Grant Final Report

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Measuring the Value of Remote ICU Monitoring

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Abstract

Purpose: To determine the value of remote monitoring of intensive care patients using telemedicine technology.

Scope: None provided.

Methods: We conducted a time-and-motion observational study, a controlled pre tele-ICU and post tele-ICU cross-sectional survey in ICUs in two non-teaching community hospitals and one tertiary care teaching hospital, and an observational study (record review) of 4142 patients in 6 ICUs of 5 hospitals in a large non-profit health care system. The main outcome measures of the chart review were ICU mortality, hospital mortality, ICU complications, and length of stay.

Results: While Safety Climate scores within the monitored ICUs improved, the overall SCS scores for these hospitals (that helped control for secular trends) decreased from 69.0 to 65.4. The tele-ICU intervention had no detectable effect on ICU complication rates (p = .20). Adjusted for hospital and SAPS II the tele-ICU intervention did not have a main effect (p = .06), but was moderated by the SAPS II such that patients with SAPS II > 50 had approximately a 20%-50% reduction in risk of hospital mortality depending upon the precise SAPS II score. Regarding LOS, only surviving patients with SAPS > 70 had shorter hospital LOS in the post-tele-ICU intervention. Use of telemedicine technology to remotely monitor ICU patients was associated with a 20-50% reduction in hospital mortality, but only for the sickest 17% of patients. Hospital length of stay was reduced for the sickest 4% of survivors.

Key Words: Workflow, Task Analysis, Interruption, Time-and-Motion Study, ICU Remote Monitoring, Telemedicine, safety climate, teamwork climate, quality of care, cost-effectiveness, intensive care, health information technology

Final Report

Purpose

1. To use human factors engineering techniques to determine how changes to the user interface of the tele-ICU may increase the value of the technology.
   Hypothesis: The value of tele-ICU technology can be improved by re design of its user interface.

2. To measure changes in healthcare provider attitudes about teamwork and safety climate after implementation of the tele-ICU.
   Hypothesis: The tele-ICU will initially worsen provider attitudes about teamwork, but improve attitudes about safety climate.

3. To measure the effect of a tele-ICU on mortality, complications, and length of stay in ICUs in a tertiary care teaching hospital, and in 7 community (including 2 "small") hospitals using a before-and-after study design.
   Hypothesis: Implementation of a tele-ICU will be associated with reduced hospital mortality, ICU lengths of stay, and the combined endpoint of ICU mortality and complications.

4. To measure the cost-effectiveness of the tele-ICU.
   Hypothesis: The tele-ICU is a cost- effective method of providing intensivist coverage to patients in tertiary care, community, and rural ICUs.

Scope

Patients in adult intensive care units (ICUs) require close monitoring, frequent invasive procedures, multiple medications, complicated decision-making processes, and multidisciplinary care. This complex care coupled with inadequate nurse-patient ratios, provider fatigue, on-the-job training, and poor communication can result in substantial morbidity, mortality, and costs. A powerful influence on the quality of ICU care is the presence of critical care physicians (intensivists) in the unit. High-intensity intensivist staffing (required intensivist consultation or closed ICU where intensivists see all patients) is associated with a 29% reduction in hospital mortality and a 49% reduction in ICU mortality. (Pronovost 2002) These observations have led influential organizations to promote intensivist staffing. (Safe Practices NQF 2003; Milstein 2000) The Leapfrog Group estimated that 53,000 lives could be saved annually by intensivist staffing in all ICUs. (Young 2000) However, only 10-15% of U.S. hospitals have high-intensity staffing by intensivists, primarily due to an existing and worsening shortage of intensivists. (Angus 2000) Thus, models of care must be developed that do not rely upon full-time onsite intensivist staffing.

Telemedicine, a common form of health information technology, has been used to provide remote intensivist monitoring for ICUs. Remote ICUs connected via telemedicine technology (tele-ICUs) allow intensivists to simultaneously monitor more patients than possible by standard onsite care, and to extend intensivist care to patients in ICUs where intensivists would otherwise be unavailable, such as rural and small community hospitals. Furthermore, tele-ICUs may have decision support software to help identify subtle trends (rising creatinine, falling oxygen saturation) that need to be addressed to prevent complications. The tele-ICU also makes intensivists more available to nurses.

More research is needed because of the growing demand for intensivist coverage in ICUs, the shortage of intensivists, and the possible effectiveness of tele-ICUs. Therefore, to measure and improve the value of remote ICU monitoring we assembled a team of investigators with expertise in critical care, measuring quality of care, cost-effectiveness analysis, and human factors engineering to address these issues.

Methods

The methods section is organized by the four specific aims/purposes of the study.

1. Use Human Factors Engineering Techniques to Determine How Changes to the User Interface of the Tele-ICU May Increase the Value of the Technology

Research Setting. We studied a large non-profit healthcare system located in the Gulf Coast region of the United States. The tele-ICU was implemented to care for all patients in 7 ICUs (one of these (a neuro-trauma ICU) was not included in this study). When describing the ICUs we use the term "closed" to indicate units in which intensivists were the only physicians allowed to admit patients to the unit, and "open" to indicate units in which a variety of physician types had admission privileges. The study ICUs and hospitals included: a closed medical ICU (16 beds) and closed shock trauma /general surgical ICU (11 beds) in a large tertiary care teaching hospital; two open med-surg ICUs (12 bed and 8 bed) in two small community hospitals; and two open med-surg ICUs (32 bed and 8 bed) in two large urban hospitals. The tele-ICU intervention had a staggered implementation with the first ICU in March 2004 and the last in September 2005. The study was approved by the Institutional Review Board of the University of Texas Health Science Center at Houston.

Description of the Tele-ICU. The tele-ICU was staffed by two intensivists from noon to 7am Monday through Friday and 24 hours a day on Saturday and Sunday. Four registered nurses and two administrative technicians worked there 24 hours a day, seven days a week. Each intensivist collaborated with two nurses and one technician to monitor half of the ICU beds. The tele-ICU used the proprietary eICU technology developed by VISICU Inc. Each physician and nurse sat at a computer workstation with either five (for nurses) or six (for physicians) monitors. This workstation provided real-time vital signs, audio-visual connections to patients' rooms, early warning signals regarding abnormalities in a patient's status (Smart Alerts), and access to laboratory values, imaging studies, and the medication administration record. Progress notes were faxed daily from monitored units to the tele-ICU and orders from the tele-ICU were given verbally. (Tang 2007)

Participants. Six intensivists and seven registered nurses were selected from a pool of 14 physicians and 19 nurses to participate in the current study.[1] They included the only two full-time physicians working in that facility. The remaining four part-time physicians and the seven nurses (all worked full-time) were randomly selected. Overall, participants' experience with the eICU technology averaged at 18 months for physicians (range: five months to 30 months[2]) and 12 months for nurses (range: six to 21 months). These were comparable to the experiences of those not included in the study (averaged at 17 and 11 months for physicians and nurses respectively).

Procedure. Institutional Review Board approval was obtained prior to the study. Each physician was observed for an entire shift. Among the six physician participants, three were observed during one of their regular dayshifts (noon – 11pm) and the other three during one of their regular nightshifts (11pm – 7am). The total observation time was 49.1 hours. For the nurses, each was observed for a 6-hour block during a regular 12-hour shift. Among the seven nurses, four were observed during the second half of a dayshift (noon – 6pm) and the other three during the first half of a nightshift (6pm – 12am).[3] The overall observation time for the nurses was 40.5 hours. Both physicians and nurses were present in the facility throughout the observation sessions. Judging by the numbers and acuities of ICU patients that the clinicians monitored, the workflow observed during the study sessions were considered typical.

One of the authors (ZT), who had expertise in behavioral science and was experienced in workflow research in critical care settings, conducted all the observations from behind the participant (facing the workstation). At the beginning of each observation session, the participant was informed of the nature of the study, signed a written informed consent, and was encouraged to perform their job duties as they normally would. The observer initiated the observation by clicking a button on the Access form. The tool automatically recorded the time as the beginning of the observation. The observer then determined the nature of the current task and activity and checked off relevant data fields on the form. As soon as the participant switched to a different task or activity, the observer clicked the "Add Record" button to conclude the current entry. The tool recorded the time again as the end of the current record and initiated a new record by refreshing the form for the next entry. During the observation, the observer did not initiate any exchange with the clinician so as not to interfere with the clinician's work.

[1] The current study was part of a larger research project conducted at this facility. Prior to this we interviewed 10 clinicians and also conducted preliminary observations on four clinicians there. Seven of the 13 current participants were involved in those activities. The broader base of participation, as well as repeated exposure to the research activities, could have helped reduce the salience of the current study and mitigate any potential reactive effects.

[2] One physician had previous experience with the same remote monitoring technology at another healthcare facility. Hence his experience exceeded the 21 months that the study site had been open.

[3] In our preliminary studies we observed a number of nurses over an entire day or night shift. The results showed that eICU nurses' role was quite limited in the morning, as there were intensivists at the bedside and no physicians in the remote monitoring facility during this time period. Nurses' workflow also slowed down during late night. Therefore, we decided to observe nurses from noon to midnight in the current study, as this time frame was most representative of the nursing workflow where nurses play an active role in remote monitoring.

Data Analysis. Study-specific events such as the observer temporarily suspending the observation or a few occasions when a participant explained to the observer were discarded before data analysis. This amounted to 1.8 and 1.7 hours (3.6% and 4.2% of the overall observation times) for physicians and nurses, respectively. As a result, the total valid observation time was 47.3 hours for physicians and 38.8 hours for nurses. Then each participant's data were analyzed to derive the percentage times spent on performing different types of tasks and activities, the frequencies of accessing different information resources, and the frequency and average duration of interruptions in workflow. In conducting inferential statistics, we first examined the effect of experience with the remote monitoring technology but found no evidence suggesting that experience had any significant impact on workflow[4]. Therefore, data from all the participants were pooled and submitted to univariate t-tests to examine potential significant differences between physicians and nurses. Finally, a Chi-square test was conducted to examine if the sources of interruptions for physicians were significantly different from those for nurses.

2. Measure Changes in Healthcare Provider Attitudes About Teamwork and Safety Climate After Implementation of the Tele-ICU

Setting. See above in aim 1.

Survey Description and Background. The survey instrument consisted of a 6-item Teamwork Climate Scale (TWS), a 7-item Safety Climate Scale (SCS), (Appendix 1) and an additional eight teamwork items and six safety climate items that were not part of the scales but have been retained because of the unique information they elicit. These two scales and items are from the psychometrically validated Safety Attitudes Questionnaire (SAQ) (13) In addition, we added 12 new items that addressed workflow and quality of care issues that could be directly related to the tele-ICU. The response option to all items was a 5-point Likert-Scale ("disagree strongly" to "agree strongly") with an option for "not applicable". We also asked respondents to indicate their position, years of experience in the organization, gender, and ethnic group.

Survey Administration. We distributed surveys to physicians and nurses who worked in three critical care units of three hospitals. Other ICUs in the system were not surveyed because they implemented the tele-ICU before this study began, or were not going to implement it in the near future. We surveyed all nurses who worked in these ICUs, and the physicians who admitted at least one patient per week to the ICU. We administered pre tele-ICU surveys during the month prior to implementation of the tele-ICU (June 2005 for two ICUs and July 2005 for one ICU), and post tele-ICU surveys during the fourth month of tele-ICU implementation. A research nurse (LW) distributed surveys to nurses during staff meetings and during breaks in regular work hours. Physicians received three mailings, each 7-10 days apart. A $5.00 gift certificate was included in the first mailing.

[4] Participants were categorized into one of three experience levels based on how long they had been using the remote monitoring technology. Two multivariate tests, one including the times on all types of patient monitoring activities and the other frequencies of accessing all types of information resources, were conducted using role (i.e., physician vs. nurse) and experience as the between-subject variables. The results showed no significant effect of experience on both tests, $F(14,2) = 1.355$, p = .504 and $F(8,8) = 1.550$, p = .275, respectively. In addition, two univariate test were conducted using role and experience as the between-subject variables to test the effect of experience on frequency and average duration of interruptions. The results were not significant, $F(2,7) = 0.685$, p = .535 and $F(2,7) = 0.330$, p = .729, respectively.

This healthcare system had been annually administering the SCS as a stand-alone survey to all hospitals since 2003. We used these results from the study hospitals to control for secular trends in SCS scores. The system was not administering the TWS prior to our study.

Data Analysis. We analyzed the data using the statistical programming environment R, version 2.5.0 (20). We scored each scale by first converting the five-point Likert scale to a 100-point scale as follows: 1=0, 2=25, 3=50, 4=75, and 5=100. Negatively worded items were reverse scored so that the higher scores reflected a more positive response. Responses to each item in a scale were summed then divided by the number of items in that scale to create a scale score that ranged from 0 to 100. Extensive exploratory and confirmatory factor analyses had already been performed on these scales (13) so it was not repeated. Internal consistency was measured using Cronbach's alpha.

We calculated the means and standard deviations of scale scores for all providers in the units for the pre and post tele-ICU surveys. Differences between the means of the pre- and post-intervention groups were tested using Welch's (unequal variances) two-sample t-test. We also calculated means and standard deviations of the five-point Likert scale for the 26 non-scaled items. To assign an acceptable type I error rate and to control for family-wise error we used the Bonferroni procedure and divided the alpha of 0.05 by the 26 comparisons to yield an alpha of 0.002. "Not applicable" responses and missing values were treated as missing data.

3. Measure the Effect of a Tele-ICU on Mortality, Complications, and Length of Stay in ICUs in a Tertiary Care Teaching Hospital, and in 7 Community (Including 2 "Small") Hospitals Using a Before-and-After Study Design

Setting. See aim 1.

Study Design. This observational study consisted of two independent groups. Patients in the pre-tele-ICU group received care based on the standards prior to the tele-ICU implementation, and patients the post-tele-ICU group received the care based on the tele-ICU. Because outcomes would be expected to differ across hospitals, a second factor reflecting hospital effects was added to the design. And because severity of illness would likewise be expected to effect outcomes, the SAPS was measured for all patients. The hospital and intervention factors were considered fixed rather than random. Because it was anticipated that the intervention might be moderated by hospital effects, by SAPS, or by hospital and SAPS jointly, higher order interaction terms for these effects were included in the statistical models.

Sample Size Determination. The primary hypotheses were that hospital mortality, ICU mortality, ICU complications, and length of stay would decrease from pre-Tele to post-Tele. Based up data available at the time the study was planned (Breslow) and setting the significance level at 5%, the sample size was determined so as to provide 80% power to detect a 27% reduction in hospital mortality from a baseline rate of 10.5%. The required sample size ranged from 1622 to 4732 depending on different assumptions about cluster size, coefficient variation of cluster size, and intracluster correlation coefficients. The final sample size was 4142 patients, which had 80% power to detect a reduction from 10.5% to 7.8% at a 5% level of significance.

Sampling Scheme. The tele-ICU intervention had a staggered implementation with the first ICU in March 2004 and the last in September 2005. The number of records per ICU was proportional to each ICU's number of beds, with half being allocated for the pre- and half for the post-tele-ICU. For a given unit, the pre-tele-ICU sample size was accrued by sampling discharges starting the day prior to implementation of the tele-ICU intervention and collecting all records of discharged patients from that day backwards in time until the requisite number of records was collected. The post tele-ICU sampling of admissions began on average 95 days after implementation (range 60-120 days) to allow for start-up problems to be addressed. Post tele-ICU sampling then continued until the requisite sample size was collected. The time required to collect its sample size thus varied from hospital to hospital depending upon the number of discharges or admissions per day.

Reliability of Data Abstraction. Registered nurses with intensive care experience and not employed by the hospital system or VISICU were trained to abstract data from medical records. To test reliability of data abstraction, 357 records were reviewed twice. The reliability of abstraction was good, with mean agreement of 93.7% for the variables required to calculate mortality and the 8 complications.

Outcome Variables. We collected patient demographic data (age, gender, race/ethnicity); Simplified Acute Physiology Score II (SAPS) (LeGall JR 1993); ICU mortality; hospital mortality; ICU length of stay (LOS), hospital LOS, and 8 ICU complications. The complication data were (1) ventilator associated pneumonia (VAP) based on either Kollef's definition (1993) or the diagnosis of VAP written in a physician plus the administration of antibiotics; (2) catheter related blood stream infection (CRBSI) based on either the Centers for Disease Control Definition used in the National Nosocomial Infections Surveillance System or the diagnosis written in a physician note plus the administration of antibiotics; (3) upper gastrointestinal bleeding as determined by clinical bleeding and hemodynamic compromise or transfusion; (4) acute renal failure indicated by new renal replacement therapy; (5) unplanned extubation; (6) cardiopulmonary resuscitation; (7) venous thromboembolic disease as determined by the presence of either deep vein thrombosis or pulmonary embolism on the official reading of an appropriate imaging study; and (8) re-admission to ICU during the hospitalization.

Preliminary, Exploratory, and Regression Diagnostic Analyses. Data were reviewed for duplicate entries, coding errors, out-of-range values, scoring algorithm errors, and mutual inconsistencies (e.g., ICU death but hospital discharge) by both the project's research nurse supervisor (who reviewed each data collection form) and the statistician (by queries of the database). All such errors were corrected.

Exploratory analyses (bar plots, boxplots, density plots, and quantile-quantile plots) were conducted on age, sex, race (ethnicity), and SAPS to assess distributional characteristics, identify extreme values, and to assess possible differences in the background variables between the pre- and post-tele ICU implementation within each hospital. Regression diagnostics were conducted on all regression models.

Statistical Analysis. The statistical models for complication, ICU death, and hospital death were logistic regressions. The independent variable of primary interest was the pre- to post-tele-ICU intervention effect (T) adjusted for Hospital (H) and SAPS (S) effects. Of additional substantive interest were tele-ICU intervention effects moderated by hospital (H × T), by SAPS (S × T), or jointly by both Hospital and SAPS (H × S × T). Each of these latter effects was adjusted for Hospital effects, SAPS effects, and joint Hospital by SAPS (H × S) effects. The initial model comprised all the above 7 possible effects and was reduced in a stepwise fashion to a final model containing only substantive effects using the Schwarz information criterion. Fitted values for the outcomes from the final logistic models and their corresponding 95% confidence intervals were computed by simulation. Likewise, the risk ratios, their standard errors, and 95% confidence intervals were also computed from the logistic regression via simulation.

The LOS analyses required more careful considerations. Only patients who survived to ICU transfer were analyzed for ICU LOS, and only patients who survived to discharge were analyzed for hospital LOS. Patients who died were assumed not to have an LOS (Zhang & Rubin, 2003; Rubin, 2006). There was no attempt to impute the hypothetical LOSs for those patients had they not died. Nevertheless, excluding patients who died creates the problem of "healthy survivor" bias or "truncation by death", as those patients with LOSs are no longer representative of patients who entered the study. Estimates of the effects of the tele-ICU intervention on ICU LOS are therefore conditional upon survival to transfer and estimates for hospital LOS on survival to discharge. In essence, the ICU and hospital survivors were treated as samples separate from that used in the complication and death analyses.

The LOS data were analyzed by log-normal regression models. Exploratory data analyses revealed the possibility of a quadratic effect of SAPS on length of stay. Thus, a SAPS-squared term was included in the models along with hospital and tele-ICU interaction. These initial models containing all possible effects were also reduced to final, substantive models via the Schwarz information criterion. Fitted values for the outcomes from the final log-normal models and their corresponding 95% confidence intervals were computed by simulation.

Software for Data Management and Statistical Analysis. All data management and statistical analyses were conducted in R (R Development Core Team, 2008). The RODBC package (Lapsley and Ripley, 2008) was used to extract data from numerous Excel files and the chron package (James and Hornik, 2008) was used for date arithmetic. The glm (generalized linear model) function was used for logistic regression (McCullagh & Nelder, 1989), the MASS package (Venables and Ripley, 2002) was used for the stepwise model reduction, and the BRUGS package (Thomas and O'Hara, 2008) was used for simulations. Documentation and automatic report generation from R into LaTeX documents was conducted with the Sweave package (Leisch, 2002).

4. Measure Cost Effectiveness

Financial outcomes were computed using the proprietary cost-accounting system. Average daily costs, costs per case, and costs per patient were computed. We used OLS regression with a log transformation for patient costs as the dependent variable to investigate differences in patient costs between the pre- and post-tele-ICU period.

Results

The results section is organized by the four specific aims/purposes of the study.

1. Use Human Factors Engineering Techniques to Determine How Changes to the User Interface of the Tele-ICU May Increase the Value of the Technology

Physicians spent 70%, 3%, 3%, and 24% of their time on patient monitoring, collaboration, system maintenance, and administrative/social/personal tasks. For nurses, the time allocations were 46%, 3%, 4%, and 17% respectively. Nurses spent another 30% of their time maintaining patients' health records. In monitoring patients, physicians accessed the in-unit clinical information system (CIS) more frequently than the nurses (42 vs. 14 times per hour, $p = .027$) and spent more time communicating with others (13% vs. 7%, $p = .026$), while nurses spent more time monitoring real-time vitals (16% vs. 2%, $p = .012$). Physicians' and nurses' workflow were interrupted and redirected at a rate of 2.2 and 7.5 times per hour ($p < .001$), with an average duration of 101 and 45 seconds respectively ($p = .006$). The mechanisms of interruptions were different for physicians and nurses.

2. Measure Changes in Healthcare Provider Attitudes about Teamwork and Safety Climate After Implementation of the Tele-ICU

The mean (SD) TWS score was 69.7 (25.3) and 78.8 (17.2), pre and post tele-ICU, respectively ($p = 0.009$). The mean SCS score was 66.4 (24.6) and 73.4 (18.5), pre and post tele-ICU, respectively ($p = 0.045$). While SCS scores within the ICUs improved, the overall SCS scores for these hospitals (that helped control for secular trends) decreased from 69.0 to 65.4. Three of the non-scaled items were significantly different pre and post tele-ICU at $p<.001$. The item means (SD) pre and post tele-ICU were: 'others interrupt my work to tell me something about my patient that I already know' 2.5 (1.2) and 1.6 (1.3); 'I am confident that my patients are adequately covered when I am off the unit' 3.2 (1.3) and 4.2 (1.1); and 'I can reach a physician in an urgent situation in a timely manner' 3.8 (1.2) and 4.6 (0.6). In conclusion, Implementation of a tele-ICU was associated with improved teamwork climate and safety climate in some ICUs, especially among nurses. Providers were also more confident about patient coverage and physician accessibility, and did not report unnecessary interruptions.

3. Measure the Effect of a Tele-ICU on Mortality, Complications, and Length of Stay in ICUs in a Tertiary Care Teaching Hospital, and in 7 Community (Including 2 "Small") Hospitals Using a Before-and-After Study Design

Sample. The initial sample consisted of 4167 subjects. Elimination of cases with missing data yielded a final sample of 4142 subjects, of whom 2034 were pre-tele-ICU and 2108 post-tele-ICU (The final sample sizes by unit were 259 (unit A), 681 (unit B), 216 (unit C), 771 (unit D), 1647 (unit E) and 568 (unit F). Patient age ($p = 0.13$), gender ($p = 0.20$), and SAPS II ($p = 0.25$) were similar in the pre and post periods, but race/ethnicity showed changes pre- to post-tele ($p = .0055$) with more Caucasians and African-Americans and fewer Hispanics and Others in the post-intervention than in the pre-intervention (Table 1).

Table 1. Patient characteristics pre and post tele-ICU (Letters A through F refer to hospital)

	A Pre	A Post	B Pre	B Post	C Pre	C Post	D Pre	D Post	E Pre	E Post	F Pre	F Post	Total Pre	Total Post
Sample Size	132	127	328	353	61	155	380	391	834	813	299	269	2034	2108
Mean Age	57.4	59.4	52.7	52.9	41.4	41.4	65.0	64.6	61.8	61.9	62.5	62.1	60.2	59.3
Mean Age SD	20.4	21.1	17.6	18.3	18.7	19.5	14.3	15.1	17.7	17.3	19.4	18.4	18.3	18.7
Male %	54.5	48.8	39.9	50.1	75.4	71.6	55.8	56.5	51.9	54.0	47.8	39.4	51.0	52.9
White %	37.9	45.7	33.2	37.4	41.0	61.3	74.2	76.2	43.0	46.5	90.6	88.8	53.9	56.9
African Amer %	39.4	37.8	47.9	37.4	16.4	24.5	10.8	14.1	25.5	28.8	3.0	4.5	23.7	24.6
Hispanic %	17.4	11.8	13.7	19.3	36.1	11.0	11.1	6.9	16.4	13.4	4.0	3.0	13.8	11.6
Asian %	3.0	1.6	0.3	0.6	1.6	1.9	1.1	2.0	5.2	5.4	0.7	1.5	2.7	3.0
Other Ethnicity %	2.3	3.1	4.9	5.4	4.9	1.3	2.9	1.0	9.8	5.9	1.7	2.2	5.9	3.9
Mean SAPS	27.9	31.2	40.4	35.1	35.7	31.8	29.6	27.4	38.1	39.3	30.8	31.3	35.1	34.3
Mean SAPS SD	17.7	16.7	22.7	17.8	22.5	18.6	14.5	13.4	26.0	25.3	18.4	17.4	22.5	20.8

ICU Complications. The crude complication rates were 17.9% for pre-tele and 19.2% for post-tele ($p = .30$) (Table 2). The SIC-reduced model revealed that the rate of complications was associated with hospital ($p < 2 \times 10^{-16}$) and SAPS II ($p < 2 \times 10^{-16}$), but no other effect, including tele-ICU ($p < .20$) or any interactions involving tele-ICU (minimum $p = .4$).

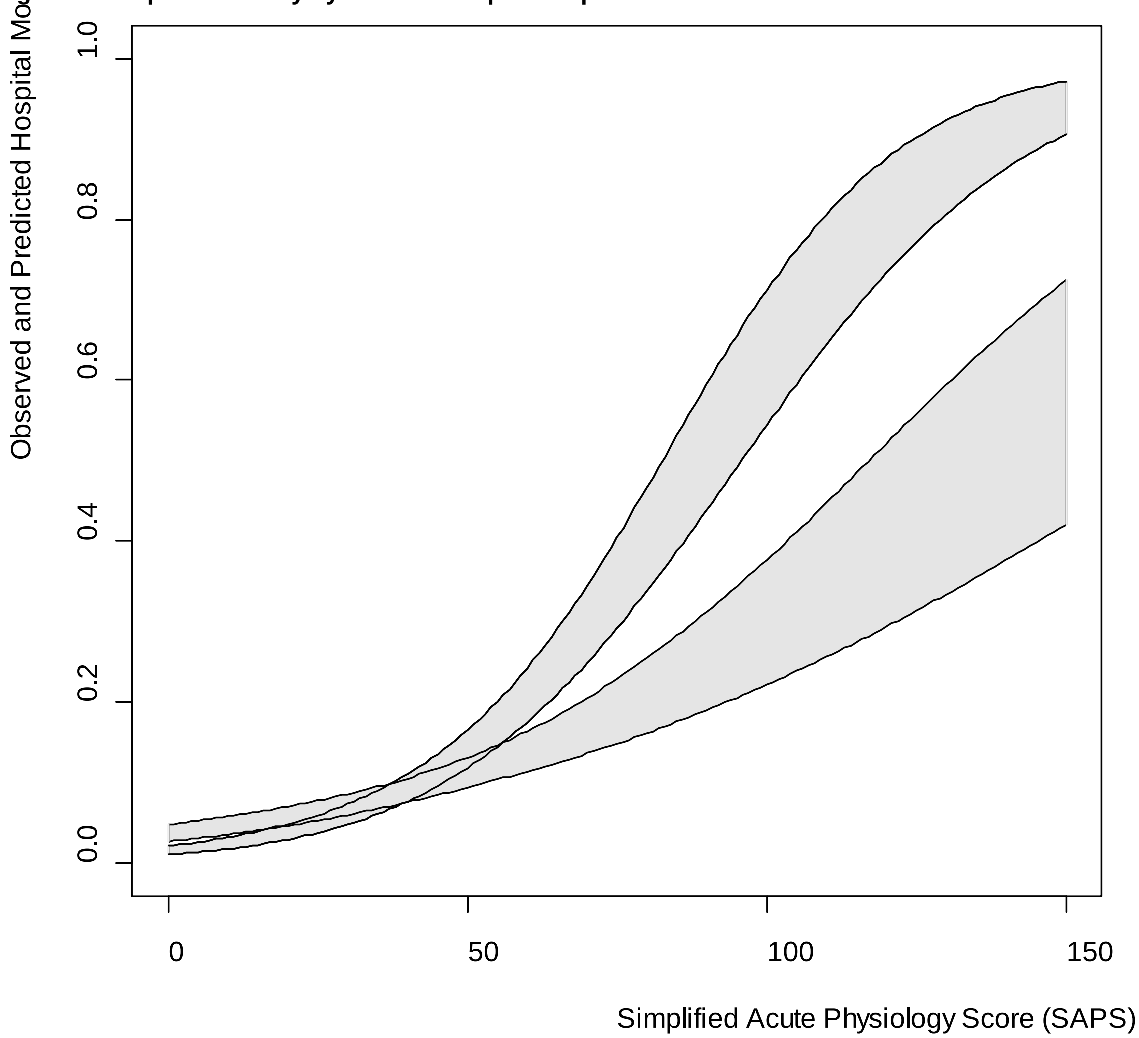
Table 2. Complications, mortality, and length of stay pre and post tele-ICU

	FB Pre	FB Post	HM Pre	HM Post	HS Pre	HS Post	MC Pre	MC Post	SW Pre	SW Post	TW Pre	TW Post	Total Pre	Total Post
Sample Size	132	127	328	353	61	155	380	391	834	813	299	269	2034	2108
reICU	0.0	3.9	6.7	6.5	6.6	7.1	5.3	5.9	9.6	8.5	3.0	4.5	6.6	6.8
VAP	0.8	2.4	4.3	4.5	14.8	9.0	3.7	1.0	3.5	2.6	1.3	0.7	3.5	2.8
CRBSI	0.0	0.0	0.0	0.0	0.0	0.0	0.3	1.5	0.2	0.5	0.3	0.4	0.2	0.6
ARF	0.0	0.0	7.3	8.2	4.9	0.6	1.6	2.6	2.3	3.8	2.0	0.7	2.9	3.6
DVT	0.0	0.8	0.6	1.1	4.9	0.6	0.5	0.5	1.1	1.5	0.7	0.7	0.9	1.0
UGIB	0.0	0.8	3.4	2.5	1.6	0.0	1.3	0.5	1.7	2.3	0.7	3.7	1.6	1.9
EXTUB	0.0	1.6	1.8	3.4	1.6	0.6	0.8	2.0	2.0	2.1	2.7	0.0	1.7	1.9
CPR	3.0	0.0	5.5	3.1	6.6	1.9	1.6	2.0	5.5	6.6	2.3	3.0	4.2	4.0
Complic-ations	3.8	9.4	25.3	24.6	27.9	18.1	12.6	13.6	21.6	23.4	10.7	13.0	17.9	19.2
ICU deaths	3.8	1.6	12.2	10.5	13.1	11.6	3.7	1.3	11.9	10.8	7.4	5.6	9.2	7.8
Hosp deaths	4.5	4.7	16.8	14.2	16.4	12.9	4.7	2.3	14.9	12.7	10.7	7.8	12.0	9.9
Mean Complic-ations per patient	0.0	0.1	0.3	0.3	0.4	0.2	0.1	0.2	0.2	0.2	0.1	0.1	0.2	0.2
(SD)	(0.2)	(0.3)	(0.6)	(0.6)	(0.8)	(0.4)	(0.4)	(0.4)	(0.4)	(0.5)	(0.4)	(0.5)	(0.6)	(0.5)
Hospital LOS	6.0	6.7	10.2	9.8	18.1	19.6	9.4	10.6	10.6	10.8	8.1	8.1	9.8	10.7
ICU LOS	3.0	3.3	4.0	4.0	6.0	9.8	4.0	4.1	4.8	4.5	4.1	4.4	4.3	4.6

reICU – readmission to ICU; VAP – ventilator associated pneumonia; CRBSI – catheter-related blood stream infection; ARF – acute renal failure; VTE – venous thromboembolic disease; UGIB – upper gastrointestinal bleeding; EXTUB – unplanned extubation; CPR – cardiopulmonary resuscitation; Complications – the percentage of patients with one or more complications.

ICU Mortality. The crude ICU mortality rates were 9.2% pre and 7.8% post tele-ICU ($p = .10$). The regression analysis revealed that mortality rates differed by hospital ($p < 2 \times 10^{-16}$) and SAPS II ($p < 2 \times 10^{-16}$). The tele-ICU intervention did not have a main effect ($p = .19$), but was moderated by the SAPS II ($p = 2\times10^{-7}$) (Figure 1). Patients with SAPS II > 60 (10.5% of the sample) had substantially less risk of mortality in the post-tele intervention compared to the pre-tele intervention, ranging from 30% less at SAPS II = 60 to 50% less for SAPS II > 80, in the post-tele intervention than those in the pre-tele intervention However, patients with SAPS II < 60 did not differ in mortality risk between the two interventions.

Figure 1. Hospital mortality by SAPS II and pre and post-tele-ICU



Patients with SAPS II > 50 (16.9%) had substantially less risk of mortality in the post-tele intervention than those in the pre-tele intervention, ranging from 20% less at SAPS II = 50 to 50% less for SAPS > 80. However, patients with SAPS II < 50 did not differ in mortality risk between the two interventions. Table 3 presents the risks and relative risk for selected SAPS II.

Table 3. Estimated risks of hospital mortality by SAPS II score for pre- and post-tele patients

SAPS II	Pre-Tele Risk %	Pre-Tele 95% CI	Pre-Tele 95% CI	Post-Tele Risk %	Post-Tele 95% CI	Post-Tele 95% CI	Relative Risk %	Relative Risk 95% CI	Relative Risk 95% CI
0	1.5	1.1	2.1	3.6	2.7	4.8	2.4	1.5	3.7
20	3.8	3.0	4.9	5.7	4.7	7.0	1.5	1.1	2.0
40	9.2	7.7	11.0	9.0	7.6	10.6	1.0	0.8	1.2
60	20.7	17.6	24.2	13.7	11.5	16.4	0.7	0.5	0.8
80	40.1	33.9	46.8	20.5	16.3	25.5	0.5	0.4	0.7
100	63.2	54.4	71.4	29.4	22.4	37.8	0.5	0.3	0.6
120	81.5	73.3	87.7	40.2	29.7	52.0	0.5	0.4	0.7
140	91.9	86.3	95.3	52.1	38.0	66.0	0.6	0.4	0.7

Hospital LOS. Of the 4142 patients, the 3688 (89.0%) patients who survived to discharge were analyzed for hospital LOS. The mean hospital LOS was 9.8 days for pre-tele intervention and 10.7 days for the post intervention (p = .006). The time-to-discharge analysis revealed differences among hospitals ($p < 2 \times 10^{-16}$) and for SAPS II ($p = 2 \times 10^{-16}$) . Adjusted for these effects, there was no main effect of the tele-ICU intervention (p = .19), but the intervention was moderated by the linear and quadratic components of the SAPS II ($p = 4 \times 10^{-6}$). Patients with SAPS II < 70 did not differ in hospital LOS between the two groups. However, patients with SAPS II > 70 (4.1%) had a 20-80% reduction in LOS in the post-tele intervention than those in the pre-tele intervention. Table 4 presents the estimated mean LOS for selected levels of the SAPS II along with the relative LOS and its 95% CI.

Table 4. Estimated hospital LOS by SAPS II score

SAPS II	Pre-Tele LOS %	Pre-Tele 95% CI	Pre-Tele 95% CI	Post-Tele LOS %	Post-Tele 95% CI	Post-Tele 95% CI	Relative Risk %	Relative Risk 95% CI	Relative Risk 95% CI
0	3.7	3.4	4.2	3.8	3.5	4.2	1.0	0.9	1.2
20	6.2	6.0	6.5	6.7	6.5	7.0	1.1	1.0	1.1
40	9.1	8.7	9.6	9.5	9.1	10.0	1.0	1.0	1.1
60	11.7	11.0	12.5	10.8	10.2	11.5	0.9	0.8	1.0
80	13.3	11.9	14.9	9.9	9.0	10.8	0.7	0.6	0.9
100	13.2	10.7	16.4	7.3	6.2	8.4	0.5	0.4	0.7
120	11.6	8.0	16.8	4.3	3.3	5.5	0.4	0.2	0.6
140	8.9	5.0	15.9	2.0	1.4	3.0	0.2	0.1	0.5

4. Measure Cost Effectiveness

The average daily costs and the cost per case increased on average 20% after the implementation of the tele-ICU ($3,664) from the period before the implementation of the Tele-ICU ($3,060). The average cost per patient also increased from $20,222 in the pre-period to

$25,813 in the post-period. The patients in the sickest quintiles, the 4th and the 5th quintile experienced the greatest difference in costs of $7,781 and $6,613 respectively. Regression analysis indicated that total patient costs differed by hospital ($p<0.0001$), SAPS quintile ($p < 0.0001$), and tele-ICU ($p < 0.0001$). In the sickest quintile (5th SAPS quintile), the cost for a 10% reduction in mortality was $5,280.

Discussion

Strengths and Weaknesses of the Study. The study has substantial generalizability. The sample size was large and the units sampled were heterogeneous, including medical, surgical, small, large, teaching, non-teaching, urban, and community-based ICUs. In contrast, a previous peer-reviewed study was conducted in only two ICUs in a single tertiary care hospital.[6] Our data were collected by an explicit and reliable medical record review (in contrast to administrative data). Implementation of the tele-ICU occurred sequentially throughout the system over an eighteen month period and we waited several weeks before starting post tele-ICU data collection. This allowed for managers of the tele-ICU and each unit to work out some of the start-up problems associated with implementation of such a complex technology, and it mediated any seasonal changes in mortality. Finally, unlike previous studies, we observed that the tele-ICU effect on mortality varied by severity of illness. This revealed the important finding that the tele-ICU's impact on mortality was restricted to the sickest patients.

Because we used an observational study design, factors other than the tele-ICU may have influenced the changes in mortality. There was no evidence that patients were less sick in the post-tele-ICU period. Secular trends toward declining mortality among ICU patients could have accounted for the reductions observed here. ICUs could have initiated quality improvement interventions designed to reduce mortality independent of the tele-ICU, but our surveys of the units revealed they did not.

Our finding of benefit restricted only to the most ill patients could be explained by lack of acceptance by physicians or nurses in the monitored units. Thus, the argument goes, only the sickest of patients, those warranting emergent attention regardless of acceptance levels, benefitted from the intervention. In a setting with better MD acceptance mortality might be reduced even in less ill patients. This argument has prima facie merit because almost two thirds of the patients had physicians who chose minimal delegation to the tele-ICU (n=1393 (66.1%). For these patients, the tele-ICU only intervened for life threatening situations. Physicians delegated full treatment authority to tele-ICU for 655 (31.1%) of the patients. For these, the tele-ICU could carry out treatment plans, give routine orders, change treatment plans when indicated, and intervene for life threatening situations. Had more physicians delegated full responsibility to the tele-ICU, less ill patients might have benefited from the routine care provided by the tele-ICU.

Another explanation for a mortality reduction confined to the sickest patients is the degree of integration of the tele-ICU and remote units. Providers in this tele-ICU had access to real-time vital signs and wave tracings, laboratory values, imaging studies, and the medication administration record. However, the tele-ICU and the monitored units did not share clinical notes or computerized physician order entry within a common electronic record. These notes were faxed to the tele-ICU daily. Greater integration of clinical information might have resulted in a broader impact on mortality.

The lack of impact of the tele-ICU intervention on complications was not anticipated but can also be explained by the above noted lack of acceptance and integration of tele-ICU. Another possible explanation is detection and surveillance bias. The presence of the tele-ICU may have led to increased surveillance for, and documentation of, complications by the providers in the monitored units.

A final limitation is lack of data on post-hospital survival. It is possible that the tele-ICU led to patients being transferred more quickly to hospice or other sites of care where they died. Such transfers may have been an appropriate improvement in care, but without post-hospital survival data we do not know if the 20-50% reduction in hospital mortality translates to the same reduction in long-term mortality.

Conclusion

The tele-ICU was associated with a marked reduction in hospital mortality for only the sickest 17% of patients, and a reduction in hospital LOS for the sickest 4% of survivors. Implementation of the tele-ICU resulted in an increase in costs. Surveys of nurses indicate that the tele-ICU improved teamwork climate and safety climate in some ICUs. Providers were also more confident about patient coverage and physician accessibility, and did not report unnecessary interruptions. Widespread application of this technology to all ICU patients seems premature pending more research on populations of the less severely ill ICU patients, and better acceptance and integration of this complex technology by the monitored units. Even among the sickest patients, this research needs replication and there is a need to compare use of tele-ICU technology with less expensive, but also powerful, quality improvement interventions.

List of Publications and Products

Papers

Tang Z, Weavind L, Mazabob J, Thomas EJ, Chu-Weininger M, Johnson TR. Workflow in Intensive Care Unit Remote Monitoring: A Time-and-Motion Study. *Critical Care Medicine* 2007;35:2057–2063.

Chu-Weininger M, Wueste L, Lucke J, Weavind L, Mazabob J, Thomas EJ. The impact of a tele-ICU on provider attitudes about teamwork and safety climate. Third revision submitted to *Quality and Safety in Healthcare* 12/08.

Thomas EJ, Lucke JF, Wueste L, Weavind L, Patel B. Telemedicine for Remote Monitoring of Intensive Care Patients: Impact on Mortality, Complications, and Length of Stay in Six Intensive Care Units. Under review.