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Telemedicine Critical Care-Mediated Mortality Reductions in Lower-Performing Patient Diagnosis Groups: A Prospective, Before and After Study

Walter A. Boyle

Christopher M. Palmer

Lisa Konzen

Bradley A. Fritz

Jason White

See next page for additional authors

Authors

Walter A. Boyle, Christopher M. Palmer, Lisa Konzen, Bradley A. Fritz, Jason White, Michelle Simkins, Brian Dieffenderfer, Ayesha Iqbal, Jill Bertrand, and Igor Zwir

OBSERVATIONAL STUDY

OPEN

Telemedicine Critical Care-Mediated Mortality Reductions in Lower-Performing Patient Diagnosis Groups: A Prospective, Before and After Study

OBJECTIVES: Studies evaluating telemedicine critical care (TCC) have shown mixed results. We prospectively evaluated the impact of TCC implementation on risk-adjusted mortality among patients stratified by pre-TCC performance.

DESIGN: Prospective, observational, before and after study.

SETTING: Three adult ICUs at an academic medical center.

PATIENTS: A total of 2,429 patients in the pre-TCC (January to June 2016) and 12,479 patients in the post-TCC (January 2017 to June 2019) periods.

INTERVENTIONS: TCC implementation which included an acuity-driven workflow targeting an identified "lower-performing" patient group, defined by ICU admission in an Acute Physiology and Chronic Health Evaluation diagnoses category with a pre-TCC standardized mortality ratio (SMR) of greater than 1.5.

MEASUREMENTS AND MAIN RESULTS: The primary outcome was risk-adjusted hospital mortality. Risk-adjusted hospital length of stay (HLOS) was also studied. The SMR for the overall ICU population was 0.83 pre-TCC and 0.75 post-TCC, with risk-adjusted mortalities of 10.7% and 9.5% ($p = 0.09$). In the identified lower-performing patient group, which accounted for 12.6% ($n = 307$) of pre-TCC and 13.3% ($n = 1671$) of post-TCC ICU patients, SMR decreased from 1.61 (95% CI, 1.21–2.01) pre-TCC to 1.03 (95% CI, 0.91–1.15) post-TCC, and risk-adjusted mortality decreased from 26.4% to 16.9% ($p < 0.001$). In the remaining ("higher-performing") patient group, there was no change in pre- versus post-TCC SMR (0.70 [0.59–0.81] vs 0.69 [0.64–0.73]) or risk-adjusted mortality (8.5% vs 8.4%, $p = 0.86$). There were no pre- to post-TCC differences in standardized HLOS ratio or risk-adjusted HLOS in the overall cohort or either performance group.

CONCLUSIONS: In well-staffed and overall higher-performing ICUs in an academic medical center, Acute Physiology and Chronic Health Evaluation granularity allowed identification of a historically lower-performing patient group that experienced a striking TCC-associated reduction in SMR and risk-adjusted mortality. This study provides additional evidence for the relationship between pre-TCC performance and post-TCC improvement.

KEY WORDS: Acute Physiology and Chronic Health Evaluation; intensive care unit organization; predictive scoring systems; telemedicine critical care; tele-intensive care unit; telemedicine

Walter A. Boyle, MD[1]
Christopher M. Palmer, MD[1]
Lisa Konzen, BSN[2]
Bradley A. Fritz, MD, MSCI[1]
Jason White, BSN[2]
Michelle Simkins, RN, MPH[3]
Brian Dieffenderfer, MPH[2]
Ayesha Iqbal, MBBS, MPH[3]
Jill Bertrand, MSN[2]
Shelley Meyer, BSN, MBA[2]
Paul Kerby, MD[1]
Sara Buckman, MD, PharmD[4]
Vladimir Despotovic, MD[5]
Jim Kozlowski, MS[1]
Patricia Crimmins Reda, BSN[2]
Igor Zwir, PhD[6,7]
C. Charles Gu, PhD[8]
Uchenna R. Ofoma, MD,MS[1]

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Telemedicine Critical Care (TCC) combines audiovisual communication technologies and real-time remote access to electronic medical record (EMR) data to allow critical care support from a distant location. TCC programs, which are now implemented in approximately one-fifth of U.S.

KEY POINTS

Question: Does a telemedicine critical care (TCC) intervention lead to an improvement in mortality in a targeted group of ICU patients in historically lower-performing diagnosis categories?

Findings: In this prospective, before and after the study, an identified lower-performing ICU patient group experienced a striking TCC-associated reduction in SMR and risk-adjusted mortality.

Meaning: This study provides evidence for the relationship between pre-TCC performance and post-TCC improvement at the diagnosis category level.

acute care hospitals (1–4), provide an enhanced level of monitoring and support, including access to critical care specialists when they are not available at the bedside. However, studies of the impact of TCC on patient outcomes have shown mixed results (5–13).

As complex interventions, TCC programs are inherently heterogeneous, with influences from a variety of contextual factors that can vary widely between programs, and which likely contribute to the variable results (14). Several studies have shed light on some aspects of TCC interventions which are favorably associated with improved outcomes including speed of remote intensivist intervention (12), improved best practice adherence (9, 12), effective delegation of decision-making authority for comanagement (15, 16), and several organizational characteristics of the remote care program (17). Additionally, it has been demonstrated that the benefits of TCC may not apply equally to all ICU populations. A recent meta-analysis demonstrated that the mortality benefit of adding TCC to existing clinical care models is dependent on pre-TCC performance of the implemented ICU population. TCC was associated with mortality reductions among ICUs with higher (>1) but not lower (<1) pre-implementation standardized mortality ratios (SMR) (18). These findings have not otherwise been confirmed at a patient group level.

In this study, we measured pre-TCC performance by deriving SMRs for each Acute Physiology and Chronic Health Evaluation (APACHE) admission diagnosis category over 6 months before TCC implementation in three adult ICUs in a large academic medical center. We then prospectively evaluated the impact of TCC implementation, which included a structured acuity-driven TCC workflow to ensure a consistently high level of TCC support for the identified lower-performing patient group over a 30-month post-TCC study period. We tested the hypothesis that a TCC-associated improvement in mortality would be evident in the targeted group of historically lower-performing diagnosis categories.

Although TCC appears to have a growing presence, adoption has been limited by uncertainty regarding expected benefits in the face of significant implementation and operational costs (19, 20). A better understanding of expected improvements in relation to pre-TCC performance may lead to greater TCC adoption where it is needed most.

MATERIALS AND METHODS

Study Design and Setting

We performed a single-center, prospective, before and after study of patients admitted into three adult ICUs at Barnes Jewish Hospital (BJC), the flagship hospital in the BJC Healthcare system, and the adult tertiary care teaching hospital of Washington University School of Medicine. The study period included a 6-month pre-TCC period (from January to June 2016) and a 30-month post-TCC period (from January 2017 to June 2019). We a priori excluded the 6-month TCC "implementation/stabilization" period (from July to December 2016), during which TCC (e-ICU, Philips Healthcare, Amsterdam, The Netherlands) was sequentially implemented in the three study ICUs, and the acuity-driven workflow to target the lower-performing patient group was developed and iterated (**Fig. 1**). This implementation represented the initial phase of an ICU quality improvement project to implement TCC in all BJC hospital ICUs. Deidentified patient-level data from the local "eSearch" database (Philips Healthcare) were accessed for this observational study. The project was reviewed by the Washington University Human Research Protection Office and determined to not involve activities subject to institutional review board oversight (FWA00002284).

The three study ICUs—a 36-bed surgical ICU (SICU), a 30-bed cardiothoracic ICU (CTICU), and a 15-bed coronary care ICU (CCU)—operated with

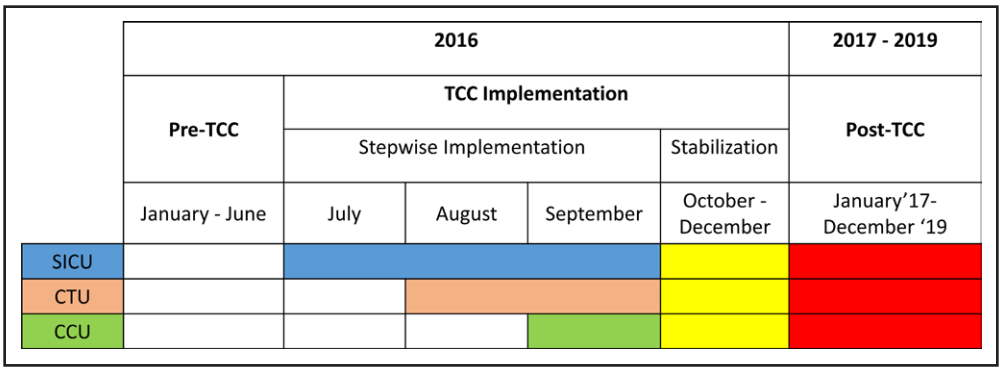

Figure 1. Telemedicine critical care (TCC) implementation study timeline.

daytime on-site attending physicians and bedside teams consisting of critical care, cardiology, and/or cardiothoracic surgery fellows, a combination of advanced practice providers and resident physicians, critical care nurses, pharmacists, respiratory therapists, and nutrition specialists. The SICU had 24-hour on-site attending coverage, whereas on-site fellows supervised by on-call attending intensivists (CTICU) or cardiologists (CCU) provided overnight coverage in the CTICU and CCU. TCC coverage for the study ICUs involved 24-hour continuous monitoring and support by a remote team consisting of an intensivist and three experienced critical care nurses located in a dedicated off-site TCC center. The TCC nurse to ICU bed ratio for the study ICUs was 25–30 ICU beds per TCC nurse, and the TCC intensivist covered all 81 ICU beds. The bedside staffing in the three ICUs did not change over the study period. The three study ICUs had very similar unit policies and practices that reflect the same ICU standards of care for acuity-based bedside nurse-to-patient staffing ratios of 1:2 to greater than 1:1 as needed.

Study Subjects and Measurements

All adult ICU admissions were eligible for inclusion. Patient-level data including demographic, clinical, outcome, and APACHE data from the TCC application (eCareManager 4.1.1; Philips Healthcare) that were embedded in the eSearch database were used for this study. SMRs and standardized hospital length of stay (HLOS) ratios were calculated using APACHE IVa (21). Per-APACHE methodology, patients who died within 4 hours of ICU admission were excluded, as were 28 patients in the pre-TCC period and 178 patients in the post-TCC period admitted with a "Heart Transplant" diagnosis that included patients with heart transplants, with extracorporeal membrane oxygenation, or left ventricular assist devices. APACHE predictions provide the probability of mortality and a predicted HLOS for 112 APACHE diagnosis categories with individual coefficients in the model. Vital signs and laboratory data required for the APACHE predictions were interfaced with eCareManager. Other required APACHE data elements were manually entered by TCC nurses trained in data abstraction and APACHE admission diagnosis selection. Our primary outcome of interest was risk-adjusted hospital mortality. We also studied TCC impact on risk-adjusted HLOS.

Identification of Lower-Performing Intervention Group

During the 6-month pre-TCC study period, APACHE admission diagnosis categories with at least 10 patients and 2 mortalities were analyzed. A "lower-performing" group of ICU diagnosis categories with SMRs greater than 1.5 were identified. This cutoff satisfied an a priori goal to identify and target ~15% of patients with the highest SMRs for use of the structured acuity-driven TCC workflow so as not to compromise the ability to provide comprehensive "routine" TCC support implemented for all patients admitted to the three study ICUs.

Components of Routine and Structured Telemedicine Support

Following TCC implementation, all patients in the three ICUs received TCC support consisting of continuous remote monitoring of vital signs and EMR data, remote clinical rounding and video assessments by the TCC nurse and TCC physician at admission to confirm the diagnosis and care plan, and routine reassessments by the TCC nurse every 12 hours thereafter that included a review of care plan effectiveness and compliance with deep venous thrombosis and stress ulcer prophylaxis protocols, ICU glucose control goals, and mechanical ventilation bundle parameters. Additional TCC support was provided at other times

upon request from a TCC or bedside provider, or in response to physiologic monitoring or laboratory alerts, or evidence of clinical deterioration captured by the real-time automated acuity (AA) decision support tool embedded in the eCareManager application.

A structured TCC workflow for the identified lower-performing patient group was developed and implemented throughout the 30-month post-TCC period. This structured workflow differed from "routine" care in the codified use of the AA tool to determine TCC reassessment frequency for the first 24 hours (**Fig. 2**). Compliance with the structured workflow was followed using a "tracker" and quarterly audits indicated compliance rates of greater than 80% for documented reassessments. The frequency and duration of all video assessments were also tracked using the eCareManager administrative database.

Statistical Analysis

The primary analysis compared admissions between the pre-TCC and post-TCC periods using standardized rates and ratios (22). Admission characteristics, including observed and expected (APACHE-predicted) hospital mortality and HLOS were compared using the Chi-square test for categorical variables and the Wilcoxon rank-sum test for continuous variables. SMRs within the pre- and post-TCC periods were calculated by dividing the number of observed deaths by the sum of the APACHE mortality predicted deaths, and the standardized HLOS ratios (23) were calculated during these periods by dividing the sum of observed HLOSs by the sum of the APACHE-expected HLOSs. Risk-adjusted mortality and risk-adjusted HLOS for patient groups in the pre- and post-TCC periods were calculated by multiplying the corresponding SMR and standardized HLOS ratio for that period with the group-wise pooled expected mortality and pooled expected HLOS, respectively. Risk-adjusted mortality and risk-adjusted HLOS were then compared between the pre- and post-TCC periods using the Chi-square and Wilcoxon rank-sum tests, respectively. Several additional analyses were done to test the robustness of our findings (**Supplemental Statistical Analyses**, http://links.lww.com/CCX/B253); these include: (1) analyses stratified by ICU type and surgical versus medical APACHE diagnosis categories, (2) analysis

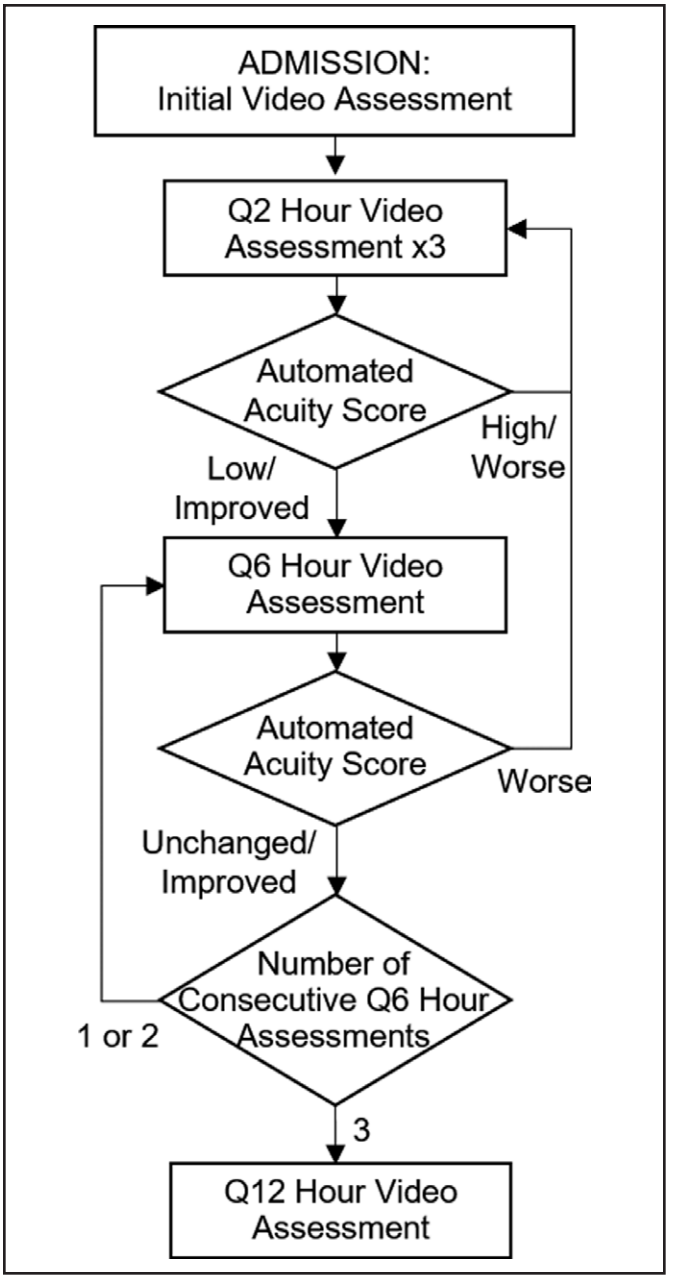

Figure 2. Telemedicine critical care nurse-driven workflow. The workflow incorporates codified use of the real-time automated acuity (AA) score to determine scheduled video reassessments in lower-preforming group patients. Starting from time of admission, designated lower-performing patients were reassessed every 2 hr for the initial 6 hr, followed by reassessments every 6 hr. Low acuity or improving patients were de-escalated after 24 hr to routine mandatory reassessments every 12 hr. Patients with high or worsening AA scores were returned to being reassessed every 2 hr. The AA score is derived from a proprietary algorithm embedded in the eCareManager application (Philips Healthcare). Data from six clinical domains (cardiovascular, respiratory, infectious disease, CNS, renal, and hematology) are used to determine the AA score, which has been validated by correlation with mortality (Philips Healthcare, personal communication). Each component value is calculated upon admission and updated as new data becomes available.

of the relationship between pre-TCC SMR and SMR delta (post-TCC minus pre-TCC SMR) for each diagnosis category, and (3) sensitivity analysis using generalized linear mixed models (GLMM) in lieu of standardized rates and ratios. All analyses were performed using R version 4.0.3 (R Foundation for Statistical Computing, Vienna, Austria). All hypothesis tests were two-sided with a significance level of 0.05.

RESULTS

A total of 14,908 admissions were analyzed, consisting of 2,429 admissions in the pre-TCC period, of which 307 (12.6%) were designated as lower-performing, and 12,479 admissions in the post-TCC period, of which 1,671 (13.4%) were in the lower-performing group (**Table 1**). The median overall age was 62 years, and approximately 60% were male. Most admissions were nonoperative, and approximately 50% of the primary admission diagnoses were related to the cardiovascular system. The post-TCC period had a slightly higher proportion of male admissions, and cardiovascular and trauma admission diagnoses. Median (interquartile range) APACHE IVa scores were higher post-TCC compared with pre-TCC for the overall cohort (55 [41–73] vs 53 [40–67], $p < 0.001$), and in both performance groups. Discharge destinations among survivors in the pre- and post-TCC periods were generally similar in the two performance groups.

Compared with the higher-performing group, there were significantly more video assessments for the lower-performing group by TCC nurses [12 vs 8, $p < 0.001$] and physicians [7 vs 5, $p < 0.001$]. The TCC nurse assessment durations were slightly longer for lower-performing group compared with higher-performing group patients (16 vs 15 min, $p < 0.001$) (**Supplemental Table 1**, http://links.lww.com/CCX/B253).

Hospital Mortality

Overall, 1,442 of the 14,908 admissions died during their hospital stay, yielding an observed hospital mortality of 9.7%, of which 211 (8.7%) occurred during the pre-TCC period and 1,231 (9.9%) occurred during the post-TCC period. Stratified by performance group, 356 deaths occurred among the 1,978 lower-performing (18.0%) and 1,086 deaths occurred among 12,930 higher-performing (8.4%) patient admissions. In the overall cohort, and in both performance groups, expected mortality was significantly higher post-TCC compared with pre-TCC (**Table 2**).

Among the overall cohort, there was no statistically significant difference in risk-adjusted mortality between the pre- and post-TCC periods (10.7% and 9.5%, respectively; $p = 0.09$). This corresponded to SMRs of 0.83 (95% CI, 0.72–0.95) pre-TCC and 0.75 (0.70–0.79) post-TCC. In the lower-performing group, risk-adjusted hospital mortality decreased from 26.4% to 16.9% ($p < 0.001$), with a corresponding decrease in SMR from 1.61 (1.21–2.01) to 1.03 (0.91–1.15) (Table 2, **Fig. 3**, ***A*** and ***B***). In the higher-performing group, there was no change in pre- versus post-TCC risk-adjusted hospital mortality (8.5% vs 8.4%, $p = 0.86$) or SMR (0.70 [0.59–0.81] vs 0.69 [0.64–0.73]). The pre-TCC SMRs in the two performance groups were stable over the two pre-TCC quarters, in which two independent populations were evaluated, and the performance improvement coincident with TCC implementation in the lower-performing group was then sustained over the 10 successive post-TCC quarters (**Supplemental Fig. 2**, http://links.lww.com/CCX/B253). Pre- versus post-TCC changes in mortality and LOS related to performance group were similar in each of the three individual study ICUs (**Supplemental Fig. 1** and **Supplemental Table 2**, http://links.lww.com/CCX/B253) and for medical versus surgical diagnosis categories (**Supplemental Table 3**, http://links.lww.com/CCX/B253). The linear relationship at the diagnosis category level between pre-TCC SMR and SMR delta (post- [minus] pre-TCC SMR) is illustrated in **Figure 4**, with a negative correlation (slope –0.91; Pearson correlation coefficient, $\rho = -0.92$) across medical and surgical diagnosis categories in both performance groups. The slope and correlation for the lower-performing group were slightly larger (slope –1.15, $\rho = -0.90$) than that of the higher-performing group (slope –0.85, $\rho = -0.75$).

Hospital Length of Stay

There were significant increases in both expected and observed HLOS in the overall cohort and the higher-performing group between the pre- and post-TCC periods, but no significant changes in the standardized HLOS ratios or risk-adjusted HLOS between the

TABLE 1.

Patient Characteristics Before and After Telemedicine Critical Care Implementation, Stratified by Performance Group

Characteristics	Overall		Lower-Performing		Higher-Performing	
	Pre-TCC, *n* = 2,429	Post-TCC, *n* = 12,479	Pre-TCC, *n* = 307	Post-TCC, *n* = 1,671	Pre-TCC, *n* = 2,122	Post-TCC, *n* = 10,808
Age, yr, median (IQR)	62 (51–72)	62 (50–72)	64 (54–71)	62 (52–71)	62 (50–72)	62 (50–72)
Sex, *n* (%)						
Female	1,032 (42.5)	4,983 (40)[b]	113 (36.8)	586 (35.1)	919 (43.3)	4,397 (40.7)[b]
Male	1,396 (57.5)	7,480 (60)	194 (63.2)	1,085 (64.9)	1,202 (56.7)	6,395 (59.3)
Acute Physiology and Chronic Health Evaluation IVa, median (IQR)	53 (40–67)	55 (41–73)[c]	53 (42–67)	58 (44–78)[c]	52 (39–67)	54 (40–73)[c]
Primary admission diagnosis by organ system, *n* (%)						
Cardiovascular	1,162 (47.8)	6,478 (51.9)[c]	277 (90.2)	1,548 (92.6)[b]	885 (41.7)	4,930 (45.6)[c]
Respiratory	142 (5.8)	742 (6.0)	0 (0)	0 (0)	142 (6.7)	742 (6.9)
Gastrointestinal	294 (12.1)	1,229 (9.9)	28 (9.1)	94 (5.6)	266 (12.5)	1,135 (10.5)
Neurologic	213 (8.8)	865 (6.9)	0 (0)	0 (0)	213 (10.0)	865 (8.0)
Trauma	377 (15.5)	2,203 (17.7)	0 (0)	0 (0)	377 (17.8)	2,203 (20.4)
Sepsis	96 (4.0)	442 (3.5)	2 (0.7)	29 (1.7)	94 (4.4)	413 (3.8)
Other[a]	145 (6.0)	520 (4.2)	0 (0)	0 (0)	145 (6.8)	520 (4.8)
Primary admission diagnosis by postoperative status, *n* (%)						
Nonoperative	1,434 (59.0)	7,176 (57.5)	230 (74.9)	1,251 (74.9)	1,204 (56.7)	5,925 (54.8)
Postoperative	995 (41.0)	5,303 (42.5)	77 (25.1)	420 (25.1)	918 (43.3)	4,883 (45.2)
Discharge location among survivors, *n* (%)						
Home	1,867 (84.2)	9,121 (81.1)[c]	216 (87.8)	1,171 (85.1)	1,651 (83.7)	7,950 (80.5)[c]
Rehabilitation/nursing home/ skilled nursing facility	303 (13.7)	1,807 (16.1)[b]	26 (10.6)	180 (13.1)	277 (14.0)	1,627 (16.5)[b]
Other hospital	17 (0.8)	140 (1.2)	3 (1.2)	16 (1.2)	14 (0.7)	124 (1.3)
Other	31 (1.4)	180 (1.6)[b]	1 (0.4)	9 (0.7)	30 (1.5)	171 (1.7)

IQR = interquartile range, TCC = telemedicine critical care.

[a]Includes metabolic, hematologic, genitourinary, and miscellaneous.

[b]$p < 0.05$ for comparisons with pre-TCC values. Otherwise, pre-TCC vs post-TCC comparisons were not significant.

[c]$p < 0.001$ for comparisons with pre-TCC values. Otherwise, pre-TCC vs post-TCC comparisons were not significant.

TABLE 2.

Mortality and Length of Stay Outcomes Before and After Telemedicine Critical Care Implementation, Stratified by Performance Group

	Overall		Lower-Performing		Higher-Performing	
	Pre-TCC	Post-TCC	Pre-TCC	Post-TCC	Pre-TCC	Post-TCC
Outcomes	***n* = 2,429**	***n* = 12,479**	***n* = 307**	***n* = 1,671**	***n* = 2,122**	***n* = 10,808**
Hospital mortality (%)						
Observed	8.7	9.9[c]	19.9	17.7	7.1	8.7[f]
Expected	10.4	13.2[d]	12.3	17.1[d]	10.1	12.6[d]
Standardized (95% CI)[a]	0.83 (0.72–0.95)	0.75 (0.70–0.79)	1.61 (1.21–2.01)	1.03 (0.91–1.15)	0.70 (0.59–0.81)	0.69 (0.64–0.73)
Risk-adjusted	10.7	9.5[e]	26.4	16.9[d]	8.5	8.4
Hospital length of stay (d)[b]						
Observed	11.1 (11.4)	12.5 (13.6)[d]	15.0 (14.1)	16.1 (16.6)	10.5 (10.8)	11.9 (13.0)[d]
Expected	11.9 (5.3)	12.6 (4.8)[d]	13.0 (5.2)	13.2 (4.4)	11.7 (5.3)	12.5 (4.8)[d]
Standardized (95% CI)[a]	0.93 (0.38–1.48)	0.99 (0.44–1.54)	1.15 (0.57–1.74)	1.22 (0.62–1.81)	0.90 (0.36–1.44)	0.95 (0.41–1.49)
Risk-adjusted	11.8 (11.5)	12.4 (12.6)	16.1 (15.6)	16.8 (18.0)	11.2 (10.7)	11.7 (11.5)

TCC = telemedicine critical care.

[a]Standardized outcomes are expressed as ratios of observed to expected values with corresponding 95% CIs.

[b]Length of stay, expressed in days as mean values and SD.

[c]$p = 0.08$ (compared with Pre-TCC, the p value was not significant).

[d]$p < 0.001$ compared with pre-TCC values.

[e]$p = 0.09$ (compared with Pre-TCC, the p value was not significant).

f$p = 0.02$ compared with pre-TCC values.

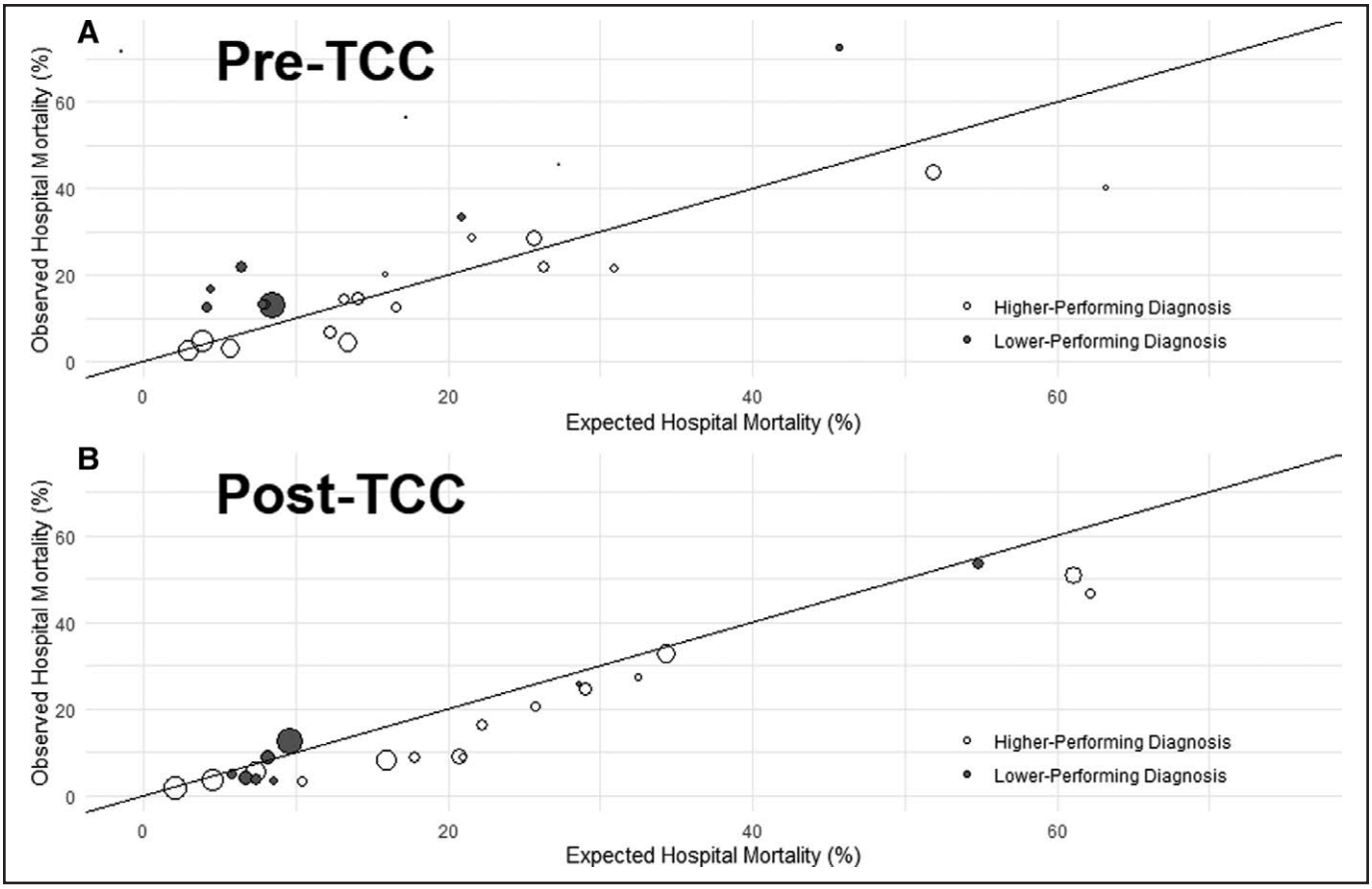

Figure 3. Plots of observed vs expected (Acute Physiology and Chronic Health Evaluation [APACHE]-predicted) Hospital Mortality in APACHE Diagnosis Categories across the Study ICUs during the pre-telemedicine critical care (pre-TCC) implementation (**A**) and post-TCC implementation periods (**B**). *Each circle* represents an APACHE diagnosis category in the three study ICUs. The *circle size* is proportional to the number of patients in that diagnosis category. The *diagonal line* represents the line of unity where observed = expected (i.e., standardized mortality ratio = 1).

pre- and post-TCC periods in the overall cohort or either performance group (Table 2). The mean (SD) risk-adjusted HLOS days were 11.8 (11.5) pre-TCC and 12.4 (12.6) post-TCC in the overall cohort ($p = 0.44$); 16.1 (15.6) pre-TCC and 16.8 (18.0) post-TCC in the lower-performing group ($p = 0.77$); and 11.2 (10.7) pre-TCC and 11.7 (11.5) post-TCC in the higher-performing group ($p = 0.39$).

Sensitivity Analyses

Sensitivity analyses using GLMM yielded results consistent with those obtained using standardized rate statistics (**Supplemental Table 4**, http://links.lww.com/CCX/B253**).** Specifically, we observed increased odds of death in the post-TCC compared with pre-TCC period (odds ratio [OR], 1.27; 95% CI, 1.05–1.53, $p < 0.05$) and higher odds of pre-TCC death in the lower-performing group compared with the higher-performing group (OR, 2.38 [1.49–3.81], $p < 0.001$). Additionally, there was significant interaction between TCC implementation and performance grouping ($p = 0.008$). In the low-performing group, there was a significant reduction in odds of mortality (from an overall OR of 1.27–0.76), and in the post-TCC period, there was a significant decrease in the OR for death in the lower-performing compared with the higher-performing group (from 2.38 to 1.43). For HLOS, there was an overall increase of about 1.13-fold in the post-TCC period. No significant interaction was detected between TCC and performance grouping on HLOS.

DISCUSSION

In this single-center, prospective, observational, before and after study of TCC implementation, we used APACHE admission diagnosis category SMR

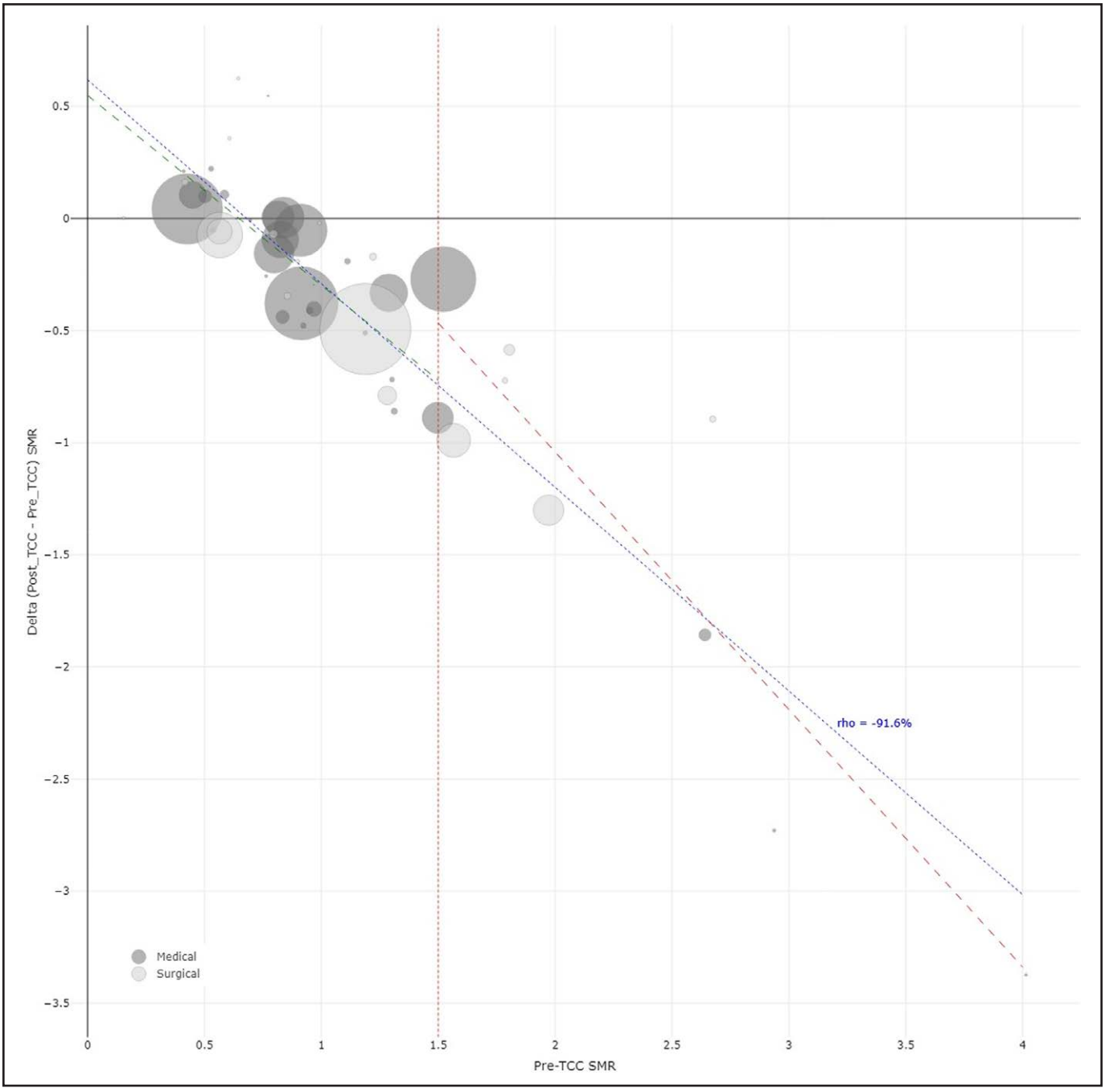

Figure 4. The standardized mortality ratio (SMR) change ("Delta") from the pre-telemedicine critical care (pre-TCC) to the post-TCC period is plotted against pre-TCC SMR in the same Acute Physiology and Chronic Health Evaluation diagnosis category. *Each circle* represents a category. The *relative sizes of the circles* are proportional to the sample size of that diagnosis group. The *three "fitted" lines* illustrate the strengths of relationships between the Delta SMR and pre-TCC SMR across all diagnosis categories (Pearson correlation coefficient, $\rho = -0.92$ [shown]; slope = −0.91) and for the lower-performing (pre-TCC SMR > 1.5) diagnosis category group ($\rho = -0.90$; slope = −1.15) and the higher-performing (pre-TCC SMR < 1.5) diagnosis category group ($\rho = -0.75$; slope = −0.85).

to identify and target a lower-performing group of patients in three ICUs in an academic medical center and found a striking improvement in SMR and risk-adjusted mortality for that group following TCC implementation that was well-maintained over time. By contrast, we observed no significant differences in SMR or risk-adjusted mortality in the higher-performing group over the same period.

Our findings add to the accumulating evidence of a favorable impact of TCC on mortality and align with

insights provided in a recent ICU-level meta-analysis by Fusaro et al (18), which found significant TCC-mediated mortality reductions in ICU study populations with pre-TCC SMRs of greater than 1, with no effect on mortality in ICU populations with pre-TCC SMRs of less than 1. The authors speculated that the benefit of TCC in ICUs with higher SMRs was mediated by multiple factors including TCC process improvements and care standardization, as well as increased nursing support and access to intensivist physicians. They further noted that the high-performing ICUs had little opportunity for further improvement with TCC. We have demonstrated a similar relationship between pre-TCC SMR and TCC-associated improvements at the diagnosis category level. Given the complexity of our TCC intervention, we similarly speculate that the mechanisms for the improvements are likely multifactorial.

The lack of impact of TCC on mortality in our overall ICU population with a pre-TCC SMR of 0.83 is consistent with the earlier findings. More importantly, the post-TCC reduction in risk-adjusted mortality in the lower-performing group, which was not observed in the higher-performing group, provides a prospective validation of the suggested relationship between pre-TCC performance and TCC improvement and supports the concept that the benefit of adding TCC is dependent on pre-intervention (i.e., historical) performance. Evaluation of pre-TCC performance at the patient diagnosis category level revealed a subpopulation of "lower-performing" ICU patients that experienced a clinically significant TCC-associated reduction in risk-adjusted mortality, even in our otherwise well-staffed and overall higher-performing ICUs.

The structured acuity-driven TCC workflow used for the lower-performing group was primarily intended to efficiently use TCC resources where they appeared to be needed most. As expected, there were significantly more TCC nurse and physician video assessments for the lower-performing group. Yet, while this workflow was associated with sustained improvement over the 30-month post-TCC study period, the role of the structured workflow in the sustained improvement, or the lack of improvement in the higher-performing group who received routine TCC support, was not tested. The linear decrease in SMR as a function of pre-TCC SMR we observed for all diagnosis categories with pre-TCC SMRs of greater than 1, across both groups, suggests that "routine" TCC support is sufficient to produce the performance improvement without the need for the structured workflow. Nevertheless, with current national TCC adoption rates of less than 20%, the performance-targeted approach presented here may help foster broader adoption of TCC (4, 24), particularly for less well-resourced hospitals where it may be needed most (19, 20, 25–27). TCC implementation focused on identifying and following lower-performing groups may perhaps provide an efficient approach to not only measure impacts but to manage TCC costs and expectations.

The importance of risk adjustment to account for differences in ICU patient study populations when assessing TCC impacts on mortality, underscored in the earlier meta-analysis (19), was also evident in our study. The raw mortality decrease in the lower-performing group was otherwise not significant, and there was a significant increase in raw mortality in the higher-performing group. By contrast, the respective 9.5% and 0.1% decreases in risk-adjusted mortality in the lower- and higher-performing groups, took into account the "sicker" ICU population in the post-TCC period, as evidenced by the significant pre- to post-TCC increases in APACHE scores and expected mortalities in our study population. Similarly, there were significant post-TCC increases in HLOS in the overall population and the higher-performing group, whereas there were no differences between the pre- and post-TCC standardized HLOS ratios or risk-adjusted HLOSs in the overall cohort or either performance group. Notably, this latter finding is consistent with that of a recent meta-analysis of 19 TCC implementation studies that found significant TCC impacts on ICU and hospital mortality, and ICU length of stay, but not on HLOS (27). The stability of the risk-adjusted HLOS also supports the inference that the decrease in risk-adjusted mortality attributed to TCC in the lower-performing group was not the result of a change in APACHE scoring or diagnosis assignment methodology. Such changes would otherwise have also been expected to result in a parallel post-TCC decrease in risk-adjusted HLOS.

The strengths of our study lie in the prospective study design, the novel uses of available severity scoring tools to identify and target the lower-performing patient group, the large sample size, and the long pre- and post-TCC study periods. There are also several

limitations, which suggest future directions for study. First, the absence of random assignment leaves room for residual confounding and does not allow a clear cause-and-effect relationship to be established. The stability of the pre-TCC SMR in the lower-performing group, and the stronger correlation between SMR delta and pre-TCC SMR for that group suggest that secular trends or regression to the mean do not account for the TCC-associated improvements. However, contributions from such a phenomenon cannot be entirely ruled out in pre-post studies such as ours. Second, although the diverse ICU settings in prior meta-analyses suggest our findings may be generalizable, this was a single-center study conducted in an academic setting. Third, although we intentionally structured our TCC implementation to include the structured TCC support for the lower-performing group, we did not separately test the impact of this structured versus routine TCC support. As TCC workflows translate to TCC operational costs, further studies are needed to address optimal levels of TCC support. Fourth, benchmarking performance by diagnosis category may be difficult or impractical in lower-volume ICUs. Fifth, the uncertainty related to APACHE diagnosis category selections (28) may have impacted both APACHE diagnosis category SMRs and the selection of lower-performing category patients. Future studies to corroborate the relationship between historical performance and TCC impact would thus be valuable. Finally, while the frequency of documented TCC video evaluations was high for patients in both groups, it is unclear what specific actions were responsible for the SMR reductions observed. Such information could be valuable to better understand specific mechanisms whereby TCC support produces improvements and to potentially embed appropriate changes in routine ICU care.

CONCLUSIONS

Before TCC implementation in three high-performing ICUs in an academic medical center, we identified a lower-performing patient group using the APACHE diagnosis category SMR granularity and implemented TCC with a structured TCC workflow that prospectively targeted this lower-performing group. We demonstrated sustained reductions in SMR and risk-adjusted hospital mortality in the identified lower-performing group over a 30-month post-TCC period. Future studies are needed to better understand the relationship between pre-TCC performance and TCC impact, and the optimal TCC workflows and mechanisms linking TCC support with improved patient outcomes.

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1 *Division of Critical Care Medicine, Department of Anesthesiology, Washington University in St. Louis, St. Louis, MO.*

2 *Barnes Jewish Hospital, St. Louis, MO.*

3 *Center for Clinical Excellence, BJC Healthcare, St. Louis, MO.*

4 *Section of Acute and Critical Care Surgery, Department of Surgery, Washington University in St. Louis, St. Louis, MO.*

5 *Division of Pulmonary and Critical Care Medicine, Department of Medicine, Washington University in St. Louis, St. Louis, MO.*

6 *Department of Psychiatry, Washington University in St. Louis, St. Louis, MO.*

7 *Department of Computer Science and Artificial Intelligence, University of Granada, Granada, Spain.*

8 *Institute for Informatics, Data Science, and Biostatistics, Washington University in St. Louis, St. Louis, MO.*

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For information regarding this article, E-mail: uofoma@wustl.edu

REFERENCES

1. Herasevich V, Subramanian S: Tele-ICU technologies. *Crit Care Clin* 2019; 35:427–438

2. Kahn JM, Cicero BD, Wallace DJ, et al: Adoption of ICU telemedicine in the United States. *Crit Care Med* 2014; 42:362–368
3. Lilly CM, Zubrow MT, Kempner KM, et al; Society of Critical Care Medicine Tele-ICU Committee: Critical care telemedicine: Evolution and state of the art. *Crit Care Med* 2014; 42:2429–2436
4. Ofoma UR, Maddox TM, Perera C, et al: Characteristics of U.S. acute care hospitals that have implemented telemedicine critical care. *Crit Care Explor* 2021; 3:e0468
5. Wilcox ME, Adhikari NK: The effect of telemedicine in critically ill patients: Systematic review and meta-analysis. *Crit Care* 2012; 16:R127
6. Kahn JM, Le TQ, Barnato AE, et al: ICU telemedicine and critical care mortality: A national effectiveness study. *Med Care* 2016; 54:319–325
7. McCambridge M, Jones K, Paxton H, et al: Association of health information technology and teleintensivist coverage with decreased mortality and ventilator use in critically ill patients. *Arch Intern Med* 2010; 170:648–653
8. Morrison JL, Cai Q, Davis N, et al: Clinical and economic outcomes of the electronic intensive care unit: Results from two community hospitals. *Crit Care Med* 2010; 38:2–8
9. Lilly CM, Cody S, Zhao H, et al; University of Massachusetts Memorial Critical Care Operations Group: Hospital mortality, length of stay, and preventable complications among critically ill patients before and after tele-ICU reengineering of critical care processes. *JAMA* 2011; 305:2175–2183
10. Kohl BA, Fortino-Mullen M, Praestgaard A, et al: The effect of ICU telemedicine on mortality and length of stay. *J Telemed Telecare* 2012; 18:282–286
11. Willmitch B, Golembeski S, Kim SS, et al: Clinical outcomes after telemedicine intensive care unit implementation. *Crit Care Med* 2012; 40:450–454
12. Lilly CM, McLaughlin JM, Zhao H, et al; UMass Memorial Critical Care Operations Group: A multicenter study of ICU telemedicine reengineering of adult critical care. *Chest* 2014; 145:500–507
13. Nassar BS, Vaughan-Sarrazin MS, Jiang L, et al: Impact of an intensive care unit telemedicine program on patient outcomes in an integrated health care system. *JAMA Intern Med* 2014; 174:1160–1167
14. Lee JT, Kerlin MP: ICU telemedicine and the value of qualitative research for organizational innovation. *Am J Respir Crit Care Med* 2019; 199:935–936
15. Kalvelage C, Rademacher S, Dohmen S, et al: Decision-making authority during tele-ICU care reduces mortality and length of stay—a systematic review and meta-analysis. *Crit Care Med* 2021; 49:1169–1181
16. Hawkins HA, Lilly CM, Kaster DA, et al: ICU telemedicine comanagement methods and length of stay. *Chest* 2016; 150:314–319
17. Kahn JM, Rak KJ, Kuza CC, et al: Determinants of intensive care unit telemedicine effectiveness. An ethnographic study. *Am J Respir Crit Care Med* 2019; 199:970–979
18. Fusaro MV, Becker C, Scurlock C: Evaluating tele-ICU implementation based on observed and predicted ICU mortality: A systematic review and meta-analysis. *Crit Care Med* 2019; 47:501–507
19. Kumar G, Falk DM, Bonello RS, et al: The costs of critical care telemedicine programs: A systematic review and analysis. *Chest* 2013; 143:19–29
20. Lilly CM, Motzkus C, Rincon T, et al; UMass Memorial Critical Care Operations Group: ICU telemedicine program financial outcomes. *Chest* 2017; 151:286–297
21. Zimmerman JE, Kramer AA, McNair DS, et al: Acute Physiology and Chronic Health Evaluation (APACHE) IV: Hospital mortality assessment for today's critically ill patients. *Crit Care Med* 2006; 34:1297–1310
22. Breslow NE, Day NE: Statistical methods in cancer research. Volume II—the design and analysis of cohort studies. *IARC Sci Publ* 1987:1–406
23. Vasilevskis EE, Kuzniewicz MW, Cason BA, et al: Mortality probability model III and simplified acute physiology score II: Assessing their value in predicting length of stay and comparison to APACHE IV. *Chest* 2009; 136:89–101
24. Lilly CM: The era of evidence-based ICU telemedicine. *Crit Care Med* 2021; 49:1217–1218
25. Yoo BK, Kim M, Sasaki T, et al: Economic evaluation of telemedicine for patients in ICUs. *Crit Care Med* 2016; 44:265–274
26. Cummings J, Krsek C, Vermoch K, et al; University HealthSystem Consortium ICU Telemedicine Task Force: Intensive care unit telemedicine: Review and consensus recommendations. *Am J Med Qual* 2007; 22:239–250
27. Chen J, Sun D, Yang W, et al: Clinical and economic outcomes of telemedicine programs in the intensive care unit: A systematic review and meta-analysis. *J Intensive Care Med* 2018; 33:383–393
28. Simkins M, Iqbal A, Gronemeyer A, et al: Inter-rater reliability and impact of disagreements on Acute Physiology and Chronic Health Evaluation IV mortality predictions. *Crit Care Explor* 2019; 1:e0059