients' condition. The survey results indicate that when attending physicians look at the CCATT viewer for 1 minute or less, 10% of the time they change their clinical plan. Due to the success of this system, our medical center neuro ICU also adopted this viewer for daily patient care planning and rounding.

15. SUBJECT TERMS
Critical Care Air Transport Team, CCATT, physiological viewer, integrated display

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1.0 EXECUTIVE SUMMARY

Military Critical Care Air Transport Teams (CCATTs) have demonstrated reliable capability to evacuate critically injured patients from deployed hospitals. However, the long-range aeromedical transportation of patients has many challenges regarding in-flight assessments that are required to rapidly render appropriate clinical support. Clinical decision-making is further confounded by an aeromedical environment characterized by confined space, noise, vibration, and limited visibility. An automated physiological data-organizing and information-summary system could present aggregated information from multiple data sources, provide at-a-glance summaries of clinical data, and assist with prioritizing care for multiple patients. A prototype CCATT vital signs (VS) viewer has been specifically designed and implemented for this unique and hostile environment. The viewer's capacity for data throughput and stability in a major level 1 trauma center was also tested. It was evaluated for its usefulness in a critical care air transport setting.

In the University of Maryland Shock Trauma Center, the viewer displays 230 beds (grouped into 14 clinical units) for up to 72 hours of continuous VS data with 1-minute temporal resolution. It shows up to nine VS in complete trajectories (shock index, heart rate, systolic blood pressure, oxygen saturation, intracranial pressure, etc.) that are routinely monitored for patients with shock, burns, trauma, traumatic brain injury, or respiratory failure. The system has high reliability; with asynchronous communication, it can tolerate temporary network failure.

To evaluate the viewer's usefulness, we conducted surveys during our trauma center neurotrauma and multi-trauma intensive care unit (ICU) morning rounds from February 15, 2017, to June 30, 2017. In total, 908 surveys were collected. The questionnaire collected changes to physicians' opinions before and after seeing the patient's data on the viewer in each ICU round. The physicians were asked questions regarding the patient's stability, status, and need for a higher or lower level of care. Physicians were also asked if they intentionally plan to change interventions after seeing the viewer. Last, they were asked to give an overall rating on how the viewer helped them understand the patient's physiologic condition in that round.

The results indicate attending physicians, after looking at the CCATT viewer for 1 minute or less and having the viewer's more detailed and summarized information, as often as 10.1% of the time changed their clinical plan. In an overall rating of the CCATT viewer, physicians were asked if the viewer enhanced their understanding of the patient's condition—55.0% strongly agree, 56.6% agree, 35.4% neutral, 2.8% disagree, and 0.2% strongly disagree.

In a noisy, busy, and confined transport aircraft, loosely organized physiological data, oversaturated information delivery, and limited visual assessment may reduce the capability of a small clinical team to recognize changes in physiologic status and prioritize care. The CCATT viewer prototype demonstrates a method to assemble large quantities of data from multiple sources and represent trends in each patient's condition with simple color codes, greatly improving situational awareness. Our prospective CCATT viewer evaluation study conducted in the trauma center neuro and multi-trauma ICU demonstrated the effectiveness of the viewer.

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2.0 INTRODUCTION

2.1 Background

The vast amounts of high-quality, continuous, electronic data garnered by modern physiologic monitoring systems have the potential to provide an unprecedented view of dynamic physiologic response to injury, illness, and intervention. Once casualties enter continuous care, from battlefield on, a vast quantity of data is collected. It is practically important to organize those data and present meaningful analysis for efficient decision-support. Many years ago, a novel prototype video display system was implemented from the University of Maryland Vital Signs Data Recording (VSDR) project that has been deployed on a translational basis in the neurotrauma critical care unit, the two multi-trauma critical care units, the trauma resuscitation unit (TRU), and operating rooms (OR) in the Shock Trauma Center (STC) [1-4]. This display allows clinicians to track and monitor vital signs (VS) trends in up to 66 patient locations with a display of the patients' physiological status over the previous 24 hours in a single real-time monitor, with critical physiologic changes coded as green, yellow, and red based on threshold values gleaned historically from episodic, manually collected and processed data. With the advances in computing and visualization techniques, we seek to develop and optimize this VS viewer so that it can be used for a general purpose in monitoring a group of patients.

This work has two outcomes of direct and important clinical applicability. First, the VS viewer can provide clinicians with the capability to monitor individual patient trends that may improve overall decision-making. Since mechanically ventilated trauma patients may require multiple interventions to maintain cerebral perfusion and oxygenation, reduce intracranial pressure (ICP), and optimize brain trauma index (BTI) and shock index (SI) to ensure ideal long-term outcome, a significantly improved display of VS patterns will improve patient assessment and clinical decision-making. Second, the monitoring system allows remote monitoring of groups of patients through a display that is optimized to assist ongoing triage decisions and provide clinicians the ability to quickly identify patients in need of rapid intervention. Since Critical Care Air Transport Teams (CCATTs) and aeromedical evacuation (AE) staff cannot view all patient locations simultaneously using traditional monitors, this capability will facilitate management of a group of patients. Innovative visual analytics of the complex array of real-time physiological data will provide an at-a-glance view of multiple patients to promote instant decisions on attention allocation.

As a foundation for future studies, the demonstration of a novel method for analyzing digital monitoring data has the potential to provide a basis for an adaptive model capable of displaying prognostic information to predict long-term outcomes which, based on an individual's actual physiologic thresholds rather than an estimate based on past group experience, will individualize decision-support for patients on an unprecedented level.

2.2 Military Relevance

The U.S. Air Force (USAF) CCATT is a highly specialized medical asset team that can operate a portable intensive care unit (ICU) onboard any transport aircraft during flight and has been credited with allowing trauma surgeons to perform far forward damage control surgery, knowing that these patients could be quickly transported rearward with full support. This rapid transport of complex patients with multi-system trauma, shock, burns, and respiratory failure

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who are in hemodynamic flux requires continual resuscitation, stabilization, advanced care, and life-saving interventions during air transport; however, currently available advanced ICU monitoring systems suitable for the needs of such patients were developed for use in stable, hospital-based settings, not in the crowded, noisy, vibrating, and sometimes frankly jolting environment of air evacuation or long-distance air transport.

The critical care air transport environment may require patients to be completely covered with warming blankets and placed in a litter stanchion, which limits access to the patient, further complicating patient assessments. Each CCATT may be responsible for up to six critical patients. Traditional monitor alarms are not audible on the aircraft due to aircraft noise. During takeoff and landing, observation of the patients may be even more challenging. Additionally, numerous less severely injured patients are evacuated through the AE system without any type of continuous monitoring. Because of these identified challenges, remote monitoring of groups of patients, including monitoring of VS trends and current vital information, has been identified by USAF CCATT and AE as a high priority gap.

2.3 Previous Work

From 2008-2012, a prototype VS viewer was conceptualized, designed, and deployed in the University of Maryland advanced trauma ICU system. It is capable of recording, analyzing, and simultaneously visually displaying a range of clinical monitoring information, including real-time analysis and display of indices linked algorithmically to outcome [5-7]. Much of this work was done with internal and USAF funding and working closely with USAF clinicians.

The prototype system that had been deployed throughout the trauma ICUs, TRU, and ORs displays conventional real-time physiologic information, including ICP, cerebral perfusion pressure (CPP), and mean arterial pressure data as well as ongoing, real-time calculation of shock index (SI = heart rate [HR]/systolic blood pressure [SBP]) and BTI (=CPP/ICP) in an easily appreciable visual display. In the previous display version, data and indices were linked to outcome data and expert treatment guidelines, so the color-based visual alarm system provided continuously updated access to the patient's current physiologic risk status and recent trends as a basis for clinical decision-making.

As shown in Figure 1, visual analytics of the complex array of real-time physiological data provide an at-a-glance view of multiple patients as well as a view of each patient's condition over the past 1 to 24 hours. This has the potential to support essentially instant identification of an individual patient who is in need of immediate attention among a large group of fragile patients being transported in a difficult environment. Also, this capacity can be deployed at the bedside or to a remote monitor to maximize situational awareness.

The prototype VS viewer had shown great potential in organizing massive amounts of physiologic data and efficiently displaying concise information for clinical decision-making in a busy ICU environment. However, the previous version was built on a system that requires large amounts of computing power. Moreover, its images were static, which provided limited function for data exploring. The system's stability and scalability also needed improvement.

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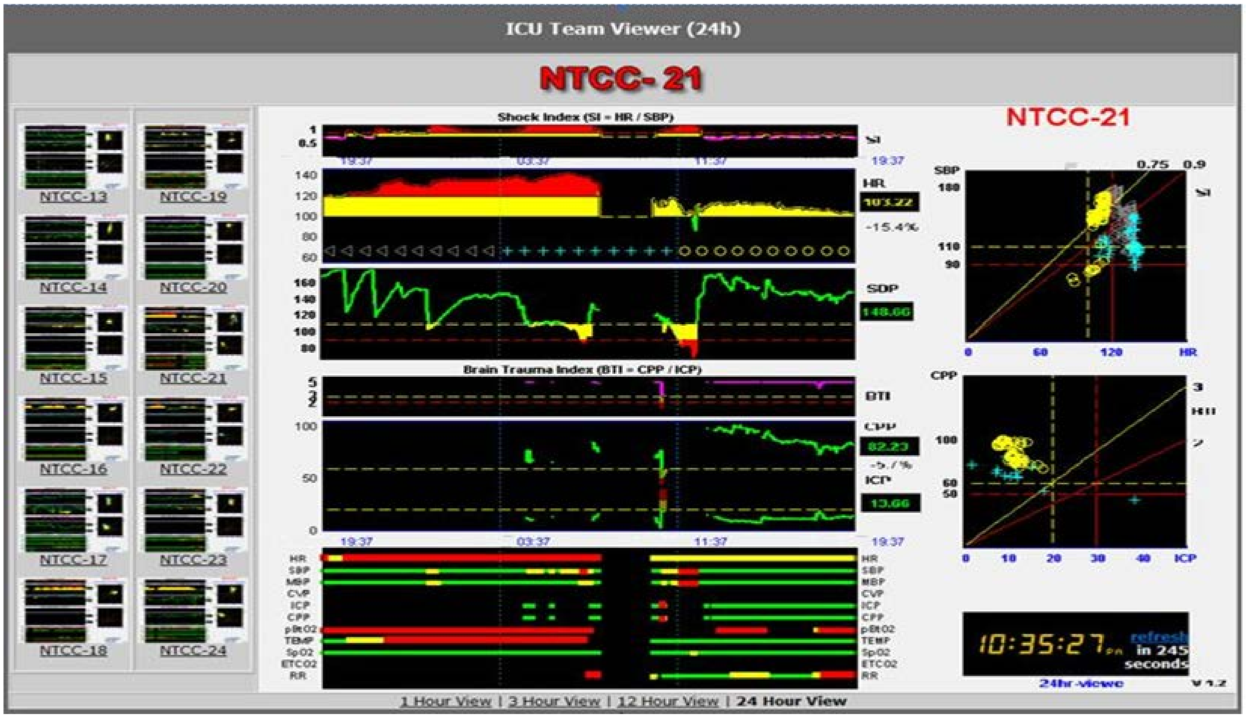

Figure 1. Interface of previous prototype real-time bedside VS viewer.

3.0 SYSTEM DESIGN

The new system design aimed for a lightweight, balanced server-client, portable architecture. The system is used to organize and visualize multiple patients' full trajectories of physiologic data. It is expected to provide high visibility with reasonable stability and scalability, even in busy, crowed, and unstable environments.

3.1 System Architecture

The CCATT viewer 2.0 is built on new system architecture that supports real-time asynchronous web applications with triple redundancy for web service fault tolerance. Figure 2 illustrates the system architecture. Based on the triple-redundant data servers (blue dots), VS data of each 1-minute median are submitted to three independent databases distributed on the three CCATT servers (red dots). As dual-purpose servers, the CCATT servers also respond to requests from clients in the University of Maryland Medical Center intranet to generate displaying content and to update it regularly.

An auto server switch has been implemented to improve user experience on the system reliability. Each active client regularly checks if the current CCATT server is available. In case the current server fails, the client will be seamlessly redirected to the next available CCATT server.

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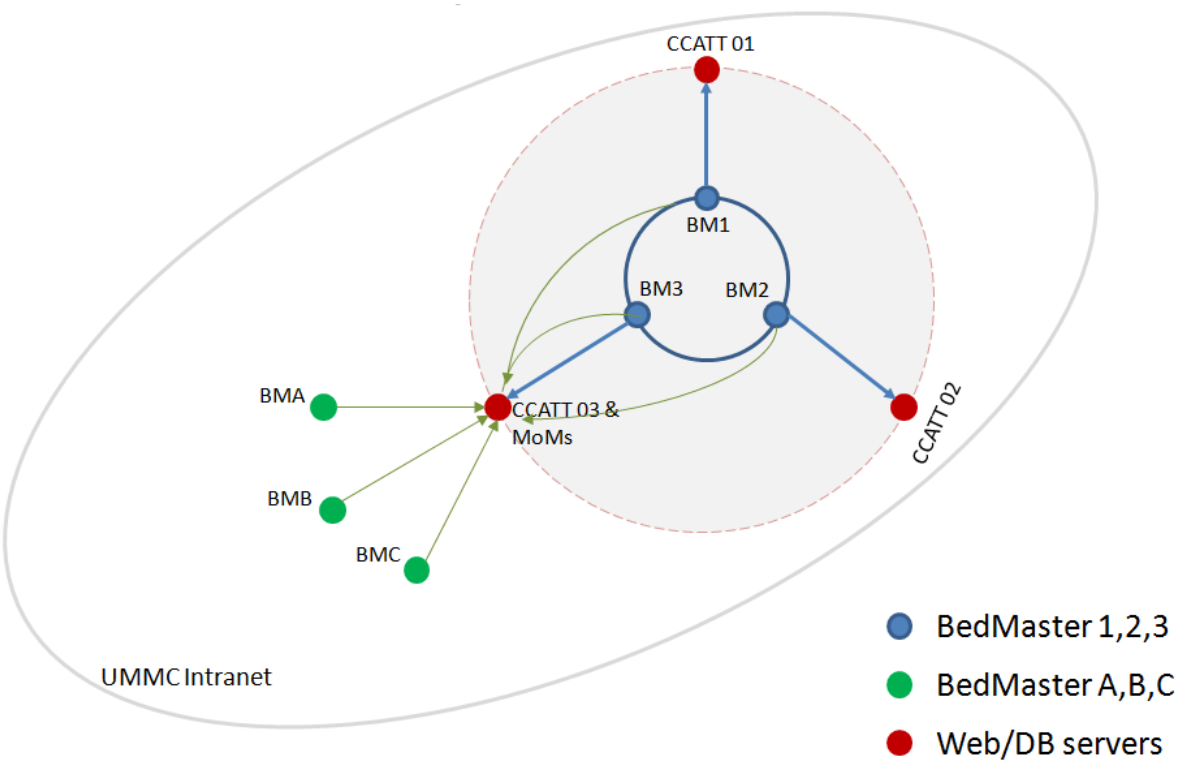

Figure 2. Illustration of a triple-redundant configured CCATT system communication architecture. *BM = BedMaster; MoMs = monitor of monitors; UMMC = University of Maryland Medical Center.*

The triple-redundant or double-redundant system could be useful in managing hundreds of bedside monitor data sources. With too many data sources, a single central server may suffer from a high chance of failure. However, multiple collaborating servers could reduce data collection failure. On the other hand, in a compact ICU environment (e.g., CCATT) with a few to a dozen patients, a single server or double-redundant system would be sufficient to maintain a high data collection rate.

3.2 Viewer Elements Design

For detailed elements to display, as well as their color, line styles, and locations on the screen, we surveyed 47 clinicians (24 medical doctors, 18 registered nurses, and 5 respiratory therapists). Among them, 20 were military personnel and 27 civilians. Institutional wise, there were 36 participants from the University of Maryland, Baltimore, and 11 from the University of Cincinnati. After the feedback survey was completed, a team of clinicians met to review the feedback survey results to reach a consensus opinion of the viewer's visual appearance. One of the most important consensus opinions was the threshold set for VS. For a given VS, it will be displayed as a temporal trajectory with certain colors, depending on the threshold range that its value falls into. Table 1 summarizes the optional threshold distributions for some important VS. Based on these threshold values, a consensus set of CCATT color coding cut-offs was determined (Table 2). These values are set as fixed parameters under the consideration of simplified and consistent user interface. Technically, the threshold settings can be modified or customized in the configuration file.

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Table 1. Surveyed Thresholds for Heart Rate, Systolic and Diastolic Blood Pressure, Blood Oxygen Saturation, and Temperature

VS	High – Red High Lower Limit	Yellow High		Green		Yellow Low		Low – Red Low Upper Limit
		Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit	
HR								
Mean	121	119	100	100	62	59	50	49
Median	120	119	101	100	60	59	51	50
Mode	120	119	101	100	60	59	51	50
SD[a]	8.68	8.59	4.26	4.90	5.98	5.09	4.83	4.57
N	19	17	17	17	17	17	17	19
SBP								
Mean	175	174	147	145	103	102	88	86
Median	180	179	150	149	101	100	90	89
Mode	180	179	160	159	100	99	81	80
SD	14.99	15.43	13.08	13.07	8.60	8.55	6.59	5.71
N	17	16	16	15	15	16	17	18
DBP[a]								
Mean	103	102	86	85	56	56	43	43
Median	100	103.5	88	87	60	59	41	40
Mode	100	99	91	90	60	59	41	40
SD	12.40	13.41	14.28	14.28	9.05	9.62	7.54	7.55
N	14	12	12	12	12	13	13	14
SaO2[a]								
Mean				100	93.92857143	92.9	89.3	88.3
Median				100	94.5	93.5	90	89
Mode				100	95	94	90	89
SD				0.00	1.77	1.77	2.37	2.37
N				14	14	14	14	14
Temp								
Mean	39	39	38	38	36	36	35	35
Median	39	39	38	38	36	36	35	35
Mode	39	39	38	38	36	36	35	35
SD	1.11	1.08	0.47	0.46	0.64	0.48	0.70	0.66
N	17	13	13	13	13	12	12	16

[a]DBP = diastolic blood pressure; SaO2 = blood oxygen saturation; SD = standard deviation.

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Table 2. CCATT Viewer Color Coding Cut-Off Values

VR	Red	Yellow	Green
HR	<50 or >120	50-59 or 100-119	59-100
SBP	<81 or >180	81-99 or 160-179	100-160
DBP	<41 or >100	41-59 or 91-99	60-90
MBP[a]	<51 or >90	51-59 or 71-89	60-70
NSBP[a]	<81 or >180	81-99 or 160-179	100-159
NDBP[a]	<41 or >100	41-59 or 91-99	60-90
NMBP[a]	<51 or >90	51-59 or 71-89	60-70
SpO2[a]	<90	90-95	95-100
"PULSE RATE"	<90	90-94	94-100
TEMP	<35 or >39	35-36 or 38-39	36-38
RR[a]	<8 or >30	8-9 or 26-30	10-25
ICP	>30	20-30	0-19
EtCO2[a]	<20 or >50	20-30 or 40-50	30-40
SI	>1.2	>0.9	<0.9
CPP	<50	50-60	>60
BTI	<2	2-3	>4

[a]EtCO2 = end-tidal carbon dioxide; MBP = mean blood pressure; NDBP = normal DBP; NMBP = normal MBP; NSBP = normal SBP; RR = respiratory rate; SpO2 = blood oxygen saturation (pulse oximetry).

3.3 Viewer Interface Design

The CCATT viewer provides a rich interactive interface for data monitoring, exploring, and recording. First, bed units are organized based on clinical divisions, such as TRU, OR/computed tomography, neurotrauma critical care, etc. Figure 3 demonstrates the group of bed units. On the left panel, a list of all groups can be used as a shortcut to bed units. Selecting a specific unit, a default 24-hour view is displaced for shock index (SI=HR/SBP), HR, SBP, ICP, CPP, BTI, EtCO2, etc. To better unitize the space, if ICP is not collected, the space is used to plot the next available VS. An overview of all collected VS is summarized with colored horizontal bars at the bottom.

When a specific bed is selected, a page for bed unit view will be displayed. Figure 4 demonstrates the structure of the information grouped. Areas 1, 2, and 3 on the top are used for navigation, basic unit and time information, and user login. Area 4 on the left panel collects all beds in the same units and shows the thumbnails of their real-time VS. Such grouping of thumbnails maintains visibility of other beds while the user is focusing on a specific case. Area 5 is the main place for displaying the selected bed's major VS. Area 6 is reserved for displaying some useful diagnostic tools. Area 7 at the bottom is for other auxiliary functions.

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Figure 3. A group view of the CCATT viewer, with the default 24-hour data display.

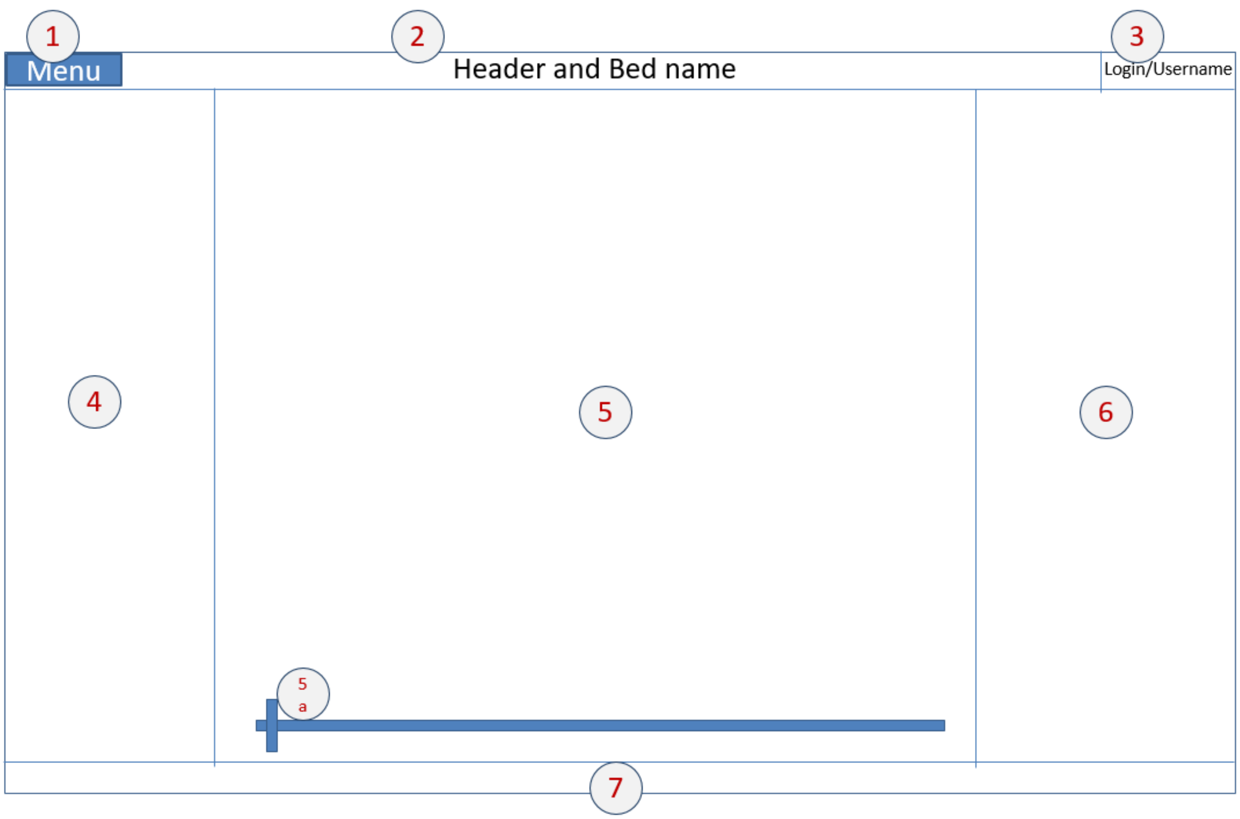

Figure 4. The structure of unit view of CCATT viewer and its main areas for grouped information.

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The viewer can host some special diagnostic tools. For example, SI is a commonly used blood transfusion diagnosis tool. The CCATT adds a two-dimensional (2D) SI diagram to show the changing trajectory. To present the temporal information, a spectrum of colors ranging from blue (cold) to red (warm) is used to code the past (blue) and current (red) time. The top right plot in Figure 5 shows an example of unit view. Figure 6 shows an SI plot in a closeup look. Similarly, the BTI (= ICP/CPP) can also visualized in the 2D plot.

Figure 5. A unit view of CCATT viewer, with a default 24-hour data display.

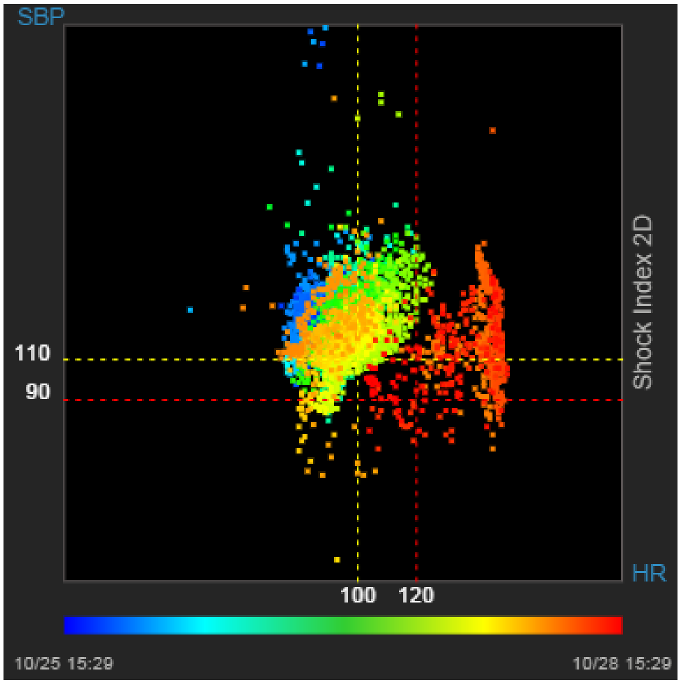

Figure 6. An example 2D SI plot. *The colored scatter plot shows from past (blue) to recent (red), from which we can observe a deteriorated SI in a 3-day range.*

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Mouse and touch screen interactive operations are also implemented. In a desktop or tablet environment, moving the cursor will draw a vertical line to show current time and the real VS values at the selected time. By selecting a time interval, the reviewer will zoom in to the selected time interval for local details. A preset time intervals setting is placed at the bottom for 1, 2, 4, 8, 12, 24, 48, and 72 hours view. In the 2D SI and BTI plots, moving the cursor along the color spectrum, the corresponding time and HR/SBP points are highlighted.

In VS value plots, green/yellow/red color code is used to show normal, warning, and alert regions. With a set of pre-defined thresholds (Table 2), VS above/below warning or alert thresholds are filled with yellow and red blocks. Such filled color can draw attention from the users to quickly identify cases of special interest.

The CCATT viewer provides a handy button to allow users to save an instant screenshot. This is useful for clinicians to use the system as a recording tool during routine rounding or diagnosis.

3.4 Viewer Computing Performance

The CCATT viewer runs efficiently on regular mainstream personal computers (PCs). The current CCATT server has an Intel i5 1.9-GHz central processing unit, 16 GB memory, and Windows 7. The CCATT server consumes a small amount of system resources. A mini-computing device (e.g., Raspberry Pi model B) can be used as a server. A typical data request from a client (24 hours view) could transfer 16 (units) x 1440 (minutes) x 16 (VS) = 0.37 million data points. Such an amount of data can be rendered in real-time on the left panel thumbnails view and the main unit view. As a debug tool shows (Figure 7), the drawing time is at the hundreds millisecond level. With Ajax (asynchronous Javascript and XML) techniques, CCATT displaying is updated every 1 minute without refreshing the entire page. Data are compressed at a level of balanced size and parsing efficiency.

Heavy (Bottom Up) ▼

Self Time		Total Time		Function	
5153.1 ms		5153.1 ms		(idle)	
183.9 ms	21.51 %	183.9 ms	21.51 %	(program)	
157.3 ms	18.40 %	459.4 ms	53.74 %	▶ drawUnitData	(index):271
87.2 ms	10.20 %	117.2 ms	13.71 %	▼ drawDataOverView	(index):742
87.1 ms	10.18 %	117.2 ms	13.71 %	▶ drawUnitData	(index):271
0.1 ms	0.01 %	0.1 ms	0.01 %	▶ drawDataOverView	(index):742
66.8 ms	7.81 %	66.8 ms	7.81 %	(garbage collector)	
63.2 ms	7.39 %	134.0 ms	15.67 %	▶ drawOneData	(index):1042
22.6 ms	2.65 %	25.5 ms	2.98 %	▶ parseDataTime	(index):226
20.3 ms	2.37 %	192.0 ms	22.46 %	▶ success	(index):1566
18.7 ms	2.19 %	18.7 ms	2.19 %	▶ fillText	
16.6 ms	1.95 %	175.8 ms	20.56 %	▶ success	(index):1492
16.4 ms	1.92 %	16.4 ms	1.92 %	▶ stroke	
16.4 ms	1.92 %	16.4 ms	1.92 %	▶ measureText	
15.4 ms	1.80 %	158.5 ms	18.54 %	▶ drawSideGroupData	(index):1437
15.2 ms	1.78 %	158.9 ms	18.59 %	▶ drawGroupData	(index):1452
14.6 ms	1.71 %	14.6 ms	1.71 %	▶ fill	

Figure 7. A snippet of CCATT profile. *For the non-idle time, the rendering function costs time at the hundreds millisecond level.*

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Within the triple-redundant architecture, data for update can be requested from any one of the three time-synchronized data servers. When one CCATT server fails, the client could detect the next available server and fetch the data. Users do not need to intervene in this switching process. The above features are further enhanced with a mobile app when CCATT viewer is used on tablets or smart phones. We built an app to stream and visualize data for hand-held devices. The app maximizes the use of limited screen space by automatically setting full screen view. It also remembers the server URL and increases the efficiency.

3.5 Auxiliary Function and System Pressure Test

To monitor system activity and quickly identify system failure, an enhanced “monitor of monitors” (MoMs) was designed based on the new system architecture. All data servers, including three VS trend data collectors (blue dots in Figure 2) and three waveform collectors (green dots in Figure 1), send the latest data with timestamps to the MoMs system. Figure 8 shows a snippet of the MoMs system. Each data server is represented by a large block (Figure 8). Each bed unit collected by such server is represented by a colored small box. If a bed unit is online in the last 5 minutes, the box is green, with the admission status (admitted or discharged) and the last HR value. If a bed unit is offline for longer than 5 minutes, the box is yellow. It turns red if the bed unit is offline longer than 6 hours. For VS of special interest, MoMs can use special colors to highlight. For example, ICP is an important VS for traumatic brain injured patients and is not often collected due to its intrusive nature. The MoMs system shows ICP collected unit in pink and its latest value.

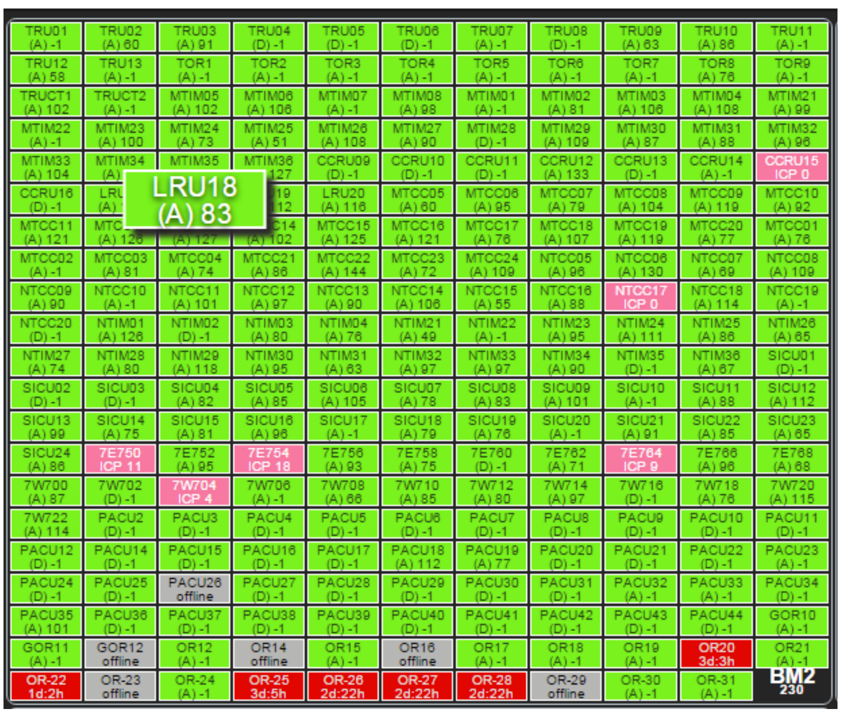

Figure 8. A snippet of MoMs system of 230 bed units in one data server.

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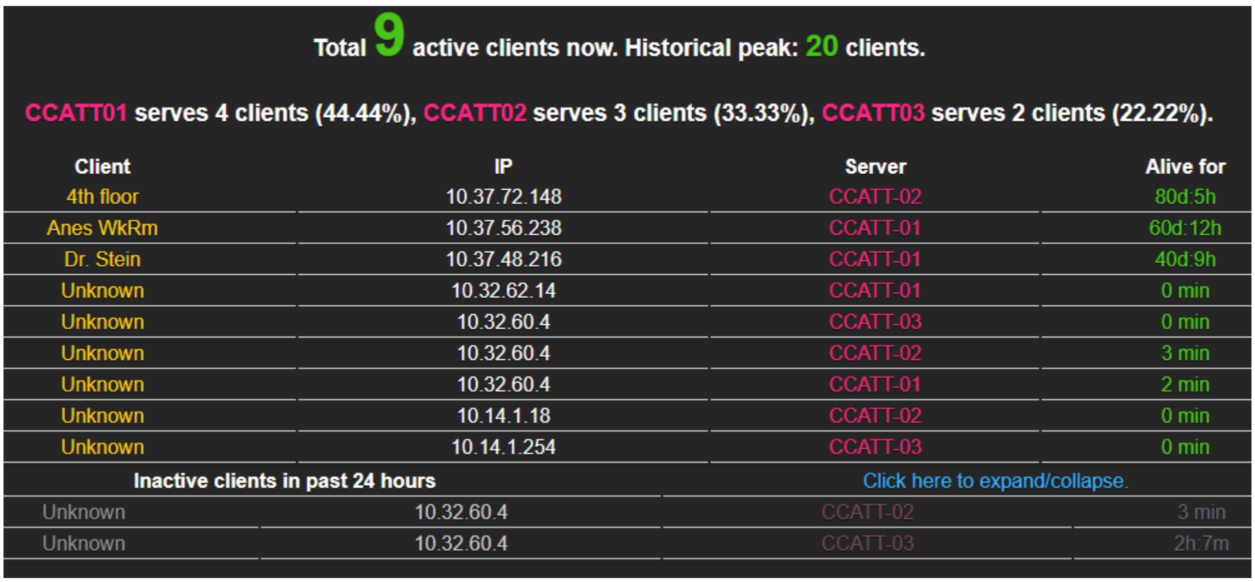
To test the new system's accuracy, reliability, and robustness, we carried out a set of tests. We verified the timestamps of data from all servers. The BedMaster data time is compared with the CCATT viewer displayed time. We visited dozens of bed units in the hospital to compare CCATT data with the bedside display. During the visit, we discovered a time zone shift between the mobile device and the BedMaster server. We fixed the issue, and the CCATT always shows the timestamp of the local time zone.

We also have conducted stress testing of the CCATT servers. We requested volunteer users to launch many clients and keep them running for a long time. A monitoring page was created to log all the clients' online status, from which we could know their online duration and the servers' load distribution (Figure 9).



Total 9 active clients now. Historical peak: 20 clients.

CCATT01 serves 4 clients (44.44%), CCATT02 serves 3 clients (33.33%), CCATT03 serves 2 clients (22.22%).

Client	IP	Server	Alive for
4th floor	10.37.72.148	CCATT-02	80d:5h
Anes WkRm	10.37.56.238	CCATT-01	60d:12h
Dr. Stein	10.37.48.216	CCATT-01	40d:9h
Unknown	10.32.62.14	CCATT-01	0 min
Unknown	10.32.60.4	CCATT-03	0 min
Unknown	10.32.60.4	CCATT-02	3 min
Unknown	10.32.60.4	CCATT-01	2 min
Unknown	10.14.1.18	CCATT-02	0 min
Unknown	10.14.1.254	CCATT-03	0 min
Inactive clients in past 24 hours		Click here to expand/collapse.	
Unknown	10.32.60.4	CCATT-02	3 min
Unknown	10.32.60.4	CCATT-03	2h:7m

Figure 9. A page to monitor clients' online status and CCATT servers' load distribution.

4.0 VALIDATION IN A REAL TRAUMA CENTER

In the R Adams Cowley STC, a level 1 regional trauma center located in downtown Baltimore, Maryland, 94 GE-Marquette-Solar-7000/8000® (General Electric, Fairfield, CT) patient VS monitors are networked to provide collection of real-time patient VS data streams in 13 TRU, 9 operating room OR, 12 post-anesthesia care, and 60 ICU individual bed/monitor units. Each patient monitor collects real-time 240-Hz waveforms and 0.5-Hz trends data, which are transferred via secure intranet to a dedicated BedMaster® server (Excel Medical Electronics, Jupiter, FL) and archived [8]. This process generates approximately 20 million data points/day/bed or roughly 30 terabits/year of data. Physiological data collected through this system, when they are displayed on the GE Marquette monitor, include electrocardiographic, photoplethysmographic, carbon dioxide, arterial blood pressure, and ICP, among others. Trends include HR, RR, temperature, SpO2, EtCO2, and ICP, among many others. They cover the categories of brain pressure, cardiac, perfusion, and respiratory.

STC attendings, physician assistants, nurse practitioners, and fellows were trained and familiarized with the viewer in sessions. After training, the clinicians filled out a survey soliciting feedback on the ICU viewer. Research staff shadowed STC attendings on rounds to

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gain experience to develop the viewer validation questionnaire. On rounds, the research staff documented the following:

1. All clinical judgments, orders, and treatment decisions made by clinicians as an open-ended survey – document which unit you are in, which types of rounds, and the judgments & decisions made.
2. When shadowing through the rounds, study the logistics, the different units, different types of rounds, and think about it from the point of view of when having a research coordinator give a clinician or nurse a survey would be least disruptive and most welcome.

Based on these data and several dedicated survey design meetings, with participation by senior trauma physicians, USAF physicians, study coordinators, principal investigators, and system design team members, a survey was generated and adjusted. The survey was used on rounds on multiple occasions before the survey was uploaded to an online database. During rounds, the survey link was pulled up for the attending on one of two tablets purchased for that purpose. On the rare occasion that the server failed, paper surveys were available and used to collect data.

Physicians who were scheduled to work in the ICU or on the team were contacted and trained on how to use the CCATT viewer. Once trained, ICU and team attendings were asked to participate in the study. Those willing were surveyed during morning rounds on ICU patients; those unwilling were rarely asked again. Physicians were only surveyed Tuesday-Friday and were asked to conduct rounds normally, using data reported from nurse charts and briefs from fellows to inform their clinical decisions. After the physicians finished their assessment and plan for the patient, they were given the pre-view questionnaire to fill out (Appendix A). Immediately after that, the CCATT viewer was presented to the physicians on a tablet PC displaying the patient's past physiologic data visualized and summarized up to 72 hours. After looking at the CCATT viewer for as long as they would like, typically for 1 minute or less, the physicians filled out the post-view questionnaire (Appendix B). In both questionnaires, the physicians are asked questions regarding the patient's stability, status, and need for a higher or lower level of care. Physicians were also asked if they intentionally plan on any of the following interventions after seeing the viewer: (a) changing any current medications, (b) ordering additional medications, (c) ordering additional diagnostic tests, (d) changing ventilation settings, (e) ordering additional labs, (f) physically reexamining this patient, (g) providing fluid bolus, or (h) providing a blood transfusion.

5.0 RESULTS

5.1 Overall Results

From February 15, 2017, to June 30, 2017, 908 surveys were collected. Besides the questions from the survey forms, we also collected the survey time, rounding type (trauma team or ICU), and whether the patient was admitted to the ICU in the last 24 hours (Figure 10). There were 758 (83%) surveys collected from the ICU and 150 (17%) from the team. Among the 908 rounds, 48 (5%) were new STC admission in the last 24 hours and 860 (95%) were not. We compared the clinicians' evaluations on the patients before and after seeing the CCATT viewer.

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Figures 11-14 show that the CCATT viewer could support their initial evaluations on infection, hemodynamic status, general condition, etc. Specifically, we asked the clinicians the following:

1. Having reviewed the last 24 hours information during rounds and before/after seeing the 24-hour CCATT viewer, do they feel that in the past 24 hours the patient has shown evidence of (a) infection, (b) hemodynamic instability, (c) uncontrolled bleeding, or (d) respiratory deterioration?
2. Over the past 24 hours, the patient's condition has (a) improved significantly, (b) improved slightly, (c) unchanged, (d) deteriorated slightly, or (e) deteriorated significantly.
3. Can the patient be transferred to a lower level of care?
4. Can the patient be transferred to a higher level of care?
5. Does the patient have TBI?
6. Did the patient have ICP problems in the past 24 hours?
7. Due to the viewer, do they plan for any changes of interventions, including (a) changing any current medications, (b) ordering additional medications, (c) ordering additional diagnostic tests, (d) changing ventilation settings, (e) ordering additional labs, (f) physically reexamining this patient, (g) providing a fluid bolus, or (h) providing a blood transfusion?
8. Does the viewer enhance their understanding of the patient's condition?

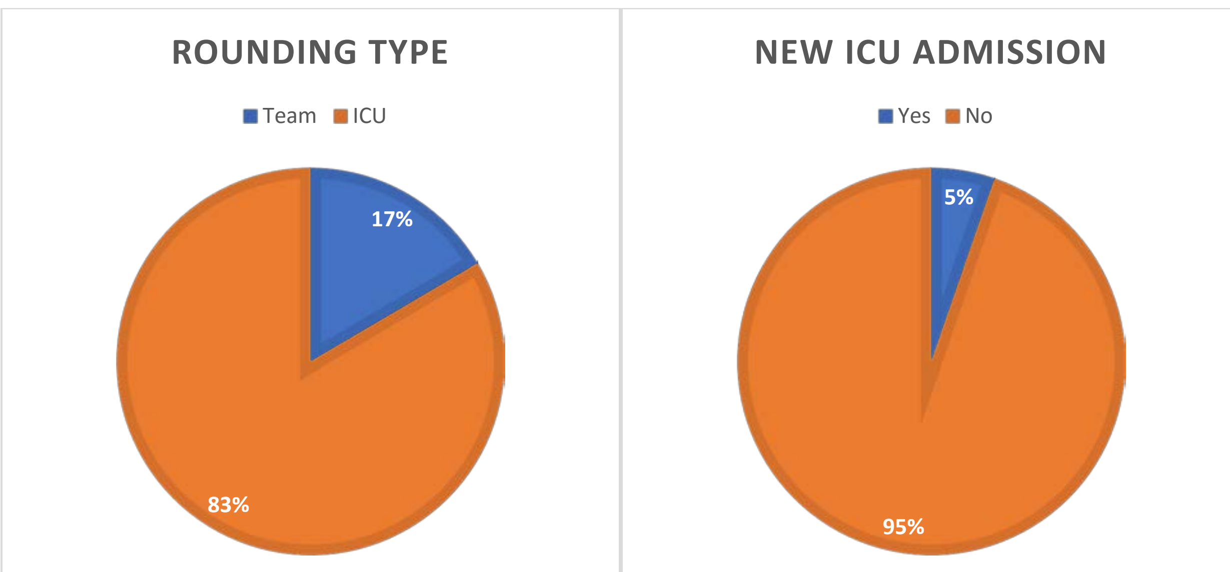

Figure 10. Pie charts of rounding type and percentage of patients who were new STC admissions in last 24 h.

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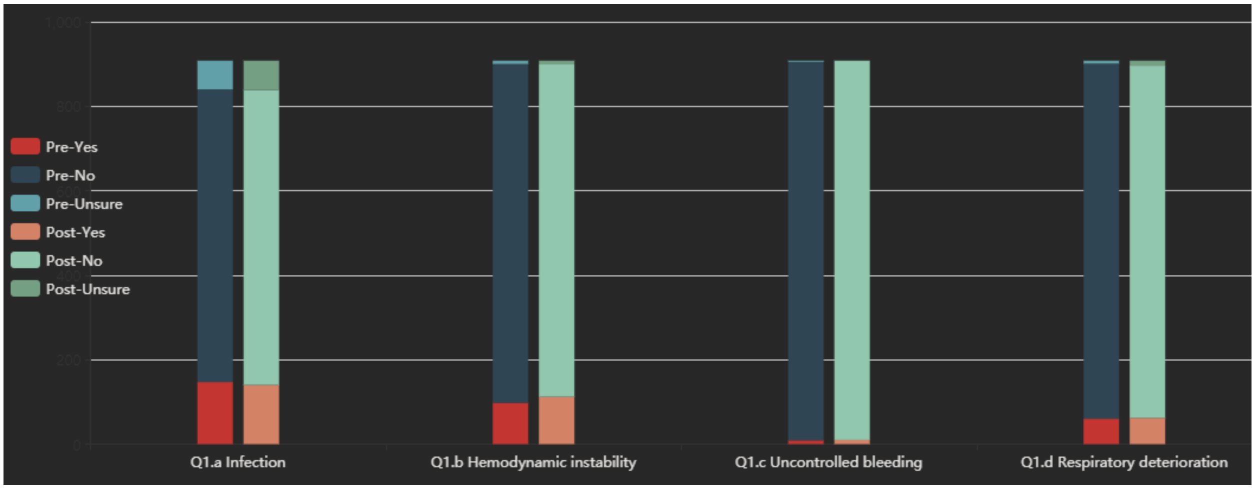

Figure 11. Comparison of answers on the following question: "Having reviewed the last 24 h during rounds [left bar]/CCATT viewer [right bar], I feel that in the past 24 h this patient has shown evidence of (a) infection, (b) hemodynamic instability, (c) uncontrolled bleeding, or (d) respiratory deterioration."

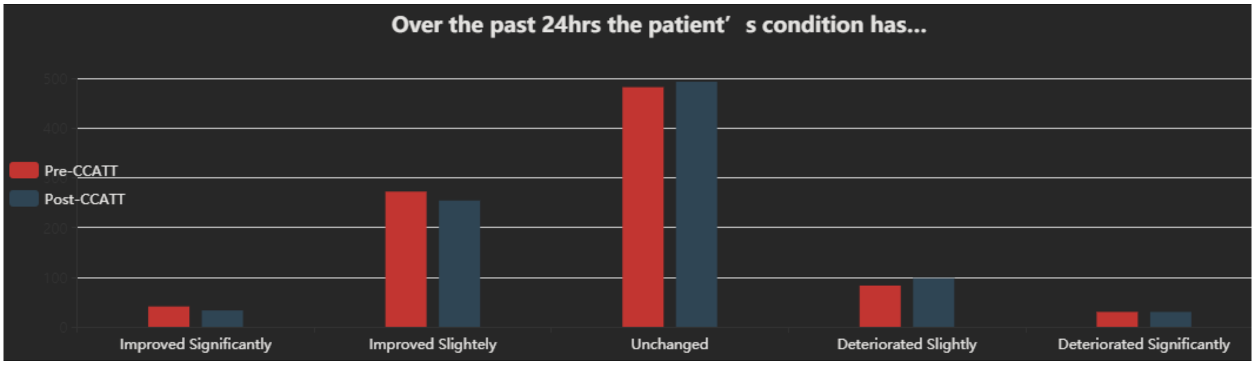

Figure 12. Comparison of answers before and after viewing the CCATT viewer for the following question: "Over the past 24 h the patient's condition has (1) improved significantly, (2) improved slightly, (3) unchanged, (4) deteriorated slightly, or (5) deteriorated significantly."

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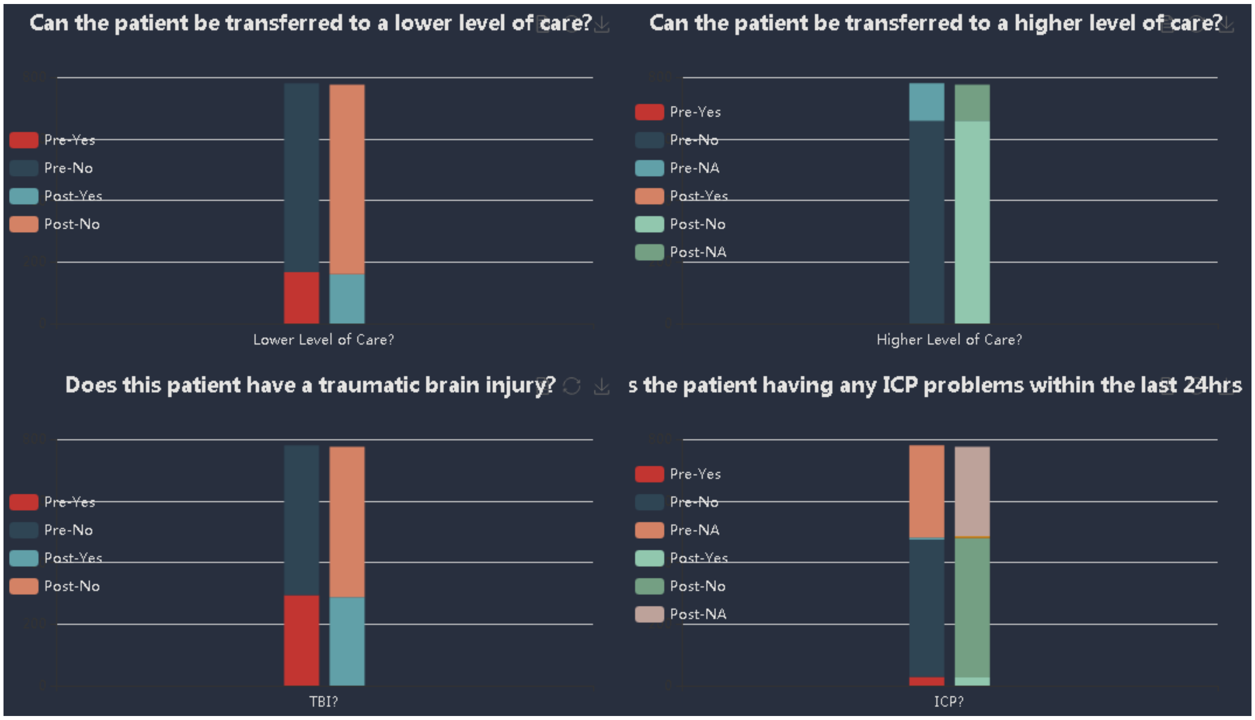

Figure 13. Comparison of answers before and after seeing the CCATT viewer for the following questions: (1) Can the patient be transferred to a lower level of care? (2) Does the patient need to be transferred to a higher level of care? (3) Does this patient have a traumatic brain injury? (4) Is the patient having any ICP problems within the last 24 h?

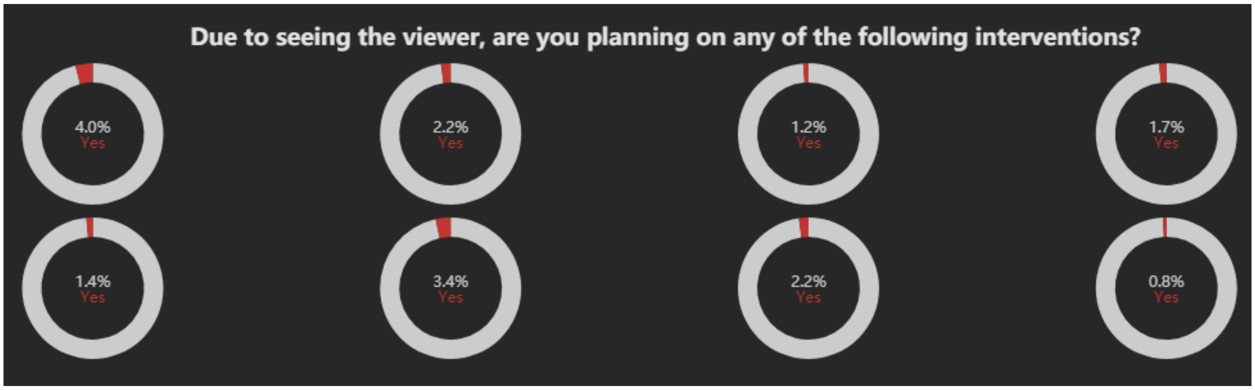

Figure 14. Ring charts for percentage of surveyed attendings positively planning interventions due to seeing the CCATT viewer.

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Overall, during the 908 surveys when asked if the CCATT viewer enhanced their understanding of the patient's condition, physicians strongly agreed 45 times (4.96%), agreed 514 times (56.61%), were neutral 321 times (35.35%), disagreed 26 times (2.86%), and strongly disagreed 2 times (0.22%) (Figure 15).

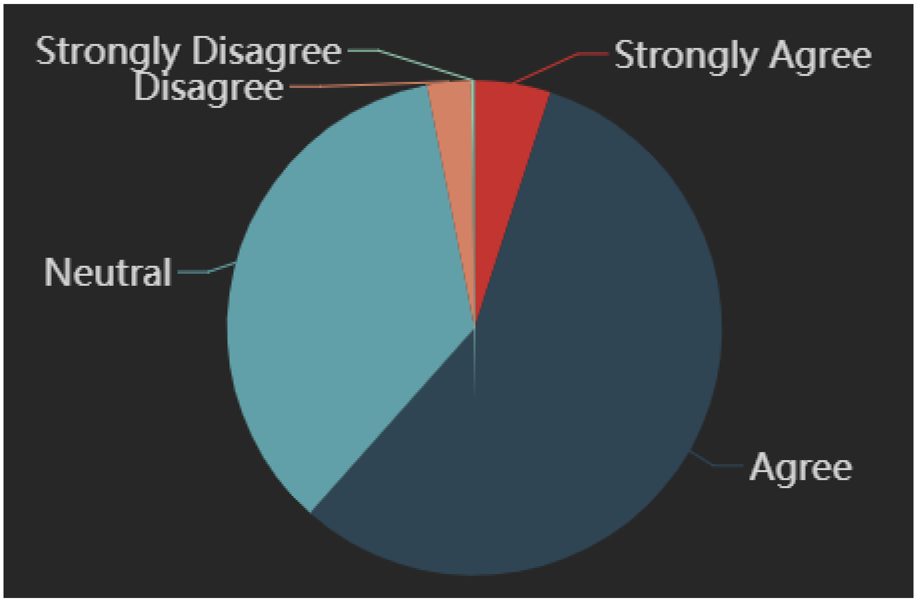

Figure 15. Pie chart showing clinicians' rating of the CCATT viewer.

Results show that physicians' clinical assessments and plans could be influenced by viewing the CCATT viewer for 1 minute or less, indicated by a "yes" answer to at least one of the eight questions. The most common change was (a) change current medications (4.0%). The next most common changes were (f) physically reexamining the patient (3.4%), (b) ordering additional medications (2.2%), and (g) providing a fluid bolus (2.2%). Other responses are shown in Figure 14.

5.2 Types of Participants

To collect and keep as many data as possible, the survey team followed clinicians who agreed to take the surveys. Twenty-four unique participants finished 908 surveys with unbalanced proportions. Figure 16 summarizes the total number of surveys that each participant had completed. The top one contributed 154 (16%) surveys, followed by 118 (13%) and 113 (12.4%) from two other participants. One participant contributed only one survey and strongly disagreed that the CCATT viewer enhanced his/her understanding of the patient's condition. The distribution of the number of surveys taken and the rating on the viewer indicate the participants may have different *a priori* attitude toward the use of the viewer. Clinicians may have different receptiveness to the new tool and various way to manage information during rounding. Therefore, their perception of usefulness of the viewer is different. The subjective question "the viewer enhanced my understanding of the patient's condition" can be used to separate the participants into different types.

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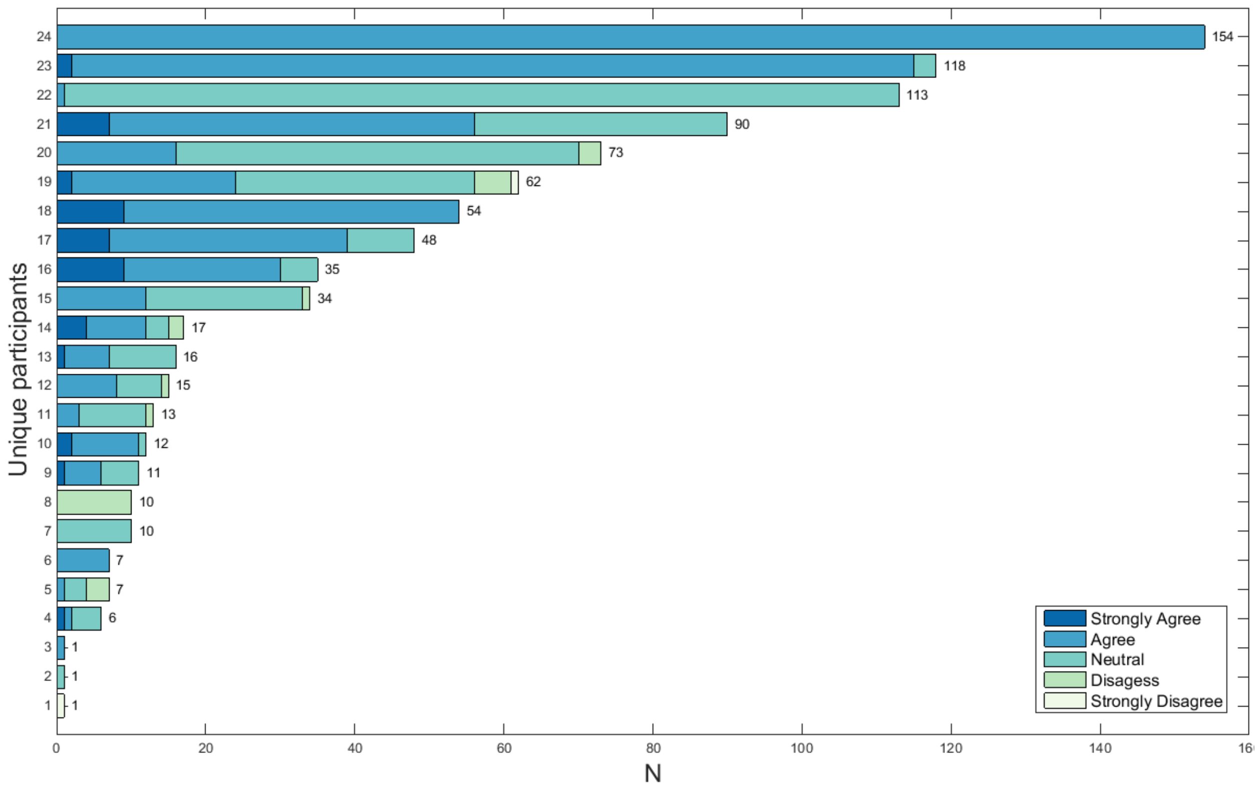

Figure 16. Distribution of each participant's rating on if the viewer enhanced his/her understanding of the patient's condition during a round.

We used a clustering method to group the participants based on their ratings for each rounding. A participant is represented by a vector, consisting of the percentage of the five categories that he/she assigned to the question "the viewer enhanced my understanding of the patient's condition." For example, one participant contributed 62 surveys and rated 2 "strongly agree," 22 "agree," 32 "neutral," 5 "disagree," and 1 "strongly disagree." The percentages of the rates 0.03, 0.35, 0.52, 0.08, and 0.02 together represent the overall attitude that this participant had about the viewer. Based on Manhattan distance, the 24 participants were clustered into five groups, as shown in Figure 17. The five groups correspond to the participants who are from mostly in favor (C1) of the viewer to those least in favor (C5). There are six in C1, six in C2, three in C3, seven in C4, and two in C5, which shows a very balanced grouping, with half of the participants in the C1 and C2 groups and the other half in the other three clusters. This shows that the sampled rounds were done by participants with almost similar proportions of different attitudes toward the viewer. In other words, the survey team sampled the rounds random enough such that the collected data are not biased by participants with certain preexisting feelings about the viewer.

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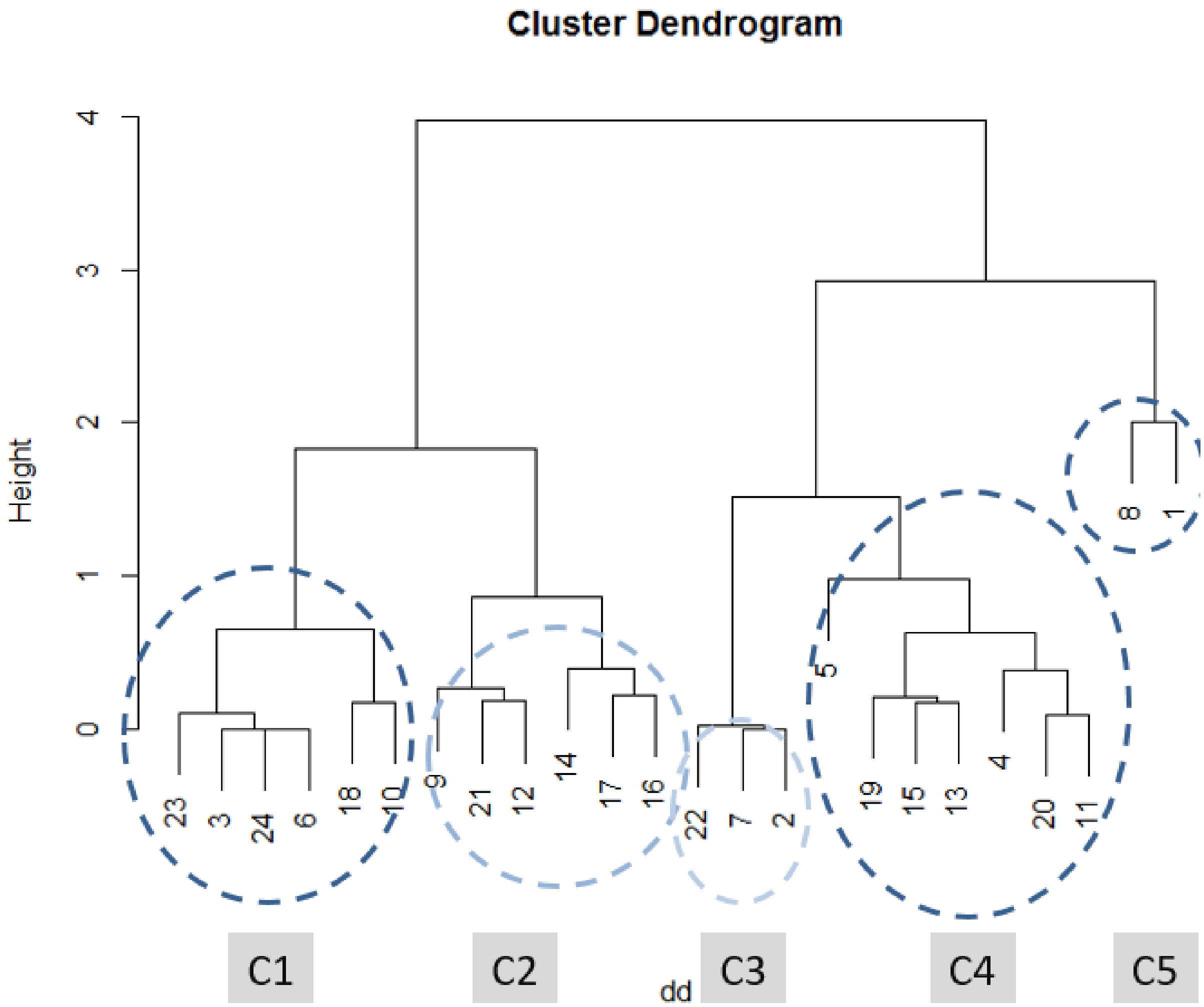

Figure 17. Clusters of participants with similar feelings about the viewer. In total, 24 unique participants are grouped into five groups, corresponding to "strongly favor," "favor," "neutral," "dislike," and "strongly dislike."

5.3 Comparison using the Clusters

For questions 1-7 listed in section 5.1, we analyzed the changes between before and after seeing the viewer, with respect to the clusters of user types. In question 1, the physicians were asked, "*Having reviewed the last 24 hours information during rounds and before / after seeing the 24-hour CCATT viewer, do they feel that in the past 24 hours the patient has shown evidence of (a) infection, (b) hemodynamic instability, (c) uncontrolled bleeding, or (d) respiratory deterioration?*" For all the four events, physicians' answers could be "yes," "no," or "unsure." There were changes from before and after seeing the viewer 129 times (14.21%). Sixteen participants (66.7%) had used the viewer's information to make changes. In terms of the clusters of user types, there were 46, 31, 10, 42, and 0 times of any opinion changes occurring in user clusters C1 to C5.

In question 2, physicians were asked, "*Over the past 24 hours, the patient's condition has (a) improved significantly, (b) improved slightly, (c) unchanged, (d) deteriorated slightly, or (e) deteriorated significantly.*" Their answer could be any one of above five opinions. There were

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112 times (12.33%) of changes from before and after seeing the viewer. Fifteen participants (62.5%) had used the viewer's information to make changes. Among the five clusters, there were 38, 34, 8, 32, and 0 times any changes occurred.

Questions 3-6 can be considered as a group of similar questions. The answers could be "yes," "no," or "not applicable." There were 145 times (15.97%) of changes from before and after seeing the viewer. Eighteen participants (75%) had used the viewer's information to make changes. There were 58, 54, 3, 30, and 0 times changes occurred in each of the five clusters.

For question 7, physicians were asked, "*Due to the viewer, do you plan for any changes of interventions, including (a) changing any current medications, (b) ordering additional medications, (c) ordering additional diagnostic tests, (d) changing ventilation settings, (e) ordering additional labs, (f) physically reexamining this patient, (g) providing a fluid bolus, or (h) providing a blood transfusion.*" Their answer could be "yes" or "no" to any combination of above eight options. A total 92 times (10.13%) rounds had at least one "yes" answer as planning on some of the interventions. Seventeen participants (70.83%) had used the viewer's information and planned some of the interventions. In the five clusters, there were 20, 32, 9, 31, and 0 times of planning. Table 3 shows the numbers of rounds in which physicians had from 0 to 8 planned interventions due to seeing the viewer.

Table 3. Numbers of Rounds in which Physicians Had from 0 to 8 Planned Interventions Due to Seeing the Viewer

No. of Planned Interventions	No. of Rounds	Percentage in All Rounds
0	816	98.87
1	**61**	6.72
2	**13**	1.42
3	**12**	1.32
4	**3**	0.33
5	**1**	0.11
6	**1**	0.11
7	**1**	0.11
8	**0**	0.00

5.4 Other Factors

The 908 surveys were collected from weekdays (except Mondays) in 4.5 months. The survey team followed the rounds and asked the leading physicians who were randomly selected and willing to take the survey. In this section, we visualize the daily collected data and see from the dimensions of time and round type.

First, we visualized the distribution of daily collected surveys along the 4.5 months (Figure 18). The 908 surveys were collected over 71 days, 13 surveys per day on average. The median collection rate was 12 surveys per day. The minimum collection rate was 1 survey in a day, and it peaked at 27 surveys in a day. There was no obvious type of distribution of the daily collection rate, either normal or uniform distribution. It shows some randomness. However, it is true that the overall daily collection rate was lower at the end than in the beginning. This is

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because of the fatigue brought on by the repeated survey. But in general, there is no evidence that the surveys were collected from a particular period of time.

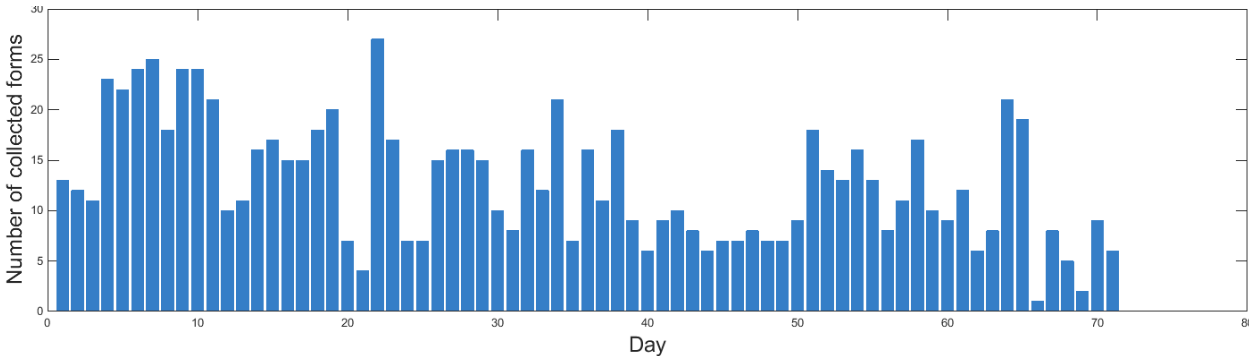

Figure 18. Number of surveys collected on each day during this study.

There are two types of rounds: team and ICU. There are three patient receiving teams led by a trauma surgeon at our trauma center. A trauma patient admitted to our trauma center is met by one of the team members. The team is responsible for following the patient throughout the trauma center stay. Team rounds are more focused on the patient's care plan such as when to go to the OR or if the patient can be moved to a lower level of care, etc. ICU rounds are led by the ICU intensivists (clinicians with critical care certification). They will round through all the patients in the unit. They are more focused on the patient's stability in the unit and coordinate care with each of the specialists (orthopedic, cardiovascular, pulmonary, infectious diseases) as needed. There were more surveys collected from ICU rounds, but the two types were spread out over the collection time (Figure 19). Table 4 summarizes the number of surveys with answer changes in terms of round type. For questions 1 and 3-6, there was no significantly different proportion of changes between the team and ICU rounds. For questions 2 and 7, team rounds had a higher answer change percentage than ICU rounds.

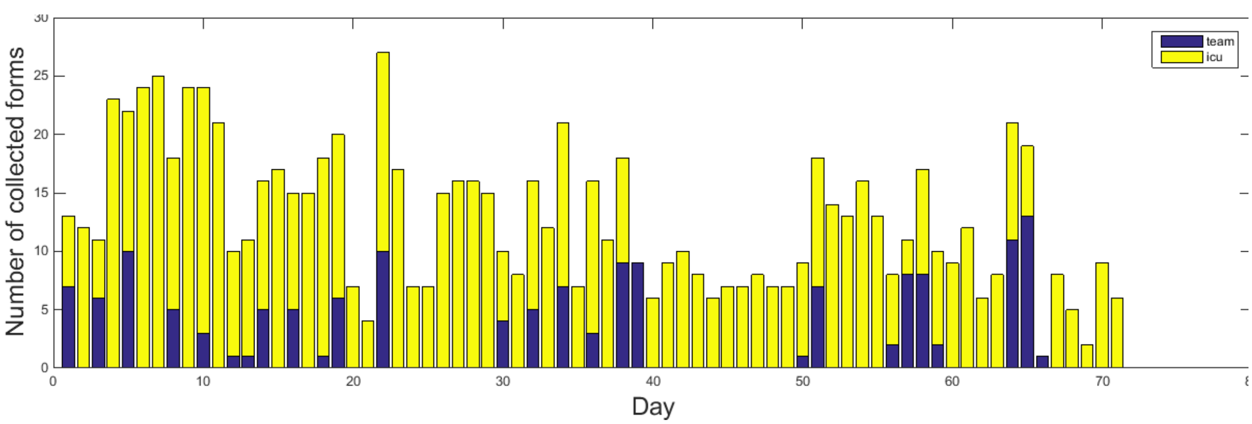

Figure 19. Number of surveys collected from team (blue) or ICU (yellow) rounds during each day of this study.

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Table 4. Number of Surveys with Answer Changes Before and After Seeing the Viewer in Terms of Round Type

Question	Team (N=150)	ICU (N=758)	Proportional Test p-Value
1	24 (16.00%)	105 (13.85%)	0.575
2	28 (18.67%)	84 (11.08%)	0.015
3-6	25 (16.67%)	120 (15.83%)	0.894
7	26 (17.33%)	66 (8.71%)	0.001

6.0 DISCUSSION

6.1 Usefulness

CCATT was created for fast, reliable AE. In the Vietnam War, it took about 45 days to transport patients from the front line to home, 10 days during Desert Shield/Storm, and less than 3 days in today's war zones. Initiated in 1994, the USAF CCATT has transported more than 8000 patients, among which up to 80% were trauma patients [9]. The team consists of a compact and specialized medical crew. They provide necessary medical care to a group of patients onboard during flight. The airplane serves as a portable ICU, but with very limited resources. CCATT has been proved to be useful in transporting critically injured patients with short-term complications [10,11]. However, these compact medical teams constantly face challenges regarding in-flight assessments that are required to rapidly render appropriate clinical support. Clinical decision-making is further confounded by an aeromedical environment characterized by confined space, noise, vibration, and limited visibility.

The viewer, which automates physiological data-organizing and information-summary, could present aggregated information from multiple data sources, provide at-a-glance summaries of clinical data, and assist with prioritizing care for multiple patients. The platform presents trends in patients' condition with simple color codes, which can greatly improve situational awareness. In addition to a small group of patients, the viewer is scalable to large hospitals with hundreds of beds.

6.2 Evaluation

The CCATT viewer has been deployed and evaluated in a regional level 1 trauma center. The trauma center environment shares some similarity with the military airplanes that fly the CCATTs. They both have busy and confined spaces, which are surrounded by many medical devices. The military airplanes are enormously noisy during flight, which makes most medical acoustic alarms hard to hear. In civilian hospitals, alarm fatigue also exists due to continuous alarms. Both currently use bedside monitors that display individual patients' instantaneous VS readings without easy access to a trajectory view. Therefore, a new VS monitoring tool, such as the CCATT viewer, could be used to improve situational awareness in both military and civilian hospital environments.

Morning rounds in a civilian trauma center ICU are conducted in a busy environment with many data sources, which is similar to a busy and confined transport aircraft. Physicians in both environments must make high-stakes decisions using loosely organized physiological data and are often oversaturated with information of varying quality. The survey shows that organized

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physiologic data and visual assessment could possibly assist clinicians to recognize changes in patient status and prioritize care.

Moreover, the STC generates more data streams than a CCATT airplane. Hence, the evaluation environment could serve as a stricter testing space for stress testing the viewer's capacity of processing and organizing massive amounts of data. The STC has more than 160 beds, each collecting 9 or more high-fidelity VS trajectories. On average, 9 million data points per minute are streamed and processed by the viewer. In the military CCATT airplane, typically dozens of patients or less are transported and monitored. Therefore, the data amount tested is far beyond the possible real use in the CCATT airplane.

From 908 survey forms collected from ICU attendings, we can observe that clinicians can use the viewer to recognize changes in patient status or confirm their judgment. They may discover more information within about 1 minute of looking at the viewer.

6.3 Limitations

We collected data from a large number of ICU doctors compared to team doctors. This is primarily because of the number of ICU patients ICU doctors are responsible for compared to team doctors. At the STC, team doctors are surgeons, responsible for the same patient throughout his/her stay, regardless of the acuity of the patient. ICU doctors are intensivists and are only responsible for ICU patients on their floor. Not only does this mean ICU doctors have more ICU patients, but it also means it was easier to find and talk to them in person. Team doctors had to return our pages for us to know where they were.

Some physicians were more amenable to being surveyed than others, which made it difficult to truly randomize the physicians we sampled. In the collected forms, there were more surveys from some clinicians than from others. To reduce the bias, we clustered the participants based on their overall rating on each round, from which we estimated each participant's *a priori* attitude toward using this viewer. The results show that there was balanced "favoring" and "non-favoring" of using this viewer.

Although the civilian ICU is similar to the CCATT environment, it is still different from the real AE condition. In this evaluation, we cannot simulate the vibating, highly stressful, unstable environment. The locations, viewing point of the bedside monitors, and the viewer could be quite different from those in the airplane. The patient care protocols could be very different in a civilian ICU and the CCATT team. Therefore, it is necessary to design a new evaluation of the viewer in a real CCATT aircraft environment to determine its stability and usefulness to the crew.

6.4 Product and Impact

The VS viewer was created to run on PCs. An Android app also has been made to run the viewer's client on Android phones. The viewer system, including its architecture and visualization scheme, has been submitted for a U.S. provisional patent application under the title "Method and Apparatus for Monitoring Collection of Physiological Patient Data."

The Technology Readiness Assessment report for the CCATT viewer was submitted to the Air Force Medical Support Agency and the viewer has achieved technology readiness level 3 and emergent 4.

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The CCATT viewer has been presented to a wide audience at various Department of Defense and international conferences and meetings.

7.0 CONCLUSIONS

With the development of sensoring and computing technologies, vast amounts of high-quality, continuous, electronic data, including VS, alarms, and clinical interventions, are collected at the bedside. Those data have the potential to provide an unprecedented view of dynamic physiologic response to injury, illness, and treatments. Therefore, data gathered from bedsides could assist clinicians for care planning and decision-support.

However, massive data that aren't well organized or presented still create a barrier for clinicians making full use of them in a busy resuscitation or intensive care environment. Bedside monitors often only display instantaneous readings or a short strip of recent physiologic VS for diagnosis. Clinicians need to rely on separate nursing charts, hand-written or electric, to review a patient's developing conditions. Also, auditory alarms often cause "alarm fatigue" instead of increasing situational awareness. Moreover, many bedside monitors only display one or two patients' information. Health providers lack a convenient tool to maintain an overall summary of multiple patients in different beds and hence may spend more time to track multiple patients and to decide care priority.

We designed, implemented, and evaluated an automated physiologic data organizer and visualization platform, the CCATT viewer. It provides at-a-glance summaries and assists with prioritizing care for multiple patients. The CCATT viewer prototype demonstrates a method to assemble large quantities of data from multiple sources and represents trends in each patient's condition with simple color codes, greatly improving situational awareness.

Morning rounds in a civilian trauma center ICU are conducted in a busy environment with many data sources, which is similar to a busy and confined transport aircraft. Physicians in both environments must make high-stakes decisions using loosely organized physiological data and are often oversaturated with information of varying quality. The survey shows that the organized physiologic data and visual assessment could assist clinicians to recognize changes in patient status and prioritize care.

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APPENDIX A
Survey 1, Pre-CCATT Viewer Questionnaire

CCATT Viewer
Rounding Survey

Badge ID#: _ _ _ _
Rounding Type: Team/ICU
Floor: 4IMC/4ICU/5IMC/5ICU/6IMC
New STC Admit in last 24 h: Yes/No

After traditional rounds and before accessing the viewer

Directions: For the following questions please circle your responses

1. I have previewed the viewer for this patient before rounding. *Yes* *No*

2. Having reviewed the last 24 h during rounds, I feel that in the past 24 h this patient has shown evidence of:
   a. Infection *Yes* *No* *Unsure*
   b. Hemodynamic instability *Yes* *No* *Unsure*
   c. Uncontrolled bleeding *Yes* *No* *Unsure*
   d. Respiratory deterioration *Yes* *No* *Unsure*

3. Over the past 24 h the patient's condition has

Improved significantly	*Improved slightly*	*Unchanged*	*Deteriorated slightly*	*Deteriorated significantly*
1	*2*	*3*	*4*	*5*

4. Can the patient be transferred to a lower level of care? *Yes* *No*

5. Does the patient need to be transferred to a higher level of care? *Yes* *No*

6. Does this patient have a traumatic brain injury? *Yes* *No*

7. Has the patient had any ICP problems within the last 24 h? *Yes* *No* *Unsure* *N/A*

Show Attending the Viewer

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APPENDIX B
Survey 2, Post-CCATT Viewer Questionnaire

1. ***<u>Having reviewed the last 24 h during rounds and seen the 24-h CCATT viewer screen, I feel that in the past 24 h this patient has shown evidence of</u>*:**
   a. Infection *Yes No Unsure*
   b. Hemodynamic instability *Yes No Unsure*
   c. Uncontrolled bleeding *Yes No Unsure*
   d. Respiratory deterioration *Yes No Unsure*

2. Over the past 24 h the patient's condition has

Improved significantly	*Improved slightly*	*Unchanged*	*Deteriorated slightly*	*Deteriorated significantly*
1	*2*	*3*	*4*	*5*

3. Can the patient be transferred to a lower level of care? *Yes No*

4. Does the patient need to be transferred to a higher level of care? *Yes No*

5. Does this patient have a traumatic brain injury? *Yes No*

6. Has the patient had any ICP problems within the last 24 h? *Yes No Unsure N/A*

7. Due to seeing the viewer, are you planning on any of the following interventions?
   a. Changing any current medications *Yes No*
   b. Ordering additional medications *Yes No*
   c. Ordering additional diagnostic tests *Yes No*
   d. Changing ventilation settings *Yes No*
   e. Ordering additional labs *Yes No*
   f. Physically reexamining this patient *Yes No*
   g. Providing a fluid bolus *Yes No*
   h. Providing a blood transfusion *Yes No*

8. I found that the CCATT viewer enhanced my understanding of the patient's condition.

Strongly Agree	*Agree*	*Neutral*	*Disagree*	*Strongly Disagree*
1	*2*	*3*	*4*	*5*

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LIST OF ABBREVIATIONS AND ACRONYMS

2D	two-dimensional
AE	aeromedical evacuation
BTI	brain trauma index
CCATT	Critical Care Air Transport Team
CPP	cerebral perfusion pressure
DBP	diastolic blood pressure
EtCO2	end-tidal carbon dioxide
HR	heart rate
ICP	intracranial pressure
ICU	intensive care unit
MoMs	monitor of monitors
OR	operating room
PC	personal computer
RR	respiratory rate
SBP	systolic blood pressure
SI	shock index
SpO2	blood oxygen saturation (pulse oximetry)
STC	Shock Trauma Center
TRU	trauma resuscitation unit
USAF	U.S. Air Force
VS	vital signs

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