Hospital Mortality, Length of Stay, and Preventable Complications Among Critically Ill Patients Before and After Tele-ICU Reengineering of Critical Care Processes

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P ATIENT NEEDS AND SOCIETAL costs of adult critical care have increased as predicted from population-based models,[1-3] and more efficient methods of delivery of care are needed. A tele-intensive care unit (ICU) is a promising technological approach designed to systematically alter processes of care that affect outcomes. Tele-ICU can be defined as the provision of care to critically ill patients by health care professionals located remotely. Tele-ICU clinicians use audio, video, and electronic links to assist bedside caregivers in monitoring patients, to oversee best practice adherence, and to help create and execute care plans. Tele-ICU programs have the potential to target processes that are associated with better outcomes, including shorter response times to alarms[4] and abnormal laboratory values,[5] more rapid initiation of lifesaving therapies,[6,7] and higher rates of adherence to critical care best practices.[8]

For editorial comment see p 2227.

Context The association of an adult tele-intensive care unit (ICU) intervention with hospital mortality, length of stay, best practice adherence, and preventable complications for an academic medical center has not been reported.

Objective To quantify the association of a tele-ICU intervention with hospital mortality, length of stay, and complications that are preventable by adherence to best practices.

Design, Setting, and Patients Prospective stepped-wedge clinical practice study of 6290 adults admitted to any of 7 ICUs (3 medical, 3 surgical, and 1 mixed cardiovascular) on 2 campuses of an 834-bed academic medical center that was performed from April 26, 2005, through September 30, 2007. Electronically supported and monitored processes for best practice adherence, care plan creation, and clinician response times to alarms were evaluated.

Main Outcome Measures Case-mix and severity-adjusted hospital mortality. Other outcomes included hospital and ICU length of stay, best practice adherence, and complication rates.

Results The hospital mortality rate was 13.6% (95% confidence interval [CI], 11.9%-15.4%) during the preintervention period compared with 11.8% (95% CI, 10.9%-12.8%) during the tele-ICU intervention period (adjusted odds ratio [OR], 0.40 [95% CI, 0.31-0.52]). The tele-ICU intervention period compared with the preintervention period was associated with higher rates of best clinical practice adherence for the prevention of deep vein thrombosis (99% vs 85%, respectively; OR, 15.4 [95% CI, 11.3-21.1]) and prevention of stress ulcers (96% vs 83%, respectively; OR, 4.57 [95% CI, 3.91-5.77], best practice adherence for cardiovascular protection (99% vs 80%, respectively; OR, 30.7 [95% CI, 19.3-49.2]), prevention of ventilator-associated pneumonia (52% vs 33%, respectively; OR, 2.20 [95% CI, 1.79-2.70]), lower rates of preventable complications (1.6% vs 13%, respectively, for ventilator-associated pneumonia [OR, 0.15; 95% CI, 0.09-0.23] and 0.6% vs 1.0%, respectively, for catheter-related bloodstream infection [OR, 0.50; 95% CI, 0.27-0.93]), and shorter hospital length of stay (9.8 vs 13.3 days, respectively; hazard ratio for discharge, 1.44 [95% CI, 1.33-1.56]). The results for medical, surgical, and cardiovascular ICUs were similar.

Conclusion In a single academic medical center study, implementation of a tele-ICU intervention was associated with reduced adjusted odds of mortality and reduced hospital length of stay, as well as with changes in best practice adherence and lower rates of preventable complications.
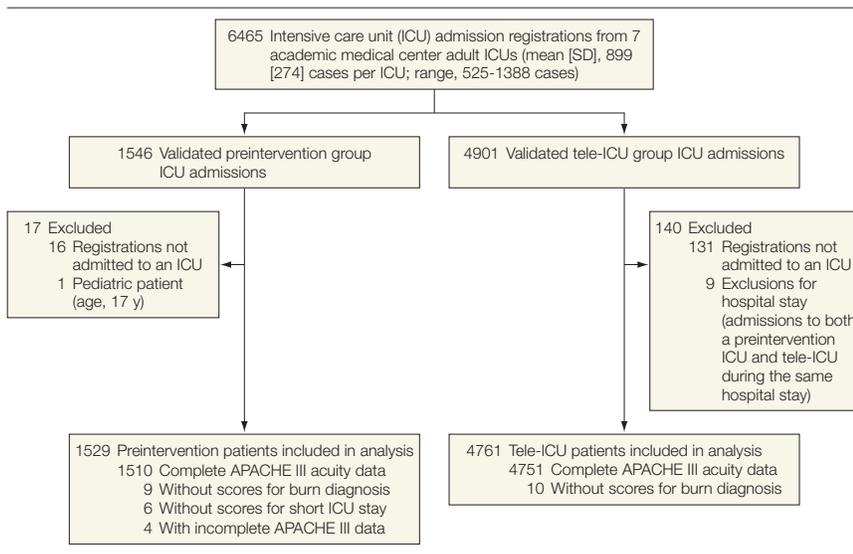
Studies of the effects of tele-ICU programs to date have focused primarily on community and rural hospitals and have yielded both positive and negative results. Several studies have highlighted low levels of acceptance of the tele-ICU

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Figure. Enrollment of Study Participants

6465 Intensive care unit (ICU) admission registrations from 7 academic medical center adult ICUs (mean [SD], 899 [274] cases per ICU; range, 525-1388 cases)

1546 Validated preintervention group ICU admissions

4901 Validated tele-ICU group ICU admissions

17 Excluded
  16 Registrations not admitted to an ICU
  1 Pediatric patient (age, 17 y)

140 Excluded
  131 Registrations not admitted to an ICU
  9 Exclusions for hospital stay (admissions to both a preintervention ICU and tele-ICU during the same hospital stay)

1529 Preintervention patients included in analysis
  1510 Complete APACHE III acuity data
  9 Without scores for burn diagnosis
  6 Without scores for short ICU stay
  4 With incomplete APACHE III data

4761 Tele-ICU patients included in analysis
  4751 Complete APACHE III acuity data
  10 Without scores for burn diagnosis

APACHE indicates Acute Physiology and Chronic Health Evaluation.

intervention but few studies have identified the care processes or ICU structural elements that were part of the intervention; these issues have limited the ability to compare studies and identify processes associated with improved outcomes.[9] To provide insight into which tele-ICU–related process changes are associated with better outcomes, we examined the association of a tele-ICU intervention with the risk of dying in the hospital and length of stay, and the contributions of best practice adherence and preventable complications to these associations. Our study focused on changes in the processes of care rather than ICU structure because the critical care team structure and governance had been previously well characterized[10] and were not changed during the intervention.

METHODS

We performed a prospective, unblinded, stepped-wedge study of a tele-ICU intervention at an academic medical center. To focus on processes of care rather than on structural elements, critical care governance, team structure (including an intensivist-led closed model), call schedules, interdisciplinary rounds, and staffing models were established before study enrollment. We standardized medical center best practices for the

prevention of venous thrombosis,[11] cardiovascular complications,[12,13] ventilator-associated pneumonia,[14,15] and stress ulcers[16] through a task force–driven consensus-building process and codified them in our medical center policies.[10] Before the start of the study, we introduced a form for ICU daily goals[17] as part of the medical record and completed a supporting educational program on March 5, 2005, across 7 adult ICUs (3 medical, 3 surgical, and 1 mixed cardiovascular) on 2 campuses of an 834-bed academic medical center.

For the primary analysis, a representative sample of preintervention cases was obtained by identifying consecutive hospital discharge cases from an administrative database for cases managed in each of the 7 ICUs. All adults admitted to an ICU bed were included in the tele-ICU group. The tele-ICU intervention implementation dates for the ICUs were staggered and occurred on June 30, 2006, July 5, 2006, July 17, 2006, November 2, 2006, November 7, 2006, November 8, 2006, and April 16, 2007. The first preintervention patient was admitted to the medical center on April 26, 2005, and the last patient was discharged on February 7, 2007. The first tele-ICU intervention case was admitted on August 6, 2006,

and the last case was discharged on September 30, 2007. Patients younger than 18 years and those admitted to a preintervention and tele-ICU intervention unit during the same hospital stay were excluded (**FIGURE**). The study was powered to have an 80% probability for detecting a 3.5% improvement in mortality using a 1:3 allocation of patients in the preintervention group and in the tele-ICU group at a significance level of .05. The University of Massachusetts Medical School human subjects committee approved the study and determined the study to be exempt from the informed consent requirement.

Admission, discharge, and laboratory information was abstracted electronically. Clinical information that was not in electronic form was collected by trained abstractors using the procedures detailed in the eSupplement at http://www.jama.com. Randomly selected subsets of individual records were abstracted electronically or manually in duplicate to measure concordance among raters and to compare electronic with hard-copy abstraction. Adherence to prespecified and well-established best practices and rates of complications were measured (described in the eSupplement). The Acute Physiology and Chronic Health Evaluation (APACHE) III system was used to measure acuity; the period from the date of admission of the first case in each group was calculated as a time-trend factor to adjust for secular trends. Tele-ICU intervention episode type,[18] severity, and determination of bedside vs off-site clinician initiation were electronically recorded. Validation procedures and data completeness are presented in the eSupplement. The guideline for managing intravenous catheters was adapted from Pronovost et al.[19] To determine whether the associations of the tele-ICU intervention on length of stay could be attributed to higher rates of transfer of patients into chronic care facilities, discharge location was measured.

The tele-ICU team participated in key critical care delivery processes throughout the entire day (24 hours every day). The off-site team included an intensiv-

ist and used tele-ICU workstations. The tele-ICU team serially reviewed the care of individual patients, performed real-time audits of best practice adherence, performed workstation-assisted care plan reviews for patients admitted at night, monitored system-generated electronic alerts, audited bedside clinician responses to in-room alarms, and intervened[18] when the responses of bedside clinicians were delayed and patients were deemed physiologically unstable. The care process elements during the preintervention and those added by the tele-ICU reengineering process are presented in TABLE 1. The off-site team had the ability to communicate with bedside clinicians or directly manage patients by recording clinician orders for tests, treatments, consultations, and management of life-support devices.[20]

Cases in the preintervention group who were admitted during nighttime hours were reviewed by telephone by the attending physician at the discretion of the bedside ICU house staff or affiliate practitioner after they had evaluated the case. The process was different for tele-ICU cases. The off-site intensivist reviewed the electronically available information including laboratory values and radiographic images, supported pre-admission management, and assigned the case to an appropriate ICU team. The intensivist assessed the patient using real-time video, communicated with the ICU nurse and patient using audio links, responded to alerts and alarms, reviewed the response to the initial plan of care in real time, and shared responsibility for altering the care plan when the patient's condition failed to respond. All off-site clinical personnel also had rotations at other times in the medical center adult ICUs. The tele-ICU tools used to facilitate and track this intervention were licensed from Visicu Inc (Baltimore, Maryland), Cerner Healthcare Solutions (Kansas City, Missouri), or developed by our team at the University of Massachusetts (Criticalware).

Case-mix and severity-adjusted hospital mortality was prespecified as the main study outcome. Other outcomes included ICU mortality, hospital and

Table 1. Comparison of Intensive Care Unit (ICU) Processes Before and After Tele-ICU Intervention

Preintervention	Tele-ICU Intervention
Bedside monitor alarms	Physiological trend alerts Abnormal laboratory value alerts Review of response to alerts Off-site team rounds
Daily goal sheet	Electronic detection of nonadherence Real-time auditing Nurse manager audits Team audits
Telephone case review initiated by house staff or affiliate practitioner	Workstation review initiated by intensivist includes electronic medical record, imaging studies, interactive audio and video of patient, interaction with nurse and respiratory therapist, and assessment of response to therapy

ICU length of stay, rates of adherence to best practice, complication rates, and whether responses to alerts were initiated by bedside or by off-site team members. We performed post hoc analyses of cases matched on acuity score, ICU, season of the year, and operative status to determine whether cases of the same type and acuity had different outcomes when managed in the same ICU. Mediation analyses for hospital and ICU mortality were performed for prespecified best practice adherence and complication metrics.

The proportion of the effects mediated by these factors was estimated from differences in model coefficients using the probability density function method.[21] Standardized coefficients were used for dichotomous outcomes.[22] To determine if the associations were different between medical and surgical patients, we performed secondary analyses by ICU type. To investigate whether tele-ICU intensivist care plan review for patients admitted during nighttime hours contribute to the associations, we measured associations of the intervention with hospital and ICU mortality, length of stay, and duration of mechanical ventilation for patients admitted during the daytime compared with the nighttime.

The nearly 1-year period between implementation in the first and last surgical ICU allowed comparison of concurrent cases managed with and without tele-ICU support for this subset. Descriptive statistics were calculated for continuous variables and univariate

comparisons between groups for continuous outcomes were made using the t test. Comparisons between groups on categorical variables were made using the Fisher exact test or the χ^2 test or by logistic regression.

Dichotomous outcomes including hospital and ICU mortality were modeled using multivariable logistic regression. Continuous outcomes were modeled using general linear mixed models[23,24] with the tele-ICU intervention as a fixed effect, an ICU identifier variable as a random effect, and using restricted estimation by maximum likelihood and by Cox proportionate hazards modeling. For continuous outcomes, type 3 F tests of effects were used to evaluate the significance of the contribution of predictors to each model and the minimum deviance ($-2 \times$ the model log likelihood) was used to select the best fitting models.

Likelihood ratio tests for nested models[25] were used to select the appropriate predictors for each logistic model. Adherence and complication factors that were significantly affected by the intervention and the mortality effects were included with appropriate interaction terms into the model of tele-ICU effects on hospital mortality for mediation analyses. Analyses that included other appropriate interaction terms in the models were performed for effects by ICU type and admission time of day. After these models were obtained, each was refitted to data sets augmented by multiple imputations.[26,27]

Table 2. General Characteristics of Adult Critically Ill Patients[a]

Characteristic	Preintervention Group (n = 1529)	Tele-ICU Group (n = 4761)	P Value
Age, mean (SD), y	62 (17)	64 (16.8)	.003
Male sex	874 (57)	2701 (57)	.77
Body mass index, mean (SD)[b]	28.5 (6.3)	28.3 (7.7)	.48
APACHE III score, mean (SD)	45 (22)	58 (27)	<.001
APS score, mean (SD)	33 (19)	46 (24)	<.001
Mechanical ventilation	572 (37)	1492 (31)	<.001
Postoperative case	546 (36)	1221 (26)	<.001
Primary admission diagnosis classified by organ system[c]			
Cardiovascular	473 (31)	1924 (40)	
Respiratory	297 (19)	897 (19)	
Neurological	260 (17)	688 (14)	
Gastrointestinal	234 (15)	593 (12)	
Trauma	125 (8)	260 (5)	
Genitourinary	50 (3)	145 (3)	
Endocrine	34 (2)	100 (2)	
Musculoskeletal	32 (2)	89 (2)	
Hematological	13 (1)	41 (1)	
Transplant	11 (1)	24 (0.5)	

Abbreviations: APACHE, Acute Physiology and Chronic Health Evaluation; APS, acute physiology score; ICU, intensive care unit.
[a] Values are expressed as number (percentage) unless otherwise indicated.
[b] Calculated as weight in kilograms divided by height in meters squared.
[c] For the difference in distribution between the 2 groups, the P value was less than .001.

Intraclass correlation coefficients were calculated to assess concordance among raters and for hard-copy and electronic medical record review.[28] All hypothesis tests were 2-sided, were not adjusted for multiple comparisons, and the statistical significance was set at a P value level of .05. Statistical analyses were performed using Stata version 10.0 (StataCorp, College Station, Texas) and SAS version 9.2 (SAS Institute Inc, Cary, North Carolina) and used the LOGISTIC, PHREG, GLM, MIXED, and GLIMMIX procedures.

RESULTS

A total of 6290 qualifying cases were identified from 6465 electronic ICU admission registrations during the preintervention period and during the tele-ICU intervention period based on their dates of service. Patients who were not admitted to an adult ICU or were not adults were excluded (Figure). The tele-ICU intervention group had a larger percentage of patients with a primary admission diagnosis classified as medical rather than surgical, slightly more abnormal laboratory and physiological values than cases in the preintervention group, and accordingly higher acuity scores (**TABLE 2**) (eTable 1 at http://www.jama.com). These differences in APACHE III acuity score did not appear to be related to any single component or to the method of abstraction. The intraclass correlation coefficient for adherence measures was 0.83 for hard-copy abstraction and 0.86 for hard-copy vs electronic abstraction (intraclass correlation coefficients for acuity scores were larger and appear in the eSupplement).

Unadjusted ICU mortality was significantly lower in the tele-ICU group (P = .01) than in the preintervention group; hospital mortality showed a nonstatistically significant reduction (P = .07; **TABLE 3**). The hospital mortality rate was 13.6% (95% confidence interval [CI], 11.9%-15.4%) during the preintervention period compared with 11.8% (95% CI, 10.9%-12.8%) during the tele-ICU intervention and yielded an odds ratio (OR) of 0.40 (95% CI, 0.31-0.52; P = .005) after adjustment for acuity, locus of care, physiological parameters, laboratory values, and time trend. The ICU mortality rate was 10.7% for the preintervention group and 8.6% for the tele-ICU group and yielded an OR of 0.37 (95% CI, 0.28-0.49; P = .003) after adjustment for acuity, locus of care, physiological parameters, laboratory values, and time trend.

Mortality for concurrent surgical ICU cases in ICUs that had the intervention and in ICUs that had not yet implemented the intervention yielded effect estimates equivalent to those observed in the before and after comparison (absolute hospital mortality: 13.3% for the preintervention group and 7.3% for the tele-ICU group; OR, 0.21 [95% CI, 0.05-0.76]; P = .02) (absolute ICU mortality: 9.3% and 3.7%, respectively; OR, 0.17 [95% CI, 0.04-0.73]; P = .02).

Unadjusted analyses revealed that both hospital and ICU length of stay were significantly lower in the tele-ICU group than in the preintervention group (Table 3). The mean length of hospital stay was 13.3 days in the preintervention group and 9.8 days in the tele-ICU group and after adjustment for acuity, time trends, physiological parameters, laboratory values, and locus of care; hospital length of stay was significantly shorter in the tele-ICU group (hazard ratio [HR] for discharge, 1.44 [95% CI, 1.33-1.56]; P<.001). The mean length of ICU stay was 6.4 days in the preintervention group and 4.5 days in the tele-ICU group and after adjustment for all of the previously listed variables, the HR was 1.26 (95% CI, 1.17-1.36; P<.001).

Comparison of length of stay for concurrent surgical ICU cases managed in units that had the intervention with units that had not yet implemented the intervention yielded likelihood estimates of discharge that were similar to those observed in the before and after comparison (hospital length of stay: 12.6 days in the preintervention group and 12.4 days in the tele-ICU group; HR, 1.8 [95% CI, 1.1-2.9]; P = .01) (ICU length of stay: 6.9 days and 3.6 days, respectively; HR, 1.50 [95% CI, 0.95-2.40]; P = .08). For the tele-ICU group

compared with the preintervention group, the fraction of patients requiring mechanical ventilation was significantly lower (Table 2) and the duration of mechanical ventilation was significantly shorter (5.70 days [95% CI, 5.27-6.13 days] and 8.50 days [95% CI, 7.47-9.53 days], respectively; $P<.001$). Compared with the preintervention group, the use of noninvasive ventilation was higher for the tele-ICU group (eTables 2-4 at http://www.jama.com).

A total of 1350 cases in the preintervention group were matched by ICU, season of the year, operative status, and APACHE III acuity score on a ratio of 1:1 to cases in the tele-ICU group (details are provided in the eSupplement). The hospital mortality was 8.5% for the tele-ICU group compared with 14.4% for the preintervention group (χ^2 test $P<.001$) and ICU mortality was 4.8% vs 11.1%, respectively ($P<.001$). The mean (SD) length of hospital stay was 10.9 (13.4) days for the tele-ICU group compared with 14.2 (18.3) days for the preintervention group (paired t test $P<.001$) and the mean (SD) length of ICU stay was 4.2 (7.6) days and 6.9 (11.0) days, respectively ($P<.001$). Tele-ICU group cases of similar type and acuity had better outcomes than their preintervention group counterparts.

To understand how tele-ICU team activities affected care processes and to evaluate the degree to which the association of the intervention with changes in mortality could be attributed to these changes in process, we performed analyses of adherence to best practices, incidence of common ICU complications, intensivist involvement for cases admitted during nighttime hours, responses to alerts, and by ICU type. The associations were not attributable to any single ICU or type of ICU (data are presented in eTables 5-8 at http://www.jama.com).

The tele-ICU intervention was associated with significantly higher adherence to deep vein thrombosis prevention best practice and cardiovascular protection best practice, and lower rates of catheter-related bloodstream infec-

tion and ventilator-associated pneumonia (TABLE 4 and TABLE 5). We found that these factors also were associated with significantly lower ICU and hospital mortality. The magnitude of these changes in mortality was the size expected based on consensus reports of best practices.[11-13] We then estimated the contribution of adherence to best practices and lower rates of complications to the lower mortality rates observed for the tele-ICU group by comparing standardized coefficients from our model estimates of tele-ICU associations for ICU and hospital mortality with and without inclusion

of these factors. Analyses adjusted for these factors still demonstrated significant associations for hospital mortality (adjusted OR, 0.54 [95% CI, 0.39-0.73]; $P<.001$) and ICU mortality (adjusted OR, 0.58 [95% CI, 0.41-0.83]; $P=.002$), but the magnitude was smaller without adjustment for adherence and complications (OR, 0.40 [95% CI, 0.31-0.52] for hospital mortality and OR, 0.37 [95% CI, 0.28-0.49] for ICU mortality). The proportion of the tele-ICU association with lower mortality that could be attributed to adherence to these best practices and complication measures was estimated to be 25%

Table 3. Mortality and Length-of-Stay Outcomes

Outcome	Preintervention Group (n = 1529)	Tele-ICU Group (n = 4761)	Unadjusted P Value	Tele-ICU Effect Estimates[a]	P Value
	No. (%) of Patients				
Mortality rate					
Hospital	208 (13.6)	562 (11.8)	.07	0.40 (0.31-0.52)[b]	.005
ICU	164 (10.7)	410 (8.6)	.01	0.37 (0.28-0.49)[b]	.003
	Mean (SD) and Median [IQR], d				
Length of stay					
Hospital	13.3 (17.1) 7.9 [0.2-15.0]	9.8 (10) 6.8 [0.2-12.0]	<.001	1.44 (1.33-1.56)[c]	<.001
ICU	6.4 (11) 2.5 [0.2-6.5]	4.5 (6.7) 2.4 [0.1-4.6]	<.001	1.26 (1.17-1.36)[c]	<.001

Abbreviations: ICU, intensive care unit; IQR, interquartile range.
[a] Estimate of effect size after adjustment for differences in acuity score, admission source, admission ICU, time after enrollment of first case in group, and other predictive factors including laboratory values and physiological measurements as detailed in the eSupplement at http://www.jama.com.
[b] Indicates odds ratio (95% confidence interval).
[c] Indicates hazard ratio (95% confidence interval).

Table 4. Association of Tele-ICU Intervention Group With Best Practice and Complication Measures

Clinical Practice Guideline Adherence	No./Total (%) of Patients Eligible[a]		OR (95% CI)	P Value
	Preintervention Group	Tele-ICU Group		
Prophylaxis				
Stress ulcer	1253/1505 (83)	4550/4760 (96)	4.57 (3.91-5.77)	<.001
Deep venous thrombosis	1299/1527 (85)	4707/4733 (99.5)	15.4 (11.3-21.1)	<.001
Best practice				
Cardiovascular protection	311/391 (80)	2866/2894 (99)	30.7 (19.3-49.2)	<.001
Prevention of ventilator-associated pneumonia	190/582 (33)	770/1492 (52)	2.20 (1.79-2.70)	<.001
Ventilator-associated pneumonia	76/584 (13)	32/1949 (1.6)	0.15 (0.09-0.23)	<.001
Catheter-related bloodstream infection	19/1529 (1)	29/4761 (0.6)	0.50 (0.27-0.93)	.005
Acute kidney injury	174/1452 (12)	540/4565 (12)	1.00 (0.71-1.69)	.38
After hours care plan review for ICU admissions, No. (%)	705/1529 (46)[b]	2287/4761 (48)[c]		
Interventions for physiological instability	All bedside clinician initiated	483[d] 37 573[e]		

Abbreviations: CI, confidence interval; ICU, intensive care unit; OR, odds ratio.
[a] Unless otherwise indicated.
[b] Off-hours admission reviews not using a workstation.
[c] Off-hours admissions reviews using a workstation.
[d] Initiated by bedside clinician.
[e] Initiated prior to action by bedside clinicians.

for hospital mortality and 30% for ICU mortality.

We performed analyses by time of admission because worse outcomes for ICU patients admitted after daytime hours have been reported.[29] We compared outcomes for 705 of 1529 cases in the preintervention group (46%) and 2287 of 4761 cases in the tele-ICU group (48%) that were admitted between 8 PM and 8 AM compared with those patients who were admitted during the daytime hours. In the preintervention group, the unadjusted hospital mortality rate for patients admitted after 8 PM was 16.1% compared with 11.5% for those admitted after 8 AM (P=.01). For the tele-ICU group, the unadjusted hospital mortality rate for patients admitted after 8 PM was 12.7% compared with 11.1% for those admitted after 8 AM (P=.11). There were significant interactions of the intervention with nighttime admission for hospital mortality (P=.04) and length of stay (P=.03).

Adjusted analyses demonstrated larger and significant associations of the intervention for those admitted after 8 PM (OR, 0.33 [95% CI, 0.18-0.59]; P<.001) compared with those admitted after 8 AM (OR, 0.79; 95% CI, 0.39-1.58). Cases admitted after 8 PM had longer hospital length of stay (14.3 days [95% CI, 12.99-15.57 days] in the preintervention group vs 12.4 days [95% CI, 11.22-13.58 days] in the tele-ICU group; P=.04) and ICU length of stay (7.7 days [95% CI, 6.77-8.63 days] vs 5.5 days [95% CI, 4.86-6.08 days], respectively; P<.001) than patients admitted after 8 AM. The diurnal differences were not significant in hospital length of stay (9.98 days [95% CI, 9.18-10.08 days] in the preintervention group vs 9.63 days [95% CI, 9.57-10.34 days] in the tele-ICU group; P=.27) and in ICU length of stay (4.39 days [95% CI, 4.15-4.63 days] vs 4.60 days [95% CI, 4.30-4.91 days], respectively; P=.24).

The magnitude of the association of the tele-ICU intervention with shorter hospital length of stay was greater for cases admitted after 8 PM (HR, 1.61 [95% CI, 1.35-1.92]; P<.001) than for patients admitted during daytime hours (HR, 1.26 [95% CI, 1.05-1.51]; P=.004). Analyses of ICU length of stay yielded similar results. The duration of mechanical ventilation was longer for patients in the preintervention group admitted after 8 PM (10.2 days; 95% CI, 9.16-11.24 days) than those admitted after 8 AM (6.9 days [95% CI, 6.34-7.46 days]; P<.01). Patients in the tele-ICU group admitted after 8 PM had a duration of mechanical ventilation of 5.8 days (95% CI, 5.24-6.36 days) compared with 5.5 days (95% CI, 4.99-6.01 days); P=.61) for those admitted after 8 AM.

Responses to alerts and alarms can be initiated by bedside personnel or by off-site personnel. During the preintervention period, there was no off-site patient monitoring and no off-site–initiated interventions. During the tele-ICU period, there were 6.80 (95%

Table 5. Association of Best Practice and Complication Measures With Mortality Risk

Complication Measure	Hospital Mortality	P Value	ICU Mortality	P Value
Stress ulcer prophylaxis				
OR (95% CI)	0.82 (0.57-1.20)[a]	.30	0.73 (0.48-1.10)[a]	.10
Adherent/nonadherent[b]	([181/1217]/[20/248])/([505/4214]/[19/203])		([146/1253]/[15/252])/([394/4550]/[16/210])	
Deep vein thrombosis prophylaxis				
OR (95% CI)	0.69 (0.45-1.10)	.09	0.62 (0.39-0.99)	.05
Adherent/nonadherent[b]	([171/1299]/[31/213])/([503/4365]/[1/26])		([139/1299]/[25/228])/([390/4707]/[1/26])	
Cardiovascular protection best practice				
OR (95% CI)	0.47 (0.30-0.86)	.01	0.38 (0.20-0.74)	.004
Adherent/nonadherent[b]	([27/301]/[13/80])/([239/2688]/[3/27])		([20/311]/[10/80])/([174/2866]/[3/28])	
Ventilator-associated pneumonia best practice				
OR (95% CI)	0.94 (0.76-1.20)	.60	1.10 (0.86-1.40)	.40
Adherent/nonadherent[b]	([51/181]/[82/365])/([170/706]/[151/657])		([42/190]/[75/392])/([160/770]/[129/722])	
Ventilator-associated pneumonia				
OR (95% CI)	2.3 (1.5-3.6)	<.001	2.0 (1.2-3.2)	<.001
Complication/no complication[c]	(38/108)/(470/1970)		(27/108)/(384/1970)	
Catheter-related bloodstream infection				
OR (95% CI)	3.4 (1.7-6.5)	<.001	2.9 (1.4-5.9)	.003
Complication/no complication[c]	(18/48)/(780/6242)		(13/48)/(561/6242)	
Acute kidney injury				
OR (95% CI)	1.8 (1.5-2.3)	<.001	2.1 (1.6-2.6)	<.001
Complication/no complication[c]	(167/714)/(567/4736)		(134/714)/(392/4736)	

Abbreviations: CI, confidence interval; ICU, intensive care unit; OR, odds ratio.
[a] After adjustment as detailed in the eSupplement at http://www.jama.com.
[b] Indicates ([deaths in the preintervention best practice adherent group/all preintervention group adherent cases]/[deaths in the preintervention nonadherent group/all preintervention nonadherent cases])/([deaths in the tele-ICU best practice adherent group/all tele-ICU group adherent cases]/[deaths in the tele-ICU nonadherent group/all tele-ICU group nonadherent cases]).
[c] Indicates (deaths among those with the complication/all eligible patients with the complication)/(deaths among those without the complication/all eligible patients without the complication).

CI, 6.50-7.10) alerts for physiological instability per patient per day. Among these alerts for physiological instability per patient per day, 5.05 (95% CI, 4.77-5.33) alerts were managed by bedside clinicians without tele-ICU intervention and 1.75 (95% CI, 1.69-1.81) alerts were managed with tele-ICU intervention. Most interventions were initiated by the tele-ICU team. Among 24 426 interventions that affected the diagnostic or therapeutic plan, 23 943 were initiated by off-site clinicians and 483 interventions were initiated by bedside clinicians (ratio of 50:1). Among these interventions, 1633 were documented with progress notes that included a rating of the severity of the physiological disturbance; 76% of these were classified as major (eg, requiring initiation of a vasoactive medication), 17% intermediate (eg, evaluation of an arrhythmia), and 7% as minor (eg, electrolyte correction).

Intervention-associated differences in length of stay and mortality rates could not be attributed to higher rates of transfer of cases to institutions providing care to those recovering from acute illness. Patients in the tele-ICU group were 8% more likely to go home, 6% less likely to go to a rehabilitation or long-term care facility, and 2% more likely to go to a skilled nursing facility than patients in the preintervention group (**TABLE 6**).

COMMENT

The main findings of this study are that a tele-ICU intervention was associated with lower hospital and ICU mortality and shorter hospital and ICU lengths of stay. The tele-ICU intervention also was associated with significantly higher rates of adherence to critical care best practices and lower rates of complications. This study also identified more rapid response to alerts for physiological instability, and off-hours, off-site intensivist care plan review as critical care process elements that may have contributed to the lower mortality and shorter lengths of stay associated with the tele-ICU intervention. These new care processes (Table 1)

Table 6. Location of Care After Hospital Discharge[a]

Location	No. (%) of Patients	
	Preintervention Group (n = 1529)	Tele-ICU Group (n = 4761)
Home	702 (45.9)	2543 (53.4)
Rehabilitation or long-term care facility	364 (23.8)	839 (17.6)
Skilled nursing facility	191 (12.5)	668 (14.0)
Other	64 (4.2)	149 (3.1)
Died	208 (13.6)	562 (11.8)

Abbreviation: ICU, intensive care unit.
[a] For each comparison, the P value was less than .001.

entail collaboration among bedside clinicians and off-site support team personnel. The association of lower mortality and shorter length of stay at an academic medical center implies that there are benefits of tele-ICU care beyond providing bedside intensivist expertise to ICUs. It is unique because it attributes the association of the intervention with lower mortality to best practice adherence and decreased complication rates targeted by the intervention.

The tele-ICU intervention changed the way our institution promoted adherence to critical care best practices that are widely accepted as improving outcomes.[8] For example, tele-ICU tools were developed to provide real-time auditing and reconciliation. The tele-ICU intervention was incremental and applied after checklist-based and traditional education-based programs had been used that targeted these same practices. The new care processes that did not primarily involve these best practices, including timely and consistent responses to alarms[4] and intensivist case involvement,[30,31] also were part of the intervention. The procedures used before and after the intervention are detailed in Table 1. We found that implementation of these new processes, made possible by the tele-ICU intervention, was associated with significantly higher rates of best practice adherence and lower rates of preventable complications than the educational outreach and checklist-based reminders that we had used before the tele-ICU intervention and were reported by others.[17] We used mediation analysis to estimate the portion of the association of the intervention with lower mortality that could be attributed to best practice and complication measures. The contributions of best practice and complication measures were significant in these analyses and explained between 25% and 30% of the association for the intervention. Because significant associations remained after adjustment for best practice and complication measures, we performed additional exploratory analyses.

Studies reporting higher mortality for ICU patients admitted at night[29] suggested the hypothesis that part of the lower mortality and shorter length of stay may be attributable to having a rested on-duty intensivist to assist with the creation of care plans and to monitor the initial progress of patients admitted at night using tele-ICU workstations and tools. We found larger associations of the tele-ICU intervention for patients admitted during the nighttime than those admitted during the daytime, suggesting that intensivist care plan review of off-hours cases was an important contributor to the association of the intervention with lower mortality and shorter lengths of stay observed for this study. These findings are consistent with studies that associate better outcomes with higher levels of intensivist involvement[30] and intensivist-directed care.[31]

Involvement of the tele-ICU intensivist also was associated with more cases being managed with noninvasive ventilation and lower use of conventional mechanical ventilation. We speculate that the use of noninvasive

ventilation increased when emergency department physicians perceived that patients responding favorably to noninvasive ventilation could continue to be managed safely with this approach due to the additional surveillance by the tele-ICU team.

We also explored how the tele-ICU intervention functioned with regard to the responses to alerts and alarms for episodes of physiological instability. Although we found that bedside clinicians responded to most episodes of physiological instability without prompting from the off-site team an average of 1.7 times per patient per day, the tele-ICU team prompted the bedside team when the timeliness of response was deemed to be unsafe. Taken together with studies associating better outcomes for critically ill adults receiving earlier interventions like antimicrobials[32] and resuscitation for sepsis,[7] these findings suggest that earlier responses are an additional mechanism by which tele-ICU programs can be associated with better outcomes.

One explanation for why some studies have failed to detect significant associations for their tele-ICU interventions is that most reported low rates of collaboration among tele-ICU and bedside physicians (34%-36%),[33,34] and likely did not involve the tele-ICU team in case sign out, collaborative review of bedside practices, or initial responses to alarms. We speculate that bedside and off-site team collaboration is an important determinate of favorable associations of a tele-ICU intervention with outcomes. This hypothesis is supported by the observation that studies that failed to detect significant favorable tele-ICU associations with outcomes included a pathway for bedside physicians to decline participation of the off-site team in patient care, while our workflow processes and other studies reporting significant favorable associations with outcomes for a tele-ICU intervention[20,35-37] did not provide an opt-out pathway.

Lower lengths of stay for tele-ICU group cases was not related to shifting patients to the chronic care system; rather, patients in the tele-ICU group had lower rates of complications, recovered more quickly, and were significantly more likely to be discharged to their homes than patients in the preintervention group. These findings suggest that critical care programs that implement processes that increase adherence to best practice, lower rates of complications, shorten response times to alerts and alarms, and support early intensivist case involvement will provide better care at a lower cost. Our study suggests that the introduction of a tele-ICU program that collaborates with and supports bedside clinicians is one way to accomplish these aims.

This study has important limitations and reports associations rather than cause and effect relationships. The fact that this is a single academic medical center study should be taken into account when considering its generalizability. Our study design was not a prospective, randomized, and blinded trial with its inherent protections against heterogeneity among the groups; some differences were detected among the study participants. Nevertheless, because this approach does not exclude heterogeneous patients, it has the potential to be more reflective of outcomes achieved in actual practice than those observed in many randomized controlled trials. With respect to differences in acuity between the 2 groups, we believe that they were due in part to the staggered implementation of the tele-ICU intervention and to higher rates of transfer of higher acuity medical cases from outside hospitals for the tele-ICU group; however, these differences could also be due to other unidentified factors. We also were aware that the effects of our educational outreach over time could have been mistaken for interventional effects. However, when we investigated this possibility, we learned that our findings persisted and were robust with regard to confounding by secular trends (details are provided in the eSupplement at http://www.jama.com).

We detected significant tele-ICU intervention effects both in time factor–adjusted analyses and in interrupted time-sequence analyses. In addition, comparison of concurrent surgical ICU cases revealed better outcomes for those managed using tele-ICU resources than for cases managed without them. The reduction in unadjusted hospital mortality did not reach statistical significance but generated a statistically significant and substantial adjusted OR. The major driver of the difference after adjustment was the higher acuity scores that we observed for patients in the tele-ICU group. We investigated the possibility that the association was only due to differences in acuity score or case mix by performing an analysis of cases matched on these attributes and found significant differences associated with the tele-ICU intervention that could not be attributed to acuity or case mix.

Implementation of a tele-ICU program has challenges that are distinct from those of instituting a clinical practice guideline or participation in a clinical trial. The changes in ICU process that were associated with lower hospital mortality and shorter lengths of stay were linked to a high rate of program acceptance by our ICU community. Our approach to implementation included features that are widely accepted for quality improvement, including being focused on patient-centered outcomes, having strong executive support, and targeting changes that were known to improve outcomes. It also included aspects that are relevant to interdisciplinary care, including robust participation of all critical care disciplines in the planning and implementation phases and a process[10] that empowered local leaders to define critical care best practices.

CONCLUSIONS

In conclusion, an adult tele-ICU intervention at an academic medical center that had been previously well staffed with a dedicated intensivist model and had robust best practice programs in place before the intervention was associated with lower mortality and

shorter lengths of stay. Only part of these associations could be attributed to following best practice guidelines and lower rates of preventable complications. This suggests that there are benefits of a tele-ICU intervention beyond what is provided by daytime bedside intensivist staffing and traditional approaches to quality improvement such as the process changes presented in Table 1.

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Author Contributions: Dr Lilly had full access to all of the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.
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Online-Only Material: The eSupplement, eReferences, eTables 1-8, and the eFigure are available at http://www.jama.com.

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