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ICU Telemedicine Program Financial Outcomes

Craig M. Lilly, MD, FCCP; Christine Motzkus, MPH; Teresa Rincon, RN, BSN; Shawn E. Cody, PhD, MSN/MBA, RN; Karen Landry, BS; and Richard S. Irwin, MD, Master FCCP; for the UMass Memorial Critical Care Operations Group

BACKGROUND: ICU telemedicine improves access to high-quality critical care, has substantial costs, and can change financial outcomes. Detailed information about financial outcomes and their trends over time following ICU telemedicine implementation and after the addition of logistic center function has not been published to our knowledge.

METHODS: Primary data were collected for consecutive adult patients of a single academic medical center. We compared clinical and financial outcomes across three groups that differed regarding telemedicine support: a group without ICU telemedicine support (pre-ICU intervention group), a group with ICU telemedicine support (ICU telemedicine group), and an ICU telemedicine group with added logistic center functions and support for quality-care standardization (logistic center group). The primary outcome was annual direct contribution margin defined as aggregated annual case revenue minus annual case direct costs (including operating costs of ICU telemedicine and its related programs). All monetary values were adjusted to 2015 US dollars using Producer Price Index for Health-Care Facilities.

RESULTS: Annual case volume increased from 4,752 (pre-ICU telemedicine) to 5,735 (ICU telemedicine) and 6,581 (logistic center). The annual direct contribution margin improved from $7,921,584 (pre-ICU telemedicine) to $37,668,512 (ICU telemedicine) to $60,586,397 (logistic center) due to increased case volume, higher case revenue relative to direct costs, and shorter length of stay.

CONCLUSIONS: The ability of properly modified ICU telemedicine programs to increase case volume and access to high-quality critical care with improved annual direct contribution margins suggests that there is a financial argument to encourage the wider adoption of ICU telemedicine.

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KEY WORDS: case volume; costs; direct contribution margin; processes of care; revenue

ABBREVIATIONS: ACO = Accountable Care Organization; CC = complication or comorbidity code; CPG = clinical practice guideline; DRG = diagnosis-related group; LOS = length of stay; MCC = major complication or comorbidity code

AFFILIATIONS: From the Department of Medicine (Drs Lilly and Irwin), and the Departments of Anesthesiology and Surgery (Dr Lilly), University of Massachusetts Medical School; the Clinical and Population Health Research Program (Dr Lilly and Ms Motzkus); the Graduate School of Biomedical Sciences (Dr Lilly); UMass Memorial Health Care (Dr Cody and Ms Landry); the Graduate School of Nursing Sciences (Dr Irwin); and the Department of Nursing (Ms Rincon and Dr Cody), UMass Memorial Medical Center, Worcester, MA.

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CORRESPONDENCE TO: Craig M. Lilly, MD, FCCP, Department of Anesthesiology and Surgery, University of Massachusetts Medical School, UMass Memorial Medical Center, 281 Lincoln St, Worcester, MA 01605; e-mail: craig.lilly@umassmed.edu

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Understanding the costs and benefits of establishing an ICU telemedicine program is key for defining the role of this evolving technology for increasing access to efficient, high-quality, and safe adult critical care. To date, many studies of ICU telemedicine programs have associated implementation with shorter length of stay (LOS)[1-3] and have also identified substantial implementation and operational costs.[4] Analyses of health-care economic efficiency (health improvement per dollar expended) based on financial information that is less detailed than that in this report have found ICU telemedicine programs to be cost effective for most implementations and cost saving for some.[5] The overarching aim of this study was to better define the costs of implementing an ICU telemedicine program and to identify the functional aspects that increase access to critical care and the elements that limit direct care costs. Identification of these aspects allows those considering implementation to understand the financial costs and benefits of specific ICU telemedicine program elements and is preparatory to studies that link costs to health outcomes. Published reports have focused on the ability of ICU telemedicine programs to increase rates of adherence to consensus ICU best practices, to provide intensivist workstation assisted real-time care plan reviews,[6] and to ensure timely responses to alerts and alarms.[3] Introduction of telemedicine support for best practice adherence has been associated with lower rates of critical-care complications and shorter LOS.[6,7] This report extends these patient-level aspects to include population management tools designed to increase access to critical care. Because ICU telemedicine program logistic support increased case volume for our community hospitals,[8] we suspected that the addition of logistic center functions could increase access to academic medical center services. The intervention was designed to increase functional ICU capacity by identifying and remediating impediments to timely ICU admission and discharge for a system with ICUs that were often limited by lack of bed availability. We sought to test the hypothesis that ICU telemedicine modified to serve as a logistics center and to support quality-care standardization projects is associated with increased case volume and improved financial outcomes.

Detailed reports on the impact of ICU telemedicine programs on case volume, revenue, and per-case costs in the context of program-related costs have not been widely available. The financial perspective for the primary analyses was that of the sponsoring medical center or health-care system. Detailed secondary analyses elucidate the temporal links of implementation elements, including ICU telemedicine, logistic center functionality, and care-standardization project aspects of ICU telemedicine implementation, with access to critical care measured as case volume and direct costs of providing critical care.

Methods

Study Design and Patients

This study identified a consecutive case cohort of 51,203 subjects selected as summarized in Figure 1. The primary outcome of this before and after study of an ICU telemedicine intervention was the change in the annual direct contribution margin defined as the aggregated net case revenue minus direct costs (including the operating costs of the ICU telemedicine program), which is a corporate financial construct used to describe the performance of a single product or operating unit. Secondary outcomes included changes in case volume, annual per-case revenue (ie, annual revenue per hospitalization), annual net revenue (revenue after contractual adjustments), per-case and total direct costs, diagnosis-related group (DRG) weight (also known as case mix index), hospital LOS, and the time needed to recover the initial capital investment. Detailed analyses related changes of these financial metrics to elements of the ICU telemedicine program implementation, including ICU telemedicine, logistic center functionality, and care-standardization project aspects. Outcomes were compared between three groups of patients that varied with respect to the intervention elements detailed in Table 1 and summarized in Figure 2B. The *pre-ICU telemedicine group* provided information about financial performance using guidelines without electronic support. A detailed description of this period appears in e-Appendix 1. The *ICU telemedicine group* allowed assessment of the effects of best practice, intensivist case review, and response times to ICU telemedicine system alerts—elements that changed at the time of ICU telemedicine implementation (Philips HealthTech).[6] The ICU telemedicine with logistic center support group *(logistics center group)* also reflected the effects of 51 care-standardization and quality-improvement projects that we classified into four domains: patient experience, financial sustainability, patient-care redesign, and integrated safe high-quality care (Fig 2B, e-Appendix 2, and e-Fig 1). The relation of these groups to calendar time is presented in Figure 2A.

The study was conducted in seven adult ICUs on two campuses of an 834-bed academic medical center. Before implementation of the ICU telemedicine program, a novel critical care governance model[9] was used to achieve interprofessional consensus on standard critical-care practices. The ICU telemedicine group added real-time auditing to a nonelectronic standardized daily goal sheet approach to encouraging best practice adherence (Table 1, e-Appendix 1).[6] Telemedicine ICU implementation added off-hours real-time care plan reviews by a board-certified intensivist who used a standardized workstation equipped with an electronic early detection system and audiovisual links to patients and their ICU nurses. This system enabled the real-time delivery of evaluation and management services by off-site providers.[3]

To provide a broader view of financial performance, this study included cases from before and after the previously reported clinical outcomes

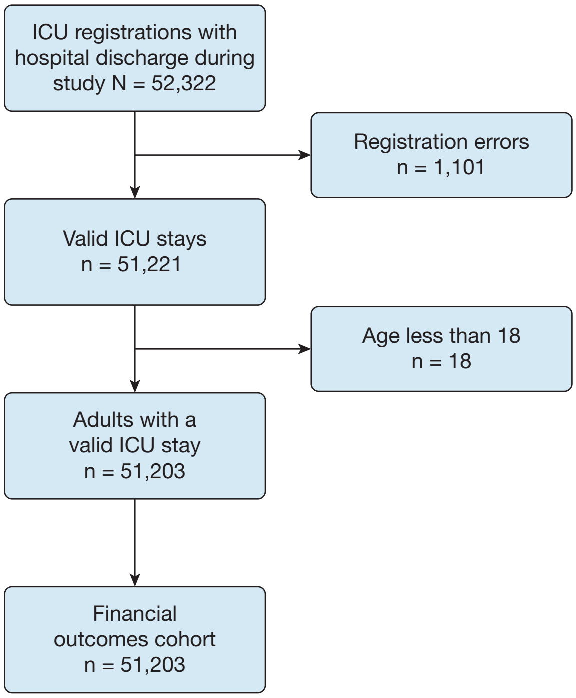

Figure 1 – *Selection of patients and study exclusions.*

study (Fig 2A, e-Fig 1).[6] All patients 18 years of age or older who were cared for in a study ICU and discharged from the hospital between January 1, 2004 and May 31, 2007 from an ICU that did not have ICU telemedicine support were included in the pre-ICU telemedicine group; those discharged between June 1, 2007 and May 31, 2009 from an ICU that had ICU telemedicine support were included in the ICU telemedicine group; and those discharged between January 1, 2010 and May 31, 2013 from an ICU that had logistic center support were included in the logistic center group (Fig 2A).

Measurements

Clinical and financial information was extracted, transferred, and loaded from electronic medical records or was transcribed from hard copy medical records and individually verified as previously reported.[6] Financial data were collected for each hospital day using an activity-based microaccounting method.[10] Costs were adjusted to 2015 US dollars using the US Producer Price Index for Health-Care Facilities.[11]

Interventions

A detailed comparison of the process differences among the groups is presented in Table 1. The financial outcomes study started on January 1, 2004 with a stabilization of practice phase for the pre-ICU telemedicine group that included the preintervention group of our ICU telemedicine clinical study, which reported patient-level quality process metrics and clinical outcomes.[6] This was followed by graded implementation of logistic center functions, designated as "transition" in Figure 2B (orange bar). The timing of implementation of care-standardization and quality-focused projects is summarized in Figure 2B (green bar) and detailed in e-Appendix 2 and e-Figure 1. The temporal relations of the ICU telemedicine, logistic center, and care-standardization aspects of the intervention to financial outcomes are presented in Figure 3. The pre-ICU telemedicine group included patients with visits during the time that interprofessional task forces created and implemented clinical practice guidelines (CPGs) to standardize care in a nonelectronic and unaudited format (Fig 2B [red bar], e-Appendix 1). The telemedicine program included electronic monitoring and reporting tools for each of these CPGs. The clinical study focused on intervention elements that provided redundancy for predefined critical-care delivery processes, including real-time review of initial care plans, auditing of bedside provider responses to abnormal laboratory values and alarms of evolving instability from bedside monitors, and real-time interactive audits of adherence to critical-care best practices.[3] Following completion of the clinical outcomes study, logistic center functions were added in a stepwise manner. After October 1, 2007, patients admitted to three medical ICUs had their ICU team assignments made by the telemedicine intensivist. A dedicated transfer request call line was added on November 21, 2007. After January 1, 2008, the telemedicine team also managed admission assignments for one surgical ICU and coordinated ICU admissions through collaboration with a community hospital ED. After January 1, 2009, the logistic center intensivist managed the off-hours surgical, trauma, and neurosciences unit patient teams and bed assignments, and after October 1, 2010, the ICU telemedicine team managed team and bed assignments for all noncardiovascular adult critically ill patients. Logistic support included managing admission request communications, admitting patients with a medical diagnosis to unused space in surgical ICUs and vice versa, and identifying and discharging patients who no longer required critical-care services. Quality- and flow-based activities included verifying source clinical information, updating complete and correct active diagnosis lists, reviewing radiological studies, and facilitating communication with specialists.

Implementation of the ICU telemedicine program provided access to data that enabled the identification of opportunities and the implementation of 51 quality- and care-standardization projects grouped by domain (patient experience, financial sustainability, patient care redesign, and integrated safe high-quality care) (e-Appendix 2, e-Fig 1).

Statistical Methods

Descriptive statistics were derived for continuous variables, and univariate comparisons between groups for continuous variables were made using the Mann-Whitney *U* test or the Student's *t* test. Comparisons between groups for categorical variables were made by logistic regression, Kruskal-Wallis analysis of variance, or the Fisher's exact test or χ^2 test. Linearity was assessed by linear regression. Changes over time were analyzed using the χ^2 test for trend or by general linear mixed models[12] using restricted estimation by maximum likelihood. Type 3 F tests of effects were used to determine the significance of the contribution of predictors to each model for continuous variables, and minimum deviance was used to select the best overall fitting model. All *P* values were calculated using two-sided tests, and values ≤ .05 were considered statistically significant. All statistical analyses were conducted using SAS, version 9.3 (SAS Institute).

Results

The demographic characteristics of the study groups are presented in Table 2. Age and sex characteristics were similar between the groups. In accord with our previous report of the clinical outcomes of this implementation,[6] the ICU telemedicine and logistic center groups had

TABLE 1] Comparison of ICU Processes With an ICU Telemedicine Intervention, Addition of Logistic Center Function, and Implementation of Quality-Care Standardization Projects

Variable	Pre-ICU Telemedicine	ICU Telemedicine	Logistic Center
Bedside monitor alarms	All patients	All patients	All patients
Daily goal sheet	Paper	Electronic	Electronic
After-hours intensivist case review	Telephone for most patients	Workstation assisted for all patients	Workstation assisted for all patients
Case reviews initiated by an intensivist	Rarely	All patients	All patients
Off-hours intensivist care review includes review of EMR and visualization of radiographic images	Rarely	All patients	All patients
Physiological trend alerts	Telephone call from laboratory staff	Real-time electronically monitored by ICU telemedicine team	Real-time electronically monitored by ICU telemedicine team
Abnormal laboratory value alerts	Telephone call from laboratory staff	Real-time electronically monitored by ICU telemedicine team	Real-time electronically monitored by ICU telemedicine team
Real-time review of responses to alerts and alarms	Not available	Performed by ICU Telemedicine	Performed by ICU Telemedicine
Real-time nurse manager best practice auditing	Not available	All patients	All patients
Off-site team rounding	Not available	All patients	All patients
Electronic monitoring of protocol adherence	Not available	All patients	All patients
Real-time telemedicine team best practice auditing	Not available	All patients	All patients
Off-hours intensivist care review includes interaction with the patient, nurse, and others using audio and video links	Not available	All patients	All patients
Off-hours intensivist care review includes following responses to treatments	Multiple phone calls are made sporadically	ICU Telemedicine team follows therapeutic responses for all patients	ICU Telemedicine team follows therapeutic responses for all patients
ICU admission and discharge decisions negotiated with each ICU team	All patients	Some patients	Rarely
Central management of admission and discharge process	Not available	Some patients	All patients
Quality-care domain:			
Patient-care redesign	None	6 projects	16 projects
Financial sustainability	None	3 projects	14 projects
Patient experience	None	2 projects	5 projects
Integrated, safe, and high-quality care	None	0 projects	16 projects

EMR = electronic medical record.

significantly higher Acute Physiology and Chronic Health Evaluation (APACHE) scores than the pre-ICU telemedicine group. These groups also had a significantly greater proportion of patients with medical APACHE IV admission diagnoses and a significantly smaller proportion of patients with surgical APACHE diagnoses than did the pre-ICU telemedicine group. The ICU telemedicine and logistic center groups had a greater frequency of respiratory and infectious diseases and fewer circulatory system classified diagnoses than did the pre-ICU telemedicine group. Significant stepwise increases in the proportion of cases that had documentation supporting an independently ascertained classification of a comorbidity or complication code (CC) or major complication or comorbidity code (MCC) were observed for the ICU telemedicine and the logistic center groups compared with the pre-ICU telemedicine group (Table 2).

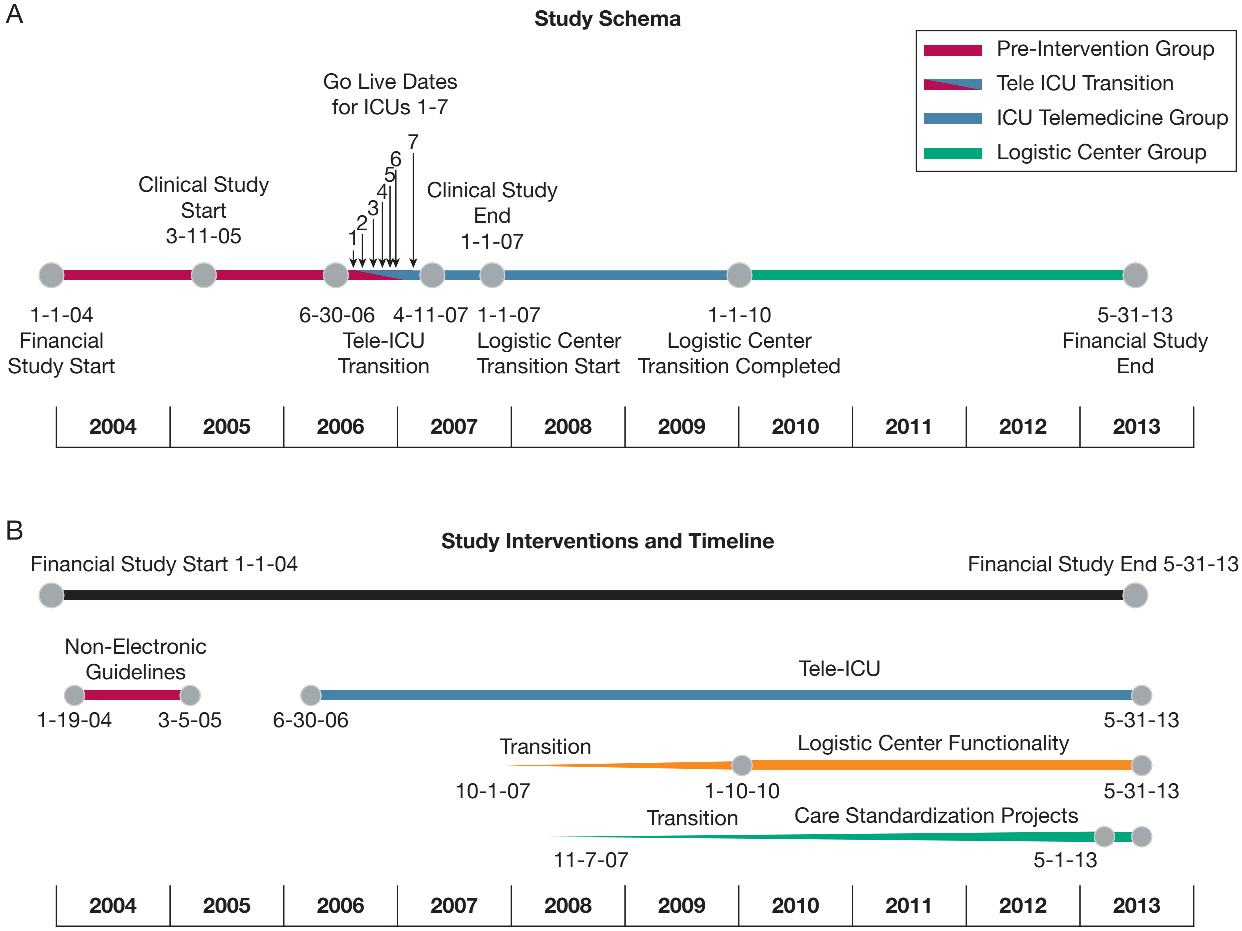

Figure 2 – *A, Study schema with representation of the pre-ICU telemedicine group (red), ICU telemedicine group (blue), and logistic group (green). The period in which some ICUs had telemedicine support, whereas others did not, is marked in blue and red with the go-live date for each ICU marked with an arrow at the times designated by the timeline in B. B, Study interventions. The study start and end dates are connected with a black line. ICU Best Practice Task Force activities that were preparatory to our clinical outcomes study are designated with the red line and are detailed in e-Appendix 1. No new task force or quality improvement interventions were made during the clinical outcomes study period. The start and end dates of the clinical outcomes study and the transition to logistic center dates are designated with a blue line. The time during which care-standardization and quality-improvement projects were implemented is designated with a green line. Detailed descriptions of the timing of individual projects appear in e-Appendix 2.*

The total annual direct contribution margin, total annual revenue, revenue per case (revenue per hospitalization), and annual case volume of the ICU telemedicine group were substantially greater than those of the pre-ICU telemedicine group, which in turn were greater for the logistic center group than for the ICU telemedicine group (Table 3). The temporal relationships of the changes in annual case volume, per case revenue, hospital LOS, and direct costs to implementation elements are presented in Figure 3. The trends of financial outcomes over time make it clear that the changes that were associated with the ICU telemedicine and logistic center aspects of the ICU telemedicine program implementation were sustained.

Implementation of the ICU telemedicine center and the addition of logistic center functions were associated with significant and incrementally shorter durations of hospital LOS that were of similar magnitude to those of our prior reports (Table 3).[3,6] Annual case volume was 4,752 for the pre-ICU telemedicine group, 5,735 for the ICU telemedicine group, and 6,581 for the logistic center group (a 38% increase over baseline) (Fig 3B, Table 3). Stepwise changes of case volume were noted at the time of ICU telemedicine implementation and with the addition of logistic functions to the ICU telemedicine support center (Fig 3B). Analyses revealed a strong linear relationship of ICU telemedicine center admission request call volume and hospital discharge case volume (linear regression-adjusted correlation coefficient $= 0.98$; $P < .001$) (e-Fig 2). The tightness of this association is also evident from plots of call and case volume (e-Fig 3).

Average annual case revenue after adjustment for inflation was $31,710 for the pre-ICU telemedicine group, $38,429 for the ICU telemedicine group, and

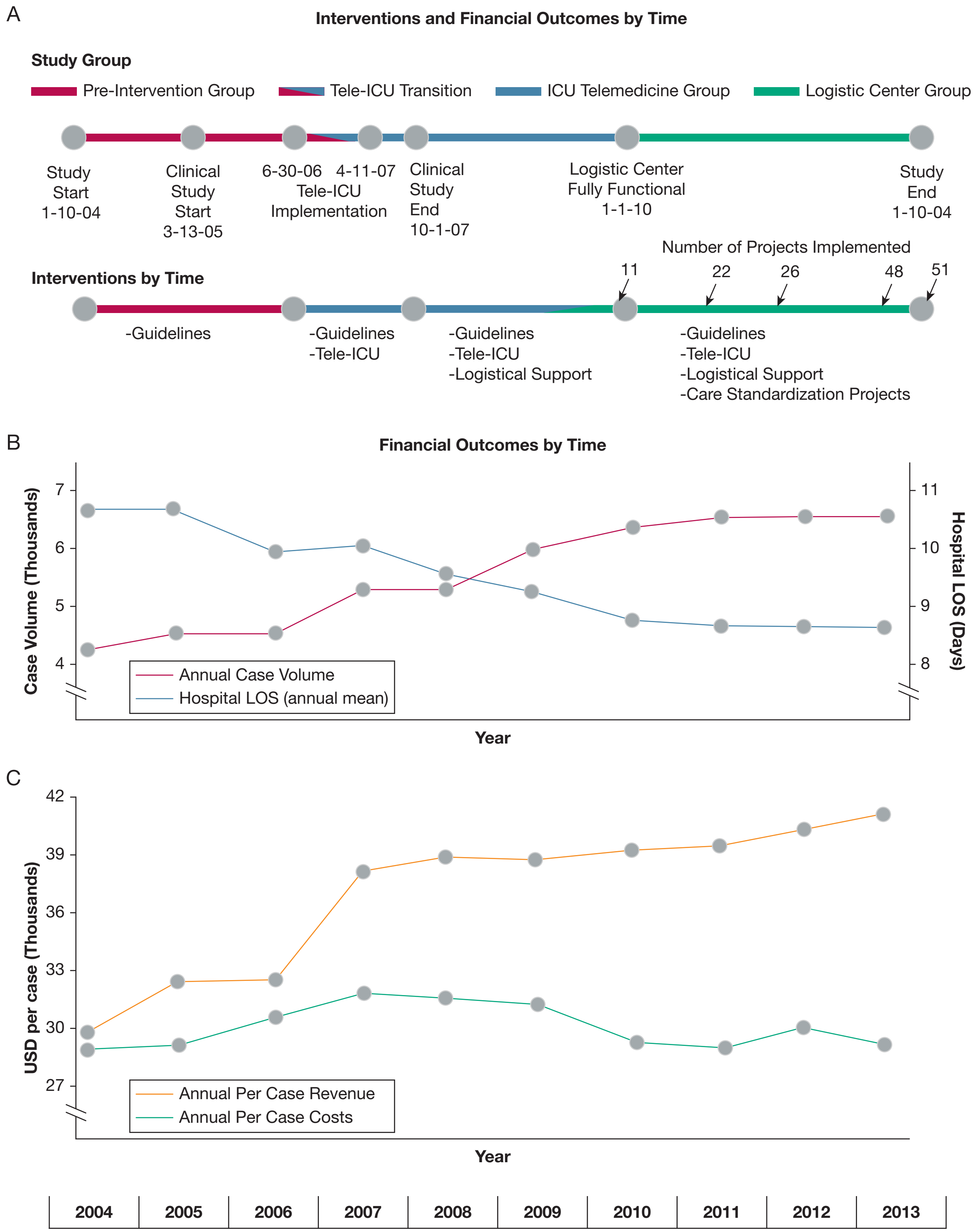

Figure 3 – *A, Relation of study interventions to financial outcomes. The study groups are indicated by color on the top bar. The pre-ICU telemedicine group is indicated by the red bar, the ICU telemedicine group by the blue bar, and the logistic center group by the green bar. The time in which some ICUs had telemedicine support, whereas others did not, is represented by the blue-red bar. The bar below presents the times of the interventions. The pre-ICU telemedicine group task forces are represented by the red bar, and the period in logistic center function was added in a graded manner is represented by the blue bar. The green bar defines the times in which care-standardization projects were implemented as detailed in Figure 2B, Table 2, and e-Appendix 1. The cumulative numbers of implemented care-standardization projects are presented at the time designated by the arrows. B, Case volume is plotted in red, and mean annual hospital LOS is plotted in red as a function of time and in relation to intervention bundle elements. C, Inflation-adjusted annual case revenue is plotted in orange as a function of time, and annual direct costs are plotted in green as a function of time. The difference between annual per-care direct costs and revenue is per-case direct margin. Direct cost and revenue plots are presented in relation to intervention bundle elements. LOS = length of stay.*

TABLE 2] Patient Characteristics by Study Group

Variable	Pre-ICU Telemedicine (n = 14,257)	ICU Telemedicine (n = 14,552)	Logistics Center (n = 22,394)
Age, mean, SD	62.2 ± 17.2	62.4 ± 17.1	62.7 ± 17.4
Female sex, No. (%)	5,995 (42.1)	6,190 (42.5)	9,871 (44.1)
APACHE IV score, mean, SD (No. with valid scores)	46.0 ± 22.3 (1,149)	61.0 ± 29.4[a] (13,841)	60.3 ±27.7[b] (18,506)
APACHE IV scores for medical patients, mean, SD (%)	50.7 ± 23.5 (43.1)	63.9 ± 29.9[a] (54.9)	62.3 ± 28.2[b] (59.4)
APACHE IV scores for surgical patients, mean, SD (%)	42.8 ± 20.8 (56.9)	57.6 ± 28.6[a] (45.1)	57.5 ± 27.0[b] (40.6)
DRG weight, median (IQR)	2.37 (1.27-3.62)	1.91 (1.37-4.10)[a]	1.91 (1.44-3.78)[a]
CC or MCC codes, % of cases	30.6	55.5[a]	62.8[a,b]
DRG group, No. (%)			
Circulatory system	3,224 (27.4)	3,803 (30.0)	5,351 (29.5)[b]
Respiratory system	1,315 (11.2)	1,513 (12.0)	2,805 (15.4)[b]
Infectious diseases	264 (2.3)	1,150 (9.1)[a]	2,634 (14.5)[a,b]
Digestive system	819 (7.0)	1,010 (8.0)[a]	1,777 (9.8)[a]
Connective tissue and musculoskeletal system	1,542 (13.1)	956 (7.6)[a]	745 (4.1)[a,b]

APACHE = Acute Physiology and Chronic Health Evaluation; CC = complication or comorbidity code; DRG = diagnosis-related group; IQR = interquartile range; MCC = major complication or comorbidity code.
[a]$P < .0001$ compared with the pre-ICU telemedicine group.
[b]$P < .0001$ compared with the ICU telemedicine group.

$39,739 for the logistic center group (a 25% increase over baseline). The sharp rise in per-case revenue (Fig 3B) was contemporaneous with the time of transition to the Medicare MS-DRG reimbursement paradigm and was associated with significant increases in the proportion of cases that were independently coded with a CC or MCC code among cases that used the ICU telemedicine documentation system. To determine whether larger annual per-case revenue was due to factors that affected all payer types or was attributable to changes in the mix of payers, we parsed net case revenue per year by payer. Although we noted increased revenue from managed care-type payers, these analyses also made it clear that annual revenue was larger for all types of payers (e-Fig 4).

Costs per case increased during the first years following the introduction of the ICU telemedicine program, in part due to the operating costs of the ICU telemedicine program (Fig 3C). Annual direct per-case costs for the pre-ICU telemedicine group were $30,044. Annual direct per-case costs that included the operating costs of the ICU telemedicine group were $31,861 and $30,533 for the logistic center group. Over the 10-year study period, direct costs per case increased 1.6% for a workforce with contractually mandated annual increases in labor costs. Cost per case for all inpatient business units other than critical care had substantially larger increases of costs over this period of observation. Larger per-case direct contribution margin and volume have multiplicative effects on financial performance. After accounting for the effects of inflation, we observed a $52.7 million annual improvement in total direct contribution margin for the logistic center group compared with the pre-ICU telemedicine group (Table 3).

Implementing the ICU telemedicine program required updating our medical center electronic infrastructure and bedside monitors, purchasing audiovisual equipment, and upgrading our physical plant with medical center initial capital costs of $7.12 million, as we have previously reported.[8] The $31 million greater annual direct contribution margin that we observed for the ICU telemedicine group compared with the pre-ICU telemedicine group was equal to this capital investment after $2^3/_4$ months of operation (Table 3).

Discussion

The main finding of this study was that implementation of an ICU telemedicine program that improved clinical outcomes[6] was associated with a significantly larger direct contribution margin (net revenue minus direct

TABLE 3] Financial Outcomes by Study Group

Variable	Pre-ICU Telemedicine	ICU Telemedicine	Logistic Center	Change Pre- ICU Tele-Medicine vs ICU Tele-Medicine (%)	Change ICU Tele-Medicine vs Logistic Center (%)	Change Pre-Logistic Center vs Logistic Center (%)
Total annual revenue	$150,685,920	$220,388,308	$261,521,372	46.3	18.7	73.55
Total annual costs	$142,766,712	$182,719,738	$200,934,975	28.0	10.0	40.74
Total annual direct contribution margin	$7,921,584	$37,668,512	$60,586,397	375.6	60.8	664.83
Hospital LOS, mean, SD	10.4 ± 13.4	9.7 ± 9.3[a]	8.8 ± 8.3[a,b]	−6.7	−9.3	−15.38
Annual case volume	4,752	5,735	6,581	20.7	14.8	38.49
Annual medical cases, mean	2,307	3,127	3,907	35.5	24.9	69.35
Annual surgical cases, mean	2,353	2,589	2,672	10.0	3.2	13.5
Revenue per case	$31,710	$38,429	$39,739	21. 2	3.4	25.32
Direct cost per case	$30,044	$31,861	$30,533	6.0	−4.2	1.63
Direct contribution margin per case[c]	$1,667	$6,568	$9,206	294.0	40. 2	452.00

LOS = length of stay.
[a] $P < .0001$ compared with the pre- ICU telemedicine group.
[b] $P < .001$ compared with the ICU telemedicine group.
[c] Net revenue minus direct costs (including ICU telemedicine program operating costs).

costs including ICU telemedicine program operating costs) than the pre-ICU telemedicine baseline group. Improved operational efficiency allowed recovery of the initial capital costs of the ICU telemedicine program in < 3 months. Improved financial performance measured as direct contribution margin was attributable to a significantly, substantially, and incrementally greater case volume and higher per-case net revenue for the ICU telemedicine and logistic center groups compared with the pre-ICU telemedicine group. Direct costs per case were slightly higher (6%) for the ICU telemedicine group than for the pre-ICU telemedicine group; program reengineering to support logistic center functions and care-standardization projects was associated with 4.2% lower costs per case for the logistic center group compared with the ICU telemedicine group (Table 3).

Improved financial outcomes have been suggested by studies of clinically effective ICU telemedicine program implementations; however, they reported fewer financial details than are available from this study or reported shorter LOS as their metric of care efficiency.[1,3,6,13-17] This study represents an advance in the field because it is based on more detailed financial information generated using activity-based accounting procedures[10] and includes the temporal relations of the implementation of specific program elements to financial outcomes.

Clear knowledge of how an ICU telemedicine logistic center affects case volume is central to understanding why this approach can be effective in the current Accountable Care Organization (ACO) era. We describe the use of an ICU telemedicine logistic center to manage increased requests for ICU services at an academic medical center and the community hospitals[8] that it serves. This approach changed the admission paradigm from having individual physicians accept or decline requests for services to having all medical center and many community hospital service requests managed by a logistic center teleintensivist. This individual was responsible for confirming that ICU services were required and for identifying an available staffed bed and accepting the patient into the care of an appropriate medical center or community hospital ICU physician and team. The telemedicine intervention included communication tools that allowed the off-site intensivist to discharge patients who no longer required ICU services, supported discharge activities of care coordinators and, with the support of the telemedicine pharmacist,[18] intervened to encourage adherence to prescribing best practices. These interventions, which shortened ICU LOS, were also associated with improved mortality outcomes.[6]

The findings of this study, which was designed before passage of the Affordable Care Act, should be interpreted in the context of the subsequent shifts of health-care finance. The increases of per-case revenue that were observed are unlikely to be achieved in the ACO era. Case volume was directly related to facility revenue for most pre-ACO contracts. Nevertheless, we contend that our results can foster an understanding of the potential benefits and costs of telemedicine during the ACO era. Telemedicine can be adapted to more efficiently provide access to high-quality care for larger volumes of critically ill adults. For example, in dealing with increasing requests for adult critical care services, one could use a strategy of providing care more efficiently with telemedicine with existing resources or by building more ICUs. Our results suggest that ICU telemedicine capital costs can compare favorably to the costs of acquiring new ICU beds, and the per-bed operating costs are generally lower than the per-bed costs of off-hours physicians and other operating costs of incremental ICU beds.

The ICU telemedicine intervention combined 24/7 intervention capacity with real-time reports from bedside monitor, laboratory, and discrete data elements from most care notes. ICU telemedicine reporting solutions and direct interventions achieved high rates of ICU best practice adherence, the near elimination of most preventable complications, and significantly shorter LOS.[6] When these solutions were leveraged by an interprofessional ICU governance group,[19] cost per case decreased by reducing the targeted costs, including drug acquisition, transfusion services, and supply costs. Although this finding does support the ACO philosophy that ICU care can be more efficient,[20] it also found that none of the 51 individual care-standardization projects had large effects for most critically ill adults. To achieve financially significant efficiencies, a substantial number of ICU focused projects that have small impacts for most patients or large impacts for some patients may be required. Although efficiencies of care for critically ill adults that are the focus of ACO incentives appear to be difficult to achieve, they are nevertheless achievable through standardization of care facilitated by telemedicine.

Secondary analyses identified several factors that were associated with increased case volume. Such increases for the ICU telemedicine group could be attributed, in part, to greater availability of adult ICU beds made possible by shorter length of ICU and hospital stays.[6] The tight inverse relationship of hospital LOS and case volume (Fig 3B) indicates that bed capacity created by reducing LOS was associated with increased case volume. This suggests that the ICU telemedicine logistic center effectively identified and discharged ICU patients who were no longer critically ill and filled the resulting ICU beds with patients who had active ICU admission requests. Our prior analyses of clinical outcomes[6] and findings from a multicenter study[3] identified factors that were associated with decreased LOS after implementation of an ICU telemedicine program. These factors included shorter provider response times to reports of abnormal laboratory values and alerts of physiological instability and real-time reminders from the ICU telemedicine team that identified and remediated variance of actual practice from ICU best practices.[7] Higher rates of best practice adherence were associated with lower rates of preventable complications and shorter LOS.[6] ICU telemedicine programs also have provided accurate and benchmarked reports of ICU performance using the ICU telemedicine program software. In this study, performance reports were leveraged by a governance structure perceived to be effective by ICU medical directors, nurse managers, and responsible administrators who used them to identify opportunities for care standardization and to efficiently implement quality improvement and financial sustainability projects.[3,21]

This report confirms and extends our understanding of how ICU telemedicine programs can bring value. It links stepwise increments of ICU telemedicine logistic center functions to lower LOS and sustainable increases in case volume. The introduction of standardized processes for managing the admission of critically ill patients allowed for a reduction in the number of calls for referring physicians, the ability to admit patients with medical admission diagnoses to surgical ICUs and vice versa, and the ability to more efficiently discharge patients who were no longer critically ill. These practices impacted care processes that directly affected LOS and ICU volume. It is plausible that the association of the introduction of ICU telemedicine logistic support with increased case volume reflects a causal relationship.

Implementation of the ICU telemedicine program was also associated with increased per case revenue (net revenue after adjustments). A stepwise and sustained increase in per-case net revenue for both medical and surgical cases occurred at the time of implementation of the ICU telemedicine program (Fig 3C). Increased per-case revenue was associated with adoption by all ICU clinical providers of a structured electronic form of ICU documentation that more efficiently captured clinical information required for accurate retrospective independent recording of CC and MCC codes than the unstructured documentation systems that it replaced. These codes mark cases of higher acuity for appropriate reimbursement under the Tax Relief and Healthcare Act of 2006.[22] Higher post-ICU telemedicine implementation case revenue could not be attributed to increased revenue from any one payer, to changes in the mix of payers (e-Fig 4), or to an increase in the proportion of more generously reimbursed surgical cases (Table 3). Slightly higher inflation-adjusted per-case revenue observed after the ICU telemedicine implementation period occurred following the implementation of care-standardization projects (Fig 2B e-Appendix 2).

Annual costs per case were 6.0% higher for the ICU telemedicine group than for the pre-ICU telemedicine group. Higher costs can be attributed to contractually mandated annual increases in labor costs for bedside staff and to the $3.15 million annual operating costs[8] of the ICU telemedicine program. Conversely, program reconfiguration to include logistic center and support care standardization projects was associated with a 4.2% lower direct cost per case. Improved cost structure over time was attributable to logistic center activities and cost reductions related to care-standardization projects that were grouped into four domains: patient experience, patient-care redesign, financial sustainability, and integrated safe high-quality care (Fig 2B, e-Appendix 2, e-Fig 1). The lower costs per case noted for adult ICU cases were not noted for other inpatient medical center operational units; rather, these units noted annual increases in costs.

Reports that were made possible by our ICU telemedicine program enabled our ICU governance structure[9] to support 51 quality-improvement programs (e-Appendix 2, e-Fig 1). Individual projects were designed to have large effects for small numbers of patients or small effects for large numbers of patients. Because none of the projects were designed to have large effects for large numbers of patients, our analyses focused on the cumulative number of projects implemented rather than on the effects of individual projects (Fig 3A, numerical values above the green bar). The temporal relation of project implementation to the reduction of per-case costs supports the view that the cumulative effects of these care-standardization and waste-reduction projects had favorable effects on the costs of providing high-quality critical care.

The largest financial barrier to implementation of an ICU telemedicine program for an integrated delivery network is the initial capital costs.[4,23] We found that implementation of an ICU telemedicine program that standardized key processes of care[3,6] and significantly reduced LOS was associated with a sustained and substantially larger direct contribution margin (Fig 3C, Table 3). The net financial benefits were of sufficient magnitude to offset the initial capital costs of the program in $<$ 3 months.

This study has several important limitations, including those related to its single-center before and after design. The study was conducted at a single medical center with adult ICUs that were near capacity, with requests for adult ICU services that exceeded its capacity (e-Fig 3). ICU telemedicine implementation in a setting with little demand for adult ICU services would not be expected to realize the increased case volume observed in this study; rather, financial benefits would come from reducing expenses. Another important limitation is that the changes of financial reimbursement of the 2010 Affordable Care Act were not evident at the time the preplanned financial analyses for this study were designed in 2006, and this may have led to confounding by secular trends. The competitive nature of health care at that time prevented us from having access to detailed financial information from a similar medical center to allow a difference in a difference study design. Likewise, using community hospitals as control subjects would be problematic because the logistic center directly affected case volume and the acuity of patients condition. We therefore used plots of outcomes over time and models that adjusted for secular trends by including time factors as described in our report of clinical outcomes.[6] In accord with convention for financial outcomes, we used the Producer Price Index to adjust for trends over time, which produced overall results similar to those of other methods and raw outcomes. Finally, we identified these changes of outcomes as specific to critical care by comparing critical-care financial outcomes with other noncritical-care inpatient financial units that did not use logistic center- or telemedicine-supported care optimization processes. Financial outcomes may be different for institutions in other reimbursement environments[24] and particularly for programs that are not able to impact LOS. In addition, programs that derive revenue from providing evaluation and management services to other institutions will have program net revenue that is greater than that reported by this study. Notwithstanding these limitations, this study makes it clear that a properly implemented ICU telemedicine program can increase adult critical-care case volume and improve financial performance by standardizing and expediting adult critical care.

Another important potential limitation of the study is that its presentation of financial outcomes is from the perspective of the sponsoring health-care system, which can obscure benefits to payers and society. Financial impacts of ICU telemedicine programs for payers include costs that integrated delivery networks account for as revenue, costs that regional community hospitals account for as revenue, and embedded capital costs of building and maintaining infrastructure. Although a definitive view of regional outcomes for payers must await future studies, the information in this report is useful for hypothesis generation.

We report here that implementation of the ICU telemedicine program was associated with a significant increase in the APACHE IV acuity scores among patients admitted to an academic medical center ICU. We previously reported that ICU telemedicine program implementation was associated with lower ICU mortality and LOS for these patients with more acute conditions.[6] We attribute the selective admission of more acute complex cases to academic medical center ICUs to ICU telemedicine center logistic center functionality, because it also diverted less complex cases for retention at lower-cost regional community hospitals. Indeed, we noted and reported that ICU telemedicine implementation was associated with higher case volume at our regional community hospitals that used ICU telemedicine logistic support.[8]

Comparison of the axes in e-Figure 3 indicates that there were > 1,000 ICU annual admission request communication episodes (each episode reflecting all calls for a single patient visit) that did not result in an admission to an academic medical center ICU. The real-time consultative advice of the ICU telemedicine clinicians sometimes allowed cases that did not require critical care services to be managed outside of an adult ICU. Many other requests for ICU admission were redirected to community hospital ICUs, in which our previous study found that unused capacity of each smaller community hospital ICU was able to provide for approximately 250 incremental cases per year at per-case costs to payers that were $10,000 less than for equivalent cases cared for at an academic medical center.[8] Applying these figures to the current study period, it can be estimated that the 986 incremental patients per year who were referred by our ICU telemedicine logistics center to community hospitals for care and retained until discharge with ICU telemedicine center support correspond to annual savings to payers of $9.8 million that would have otherwise borne the costs of providing care at the higher-cost academic medical center ICUs of our integrated delivery network.

We also found that ICU telemedicine programs were associated with increased capacity of existing academic medical center ICU infrastructure. Comparison of the case volume of the logistic center group to that of the pre-ICU telemedicine group reveals an annual incremental volume of 1,829 cases discharged. It can be conservatively estimated that this volume would have required 25 additional academic medical center ICU beds based on an actual ICU LOS of $4^1/_2$ days,[6] an ICU bed occupancy rate of 90%, and admission volume evenly distributed over the year. The initial capital costs for managing this capacity by converting non-ICU beds or building new beds can be estimated at $30 to $60 million not including annual operating and maintenance costs.

The findings of this study suggest that the total cost of providing care for critically ill adults with highly acute conditions may be lower when logistics center functions that allow for more efficient use of regional ICU resources are added to ICU telemedicine center consultative services. The $8.6 million increase in payer costs (ICU telemedicine vs logistic center group of $1,310 per case for 6,581 cases) (Table 3) that were noted after logistics center functions were added are less than the $9.8 million avoided costs (986 annual cases at $10,000 each) achieved by managing less complex cases at community hospitals and the incremental capital costs of building the capacity to manage them at the medical center. These considerations lead to the hypothesis that total costs of care may be lower when logistics center triage targets highly acute complex cases to academic medical quaternary centers and encourages the retention of less acute complex cases at community hospitals that are closer to the patient's home.

Conclusions

In summary, implementation of an ICU telemedicine program at an academic medical center had favorable clinical outcomes and financial benefits that substantially exceeded program capital and operating costs.

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Collaborators: Nicholas A. Smyrnios, MD; Stephen O. Heard, MD; Timothy A. Emhoff, MD; Peter H. Bagley, MD; Cheryl Lopriore; Greg Wongkam; J. Matthias Walz, MD; Michelle M. Fernald, MS, RN; Debra Lynn Svec, RN; Nam Heui Kim, MD; Nancy Simon, MS, RN; Bruce J. Simon, MD; Karen Shea, MS, RN; Wiley R. Hall, MD; Craig Smith, MD; Cathy Pianka, MS, RN; Michelle O'Rourke, DNP, ACNP-BC; Khaldoun Faris, MD; Scott E. Kopec, MD; Karen Landry; Maichi Tran, PharmD; Paulo Oliveira, MD; Luanne Hills, RRT; and Cynthia T. French, PhD, ANP-BC.

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Additional information: The e-Appendix and e-Figures can be found in the Supplemental Material section of the online article.

References

1. Wilcox ME, Adhikari NK. The effect of telemedicine in critically ill patients: systematic review and meta-analysis. *Crit Care*. 2012;16(4):R127.
2. Lilly CM, Zubrow MT, Kempner KM, et al. Critical care telemedicine: evolution and state of the art. *Crit Care Med*. 2014;42(11):2429-2436.
3. Lilly CM, McLaughlin JM, Zhao H, et al. A multicenter study of ICU telemedicine reengineering of adult critical care. *Chest*. 2014;145(3):500-507.
4. Kumar G, Falk DM, Bonello RS, Kahn JM, Perencevich E, Cram P. The costs of critical care telemedicine programs: a systematic review and analysis. *Chest*. 2013;143(1):19-29.
5. Yoo BK, Kim M, Sasaki T, Melnikow J, Marcin JP. Economic evaluation of telemedicine for patients in intensive care units. *Crit Care Med*. 2016;44(2):265-274.
6. Lilly CM, Cody S, Zhao H, et al. 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(21):2175-2183.
7. Kahn JM, Gunn SR, Lorenz HL, Alvarez J, Angus DC. Impact of nurse-led remote screening and prompting for evidence-based practices in the ICU*. *Crit Care Med*. 2014;42(4):896-904.
8. Fifer S, Everett W, Adams M, Vincequere J, Critical care, critical choices the case for tele-ICUs in intensive care. New England Healthcare Institute; Massachusetts Technology Collaborative, Cambridge, MA, 2010: http://www.masstech.org/sites/mtc/files/documents/2010%20TeleICU%20report.pdf. Accessed October 31, 2016.
9. McCauley K, Irwin RS. Changing the work environment in ICUs to achieve patient-focused care: the time has come. *Chest*. 2006;130(5):1571-1578.
10. Cao P, Toyabe S, Kurashima S, Okada M, Akazawa K. A modified method of activity-based costing for objectively reducing cost drivers in hospitals. *Methods Inf Med*. 2006;45(4):462-469.
11. Statistics US Bureau of Labor. Department of Labor, Bureau of Labor Statistics, Producer Price Indexes, 8602 general medical and surgical hospitals, 8011 offices of physicians, 2837 pharmaceutical preparations. Producer Price Indexes, 8602 general medical and surgical hospitals, 8011 officies of physicians, 2837 pharmaceutical preparations. http://data.bls.gov/PDQ/outside.jsp?survey=pd. Accessed October 31, 2016.
12. McLean RA, Sanders WL, Stroup WW. A unified approach to mixed linear models. *Am Stat*. 1991;45(1):54-64.
13. Breslow MJ, Rosenfeld BA, Doerfler M, et al. Effect of a multiple-site intensive care unit telemedicine program on clinical and economic outcomes: an alternative paradigm for intensivist staffing. *Crit Care Med*. 2004;32(1):31-38.
14. Zawada ET Jr, Herr P, Larson D, Fromm R, Kapaska D, Erickson D. Impact of an intensive care unit telemedicine program on a rural health care system. *Postgrad Med*. 2009;121(3):160-170.
15. Willmitch B, Golembeski S, Kim SS, Nelson LD, Gidel L. Clinical outcomes after telemedicine intensive care unit implementation. *Crit Care Med*. 2012;40(2):450-454.
16. Kohl BA, Fortino-Mullen M, Praestgaard A, Hanson CW, Dimartino J, Ochroch EA. The effect of ICU telemedicine on mortality and length of stay. *J Telemed Telecare*. 2012;18(5):282-286.
17. Kohl B, Gutsche J, Kim P, Sites F, Ochroch E. Effect of telemedicine on mortality and length of stay in a university ICU. *Crit Care Med*. 2007;3512(suppl):A22.
18. Forni A, Skehan N, Hartman CA, et al. Evaluation of the impact of a tele-ICU pharmacist on the management of sedation in critically ill mechanically ventilated patients. *Ann Pharmacother*. 44(3):432-438.
19. Irwin RS, Flaherty HM, French CT, et al. Interdisciplinary collaboration: the slogan that must be achieved for models of delivering critical care to be successful. *Chest*. 2012;142(6):1611-1619.
20. Powers BW, Chaguturu SK. ACOs and high-cost patients. *N Engl J Med*. 2016;374(3):203-205.
21. Lilly CM, Fisher KA, Ries M, et al. A national ICU telemedicine survey: validation and results. *Chest*. 2012;142(1):40-47.
22. Kocher RP, Adashi EY. Health policy and the American Taxpayer Relief Act: legislation by extension. *JAMA*. 2013;309(8):777-778.
23. Kruklitis RJ, Tracy JA, McCambridge MM. Clinical and financial considerations for implementing an ICU telemedicine program. *Chest*. 2014;145(6):1392-1396.
24. Nassar BS, Vaughan-Sarrazin MS, Jiang L, Reisinger HS, Bonello R, Cram P. Impact of an intensive care unit telemedicine program on patient outcomes in an integrated health care system. *JAMA Intern Med*. 2014;174(7):1160-1167.