**eSupplement**

Section 1: Tele-ICU Essential Functions Definitions

(1) CRISIS INTERVENTIONS: At times of deterioration and/or crisis the bedside team will send an emergency signal which triggers the tele-ICU team to connect immediately with the patient in question to provide assistance in management. *These are usually the most time-sensitive and urgent tasks but also commonly least unpredictable tasks.*

(2) PROACTIVE MONITORING: The commonly multidisciplinary tele-ICU team of nurses and doctors monitors alerts and warnings generated by computer-based algorithms based on interfaced vital sign and lab data feeds as well as other interfaced clinical information. *This is usually a discontinuous, intermittent task that is being performed in between other tasks.*

(3) NEW PATIENT EVALUATION: All patients are clinically evaluated upon admission to the ICU, a time of potentially highest acuity and patient instability. Clinical information is evaluated and data are entered into systems to generate admission notes which form the basis to generate clinical outcome predictions, most commonly following the Acute Physiologic Assessment and Chronic Health Evaluation (APACHE) methodology, which is generally considered the gold standard for clinical outcomes predictions in critical care. *Evidence shows that performing this task within one hour of patient admission to the ICU is associated with reduced ICU mortality and length of stay (LOS).1*

(4) BEST PRACTICE ADHERENCE: All patients are being evaluated on a daily basis to ensure that certain care standards are continuously being met, which have been shown in the literature to be associated with improved clinical outcomes. Examples here are therapies to prevent blood clot formation during bedbound states, preventing stress-related stomach ulcers, using the correct mechanical ventilator settings for patients with respiratory failure, using the correct transfusion thresholds and controlling blood-sugar levels during critical illness. Other care standardization initiatives undertaken through the tele-ICU like pharmacology support, sepsis evaluations etc. might also fall into this category of urgency/priority/predictability. *This task is not urgent, but still needs to be completed within certain time-frames, typically within the clinicians 12-hour shift, to create reproducible and consistent actionable data outputs by the tele-ICU.*

Section 2: Typical Daily, Weekly, and Yearly Admission/Discharge Patterns

The ICU LOS at the tele-ICU center was calculated as (discharge date) − (admission date). Figure e1 (Supplemental Digital Content 2, http://links.lww.com/CCX/A119) shows the distribution of the LOS: 42% of the patients’ LOS is shorter than or equal to 2 days, and the average LOS in the tele-ICU is 4.9 days.

**Figure e2** (Supplemental Digital Content 3, http://links.lww.com/CCX/A120), **Figure e3** (Supplemental Digital Content 4, http://links.lww.com/CCX/A121), and **Figure e4** (Supplemental Digital Content 5, http://links.lww.com/CCX/A122) display the arrival patterns of new patients to be admitted by hour, day, and month, respectively. As shown in Figure e2 (Supplemental Digital Content 3, http://links.lww.com/CCX/A120), on a typical day, the number of new admissions at the tele-ICU center is fewer in the morning but greater in the afternoon and evening. The peak arrival-time period during a day appears to be between 5pm and 10pm, while 6am to 11am is the low arrival time period. In a typical week, the arrival of new admissions is relatively constant from Monday to Friday; approximately 16% of the weekly admissions arrive each weekday; The weekend has relatively fewer number of new admissions; about 10% of weekly admissions occur on Saturday or Sunday (Fig. e3, Supplemental Digital Content 4, http://links.lww.com/CCX/A121). Over the course of a year, Figure e4(Supplemental Digital Content 5, http://links.lww.com/CCX/A122) indicates that the number of new patients admitted per month is approximately equal; about 8% of annual admissions occur each month.

Section 3: Duration and Pattern of First Video Session by Nurse and Physician

**Figure e5** (Supplemental Digital Content 6, http://links.lww.com/CCX/A123) and **Figure e6** (Supplemental Digital Content 7, http://links.lww.com/CCX/A124) show the distributions of the first video length performed by nurses and by the intensivist, respectively. Exponential distributions provide suitable fits for both video-session lengths. The average lengths of the first video session by nurses and by the intensivist 113 seconds and 127 seconds, respectively. Currently, the average lengths of follow-up videos made by nurses and by the intensivist are 123 seconds and 147 seconds. 35% (99%) of admitted patients are seen by intensivist more than once via follow-up videos.

 Section 4: Input Derivations and Explanations

Based on past experience, time management assumptions were made for this model. It was assumed that admission tasks and crisis intervention tasks require 40% and 15% of the working hours of the intensivist and nurses, respectively. The other tasks (proactive monitoring and best practices) require approximately 30% of their working hours; and the intensivist and nurses are idle for about 15% of their total working hours. Based on the data collected over the 12-month period, the average number of crisis interventions is 8 per day and the arrival process of interventions also follows a non-stationary Poisson process, where the night shift (7pm to 7am) is the peak arrival time period. Collected data suggest that a crisis intervention requires an average of 20 minutes to complete. Thus, an exponential distribution with a mean of 20 minutes is used to model the time required to complete a crisis intervention task. Based on our empirical data, we also assume that the time required for a nurse to draft a note for a patient follows an exponential distribution with mean of 71.2 minutes, and the time required for an intensivist to complete a note follows an exponential distribution with mean of 28.5 minutes. Because limited data are available tracking the time that intensivists and nurses spend on proactive monitoring and best practices tasks, we use the fact that an average of 100 patients per day are being monitored by this tele-ICU center to assume that an average of 100 proactive monitoring and 100 best practices tasks must be completed by intensivists and nurses during a 24-hour day. These tasks arrive according to a Poisson process in the simulation model. The time to perform such tasks is assumed to be exponentially distributed. These assumptions were made to insure that the workload among the tasks of crisis intervention, proactive monitoring, best practices, and admissions is consistent with that reported by the tele-ICU management.

As discussed previously, the tele-ICU leadership sought to have higher percentages of new admissions seen by the tele-intensivists for follow-up videos. Similar to having longer video times, this increase in tasks could come at the expense of longer waiting times to complete other time-sensitive tasks. **Figure e7** (Supplemental Digital Content 8, http://links.lww.com/CCX/A125) displays the impact of an increased percentage of intensivist follow-up videos on the average wait times for the other measured tasks performed by intensivists and nurses. Baseline data was obtained from our measurements of quarter 1 of 2016. The horizontal axis represents the percentage follow-up videos performed by the tele-intensivist, ranging from 30% to 100% of new admissions. Each point on Figure e7 (Supplemental Digital Content 8, http://links.lww.com/CCX/A125) represents the average over 100 discrete-event simulation replications. As the percentage of patients who have a follow-up video with an intensivist increases to 100%, the average wait time for the tele-intensivists and tele-nurses to perform the other measured tasks remain relatively unchanged, except for average wait time for the tele-intensivist to complete Best Practice Adherence, which increases from 4 hours to nearly 5 hours as video follow-up goes to 100% of new admissions. However, this is still well below the threshold of 12 hours completion threshold for this task. This suggests that the tele-ICU leadership can encourage higher percentages of follow-up by the tele-intensivist on new admissions.

Effects of Dependent Interventions

This creates an operational setting where arrivals of a certain type of tasks (Crisis Interventions in this case) are not independent, but rather correlated with waiting times for other tasks. A closely related operations model in queueing theory is called multi-class priority queuing system with state-dependent arrivals.2,3 However, to the best of our knowledge, no models for state-dependent arrivals in queueing literature is directly addressing the situation here where the arrival of one class customers is dependent on the instant average wait time of another class customers.

This potential effect is important to study because it means that whatever savings we get from our operational improvements could disappear once this correlation is included in our model. Thus, we attempt to evaluate the effects of dependent arrivals of crisis interventions on the performance of the tele-ICU center under the operational changes proposed in previous sections. Due to a lack of empirical data on the relationships between the crisis intervention arrivals and the delay of proactive monitoring, we designed the following numerical test. We assume that the rate of crisis intervention arrivals, $λ$, will be doubled from some initial level $λ\_{0}$ if the instant average wait time (*w*) at to complete proactive monitoring tasks is more than *T* minutes; we refer to this unknown parameter *T* as the delay threshold of proactive monitoring. Mathematically, we assume,

$$λ=\left\{\begin{matrix}λ\_{0}, w\leq T\\2λ\_{0}, w>T\end{matrix}\right..$$

Our discrete-event simulation model is based on the observed data from first quarter 2016 with both the priority change and the process change implemented in the model. For our base case, the average arrival rate of interventions is 8 per day and the average wait time to complete proactive monitoring tasks is about 18 minutes. Thus, we select a delay threshold of proactive monitoring of *T* = 20 minutes. Smaller values of *T* > 20 will result in more crisis intervention arrivals.

REFERENCES

1. Lilly CM, McLaughlin JM, Zhao H, et al. A multicenter study of ICU telemedicine reengineering of adult critical care. Chest 2014;145:500-7.

2. Abouee-Mehrizi H, Baron, O. State-dependent M/G/1 queueing systems. Queueing Systems 2016;82:121.

3. Bitran G, Caldentey, R. Two-Class Priority Queueing System with State Dependent Arrivals. Queueing Systems 2002;40:355.

LEGENDS

Figure e1: Distribution of Patient Length of stay.

 Figure e2: Admission Arrival Distribution by time of day.

Figure e3: Admission Arrival Distribution by day of week.

Figure e4: Admission Arrival Distribution by month.

Figure e5: Distribution of First Video Assessment Duration by tele-nurse.

Figure e6: Distribution of First Video Assessment Duration by tele-intensivist.

Figure e7: Average Time to First Video Assessment (TFVA) as a function of percentage of follow-up video assessments by tele-intensivist.