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The Implementation and Outcomes of a Nurse-Run Extracorporeal Membrane Oxygenation Program, a Retrospective Single-Center Study

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OBJECTIVES: Due to a shortage of perfusionists and increasing utilization of extracorporeal membrane oxygenation in the United States, many programs are training nurses as bedside extracorporeal membrane oxygenation specialists (i.e., nurse-run extracorporeal membrane oxygenation). Our objective was to evaluate if a nurse-run extracorporeal membrane oxygenation program has noninferior survival to discharge and complication rates compared with a perfusionist-run extracorporeal membrane oxygenation program. Additionally, to sought to describe increases in extracorporeal membrane oxygenation capacity and the potential for cost savings by implementing a nurse-run extracorporeal membrane oxygenation program.

KEY WORDS: complications; cost savings; extracorporeal membrane oxygenation; nurse; perfusion; survival

Extracorporeal membrane oxygenation (ECMO) is a type of mechanical circulatory life support offered for cardiac and/or respiratory failure that is refractory to conventional medical therapies and devices. Although definitive efficacy data are lacking, the utilization of ECMO in adult patients in the United States has substantially increased in the last decade from 1,830 cases in 2007 to 10,915 in 2019 (1, 2). The costs of using ECMO are high, with in-hospital costs of $42,554–$537,554 per patient in the United States (3). One of the major costs and limitations of ECMO is the availability of perfusionists who have historically assumed the role as bedside ECMO specialists at some centers (i.e., perfusionist-run ECMO).

Despite the increase in ECMO cases and ECMO centers, there has not been commensurate growth in certified perfusionists (**Fig. 1**) (4). There is an estimated predicted shortfall of 200–250 perfusionists per year in the United States in the coming years (5). The increasing utilization of ECMO, high cost of ECMO therapy, and simplification of ECMO devices, combined with the perfusionist shortage, have prompted some centers to have nonperfusion ECMO specialists, such as registered nurses (i.e., nurse-run ECMO) and respiratory therapists, monitor and manage ECMO at the bedside, with perfusionist backup and physician guidance (6). This practice has been endorsed by the Extracorporeal Life Support Organization (ELSO), an international organization that has guidelines for the training and continuing education for ECMO specialists (7). In 2016, a survey of 145 centers found that 59% of ECMO centers used nurses as ECMO specialists with perfusionists providing backup, but further data on outcomes are needed (8).

Our 800+ bed academic institution is a large-volume heart and lung transplant center, which provides the region's comprehensive ventricular assist

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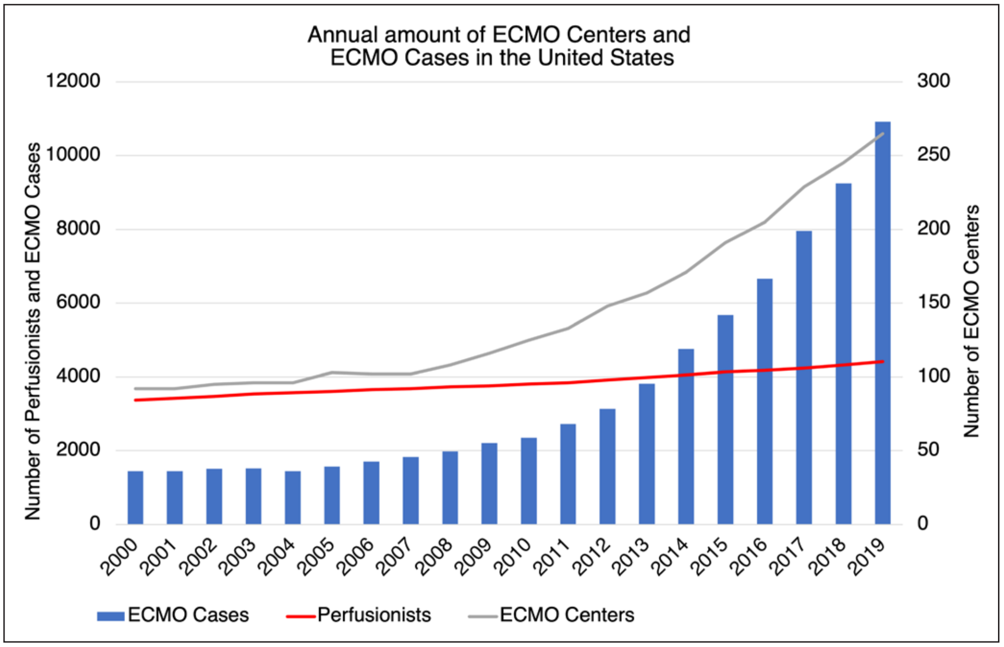

Figure 1. Numbers of perfusionists, extracorporeal membrane oxygenation (ECMO) centers, and ECMO cases in the United States per year according to the American Board of Cardiovascular Perfusion and Extracorporeal Life Support Organization. Although the number of ECMO-capable centers and cases have increased, the number of perfusionists has been relatively stable.

device program, and is the global leader in pulmonary thromboendarterectomy surgery (9). Perfusionists have been the bedside ECMO specialists since 1984 at our institution. However, due to increasing operating room (OR) and ECMO volume, perfusionists' overtime hours have increased significantly, as have staffing costs and burnout rates. Despite the utilization of per diem perfusionists, it has been necessary to delay or even cancel operations because of insufficient perfusionist availability, resulting in lost revenue for the hospital system. Although per diem perfusionists provide essential care, they are expensive and have unpredictable availability. Thus, in 2015, our institution elected to train ICU nurses as bedside ECMO specialists and implement a nurse-run ECMO program.

We describe the process of implementation and maintenance of our nurse-run ECMO program in further detail in the available **supplement** (http://links.lww.com/CCX/A661). It further outlines our program structure (see **Table S2**, http://links.lww.com/CCX/A661), education, and quality improvement measures and the multidisciplinary team approach to ECMO care (**Fig. S1**, http://links.lww.com/CCX/A661). Here, we review the outcomes of our nurse-run ECMO program, including survival to discharge, complications, ECMO capacity, and cost savings when compared with perfusionist-run ECMO. We hypothesized that nurse-run ECMO would have noninferior survival to hospital discharge and complication rates compared with perfusionist-run ECMO.

METHODS

This is a retrospective cohort study from a single tertiary care academic hospital system. Patient records were identified in a previously existing secure local ECMO database. The ECMO database contains data required by the ELSO registry and is maintained by a group of physician and nurse leaders as part of an institutional quality improvement database (1). Authors had full access to the ECMO database. All study and ECMO data were extracted from the electronic health record (Epic Systems, Verona, WI) by the study team. The institutional review board waived the need for informed consent (Project number 190181X).

Patients:

All adult patients (18 yr or older) who were treated with ECMO from January 1, 2017, to December 31, 2019 were included.

Exposure

The nurse-run ECMO program started January 1, 2018. All patients treated with ECMO from January 1, to December 31, 2017, had a perfusionist as the bedside ECMO specialists (perfusionist-run ECMO), whereas all patients treated with ECMO from January 1, 2018, to December 31, 2019, had a nurse as the beside ECMO specialist (nurse-run ECMO). Starting January 1, 2018, there were also substantial changes to the ECMO program (supplement, http://links.lww.com/CCX/A661), including hiring an ECMO coordinator, creation of the ECMO committee, protocolization of ECMO care

(care order sets, anticoagulation protocols, emergency contingency plans, etc.), regular provider and nurse education, and quality improvement measures.

Outcomes

The primary outcome was survival to hospital discharge. Secondary outcomes were ECMO complications. Complications were determined and defined according to the ELSO registry and included both patient (e.g., stroke, bleeding) and equipment factors (e.g., circuit failure) (1, 10). These are further described in the **Figures S3** and **S4** (http://links.lww.com/CCX/A661). ECMO complications were determined by retrospective chart review during perfusionist-run ECMO (2017) and by review of the daily checklist during nurse-run ECMO (2018–2019). ECMO complications-per-patient were calculated and standardized by the number of days each patient was on ECMO (i.e., complications per ECMO day).

Capacity

During the perfusionist-run period, our maximum ECMO capacity was four patients concurrently. During nurse-run ECMO, capacity was determined by the total number of nurses trained as ECMO specialists and the number of patients they could care for simultaneously (i.e., patient-to-nurse ratio). After 6–12 months of experience and competency evaluation, a nurse ECMO specialist could provide care for two ECMO patients simultaneously.

Survival and Complications Statistical Analysis

Descriptive statistics were determined for each variable. The *t* test or Wilcoxon rank-sum test (if distributions are highly skewed) was used for comparing continuous outcomes, whereas the chi-square test was used for comparing categorical outcomes. A two-sided α value of less than 0.05 was considered significant for all analyses. Statistical analysis was performed with SPSS (Version 27.0, IBM, Chicago, IL) and R statistics software (Version 3.5.1, R Core Team, 2019; R Foundation for Statistical Computing, Vienna, Austria).

The primary analysis was noninferiority of survival to hospital discharge during nurse-run ECMO (2018-2019) compared with perfusionist-run ECMO (2017). The generalized estimating equations (GEEs) with an appropriate link function (identity link for continuous, logit link for binary, and log link for count outcomes) was used to determine the effect of our intervention on our primary and secondary outcomes (11). Unlike parametric models such as the parametric generalized linear models, GEE posts no mathematical models for data distributions and thus provides valid inference for a broader class of data distributions (12). For survival to hospital discharge, we used the GEE with the logit link. Our secondary outcome was complications per ECMO day, where we used the GEE with the log link. We used the variance of a Bernoulli distribution as the working variance for the logit link and the variance of a Poisson as the working variance for the log link. The estimates are most efficient if the binary outcome of hospital discharge follows the Bernoulli and/or the count outcome of complications per ECMO day follows the Poisson. Note that we used the term "GEE" to refer to inference based on estimating equations, rather than score equations, to provide robust inference. This term is typically used for longitudinal data analysis, but the inference approach applies to cross-sectional data as well, with the same implications that inference is valid regardless of whether data follow the parametric distribution model upon which the working variance is specified.

For both models, covariates included ECMO configuration (venoarterial or venovenous), Sequential Organ Failure Assessment (SOFA) score, age, body mass index (BMI), and gender. Each analysis had 123 patients. We further performed a secondary analysis with 97 patients due to missing data. This analysis further included length of intubation before ECMO, respiratory ECMO survival prediction (RESP) score, and survival after venoarterial ECMO (SAVE) score as covariates.

Subgroup analysis based on ECMO configuration, venoarterial ECMO, and venovenous ECMO was performed with the same covariates. There were 83 patients included in the venoarterial-ECMO subgroup. A second analysis was performed with 65 of these patients with available data for the including length of intubation and SAVE score covariates. There were 40 patients included in the venovenous-ECMO subgroup. A second analysis was performed with 32 of these patients with available data for the length of intubation and RESP score covariates. All missing SAVE or RESP score and length of intubation data were due to patients transferred from outside institutions with incomplete records.

Cost Analysis

A cost analysis was completed to evaluate the financial differences between staffing a nurse or perfusionist as the ECMO specialist at the bedside. All costs were based on the institutional costs at our Southern California academic medical center. The perfusionist-run ECMO staffing costs in 2017 were determined by totaling the number of ECMO cases (separated by OR and bedside initiation) and the number of hours who patients spent on ECMO. The number of hours that multiple patients were on ECMO in the institution simultaneously was also calculated, as perfusionists are able to oversee up to four ECMO patients simultaneously. The total ECMO patient-hours were then divided into hours that were staffed by the institutional perfusion team and hours that were staffed by per diem perfusionists. The total hours for each were multiplied by the average hourly rates of institutional and per diem perfusionists to obtain the total costs. The OR team was activated for all ECMO cannulations in 2017, and this cost was included as well.

Projected costs for 2018 and 2019 were estimated for continuing the historical system of having perfusionists as the bedside ECMO specialists. Based on the patient census for those years, it was estimated that 20% of the ECMO patient-hours would have been staffed by salaried institutional perfusionists, and 80% of the hours would have been staffed by per diem perfusionists. These projected costs did not include OR activation, as such practice was discontinued after 2017. Subsequently, the majority of ECMO cannulations were done at bedside in the ICU.

Actual costs for nurse-run ECMO in 2018 and 2019 were determined by totaling the number of ECMO cases (separated by OR and bedside initiations) and the number of hours that patients spent on ECMO. In 2018, a nurse ECMO specialist was limited to having only one ECMO patient (i.e., 1:1 patient-to-nurse ratio); thus, the total ECMO hours were multiplied by the average hourly ICU nursing wage. In 2019, with increased experience, nurse ECMO specialists were responsible for up to two patients simultaneously. It was estimated that approximately two third of that time, two ECMO patients would be staffed by one nurse ECMO specialist (i.e., 2:1 patient-to-nurse ratio). The remaining one third of the time, a 1:1 ratio was used, as only one patient was on ECMO at a time. The total hours at 2:1 and 1:1 were added and multiplied by the average hourly nursing wage to determine the total ECMO staffing cost.

We also included initial training costs for the nurse ECMO specialists (56 nurses, 24 hr per nurse) and the experienced ECMO specialist consultant. In 2018 and 2019, additional costs for continuing education, a full time ECMO coordinator, and 24-hour nurse ECMO specialist call coverage were also included. If used, the cost of an OR team was added for ECMO cannulations performed in the OR.

RESULTS

Fifty-six nurses were trained as ECMO specialists in 2017-2018, compared with the 8 perfusionists in 2017. With 56 nurse ECMO specialists by the end of 2019, at a 2:1 patient-to-nurse ratio, our center was able to provide care for up to six ECMO patients at a time. A total of 123 patients were placed on ECMO from 2017 to 2019; all patients were included in our analysis. Patient demographics were similar during perfusionist-run ECMO and nurse-run ECMO, other than BMI, SAVE score, and days of mechanical ventilation before and after ECMO (**Table 1**). In 2017, 29 patients were placed on ECMO with perfusionists as the bedside specialist. From 2018 to 2019, 94 patients were placed on ECMO with a nurse as the bedside specialist (**Table 2**; and **Table S3**, http://links.lww.com/CCX/A661). The median duration of ECMO-per-patient during perfusionist-run ECMO versus nurse-run ECMO was 5.5 and 6 days, respectively.

Nurse-run ECMO had noninferior survival to hospital discharge compared with perfusionist-run ECMO (52% vs 27.5% respectively; $p = 0.279$). Factors that improved survival to hospital discharge included venovenous-ECMO versus venoarterial-ECMO ($p = 0.004$), higher RESP score for venovenous-ECMO patients ($p = 0.017$), and lower age ($p = 0.006$) and BMI ($p = 0.001$). There was no significant effect on survival when adjusting for SOFA score ($p = 0.3$), length of intubation pre-ECMO

TABLE 1.
Patient Characteristics of Extracorporeal Membrane Oxygenation Program

Variables	Perfusionist-Run ECMO (*n* = 29)	Nurse-Run ECMO (*n* = 94)	*p*
Year	2017	2018 and 2019	
Age, mean ± SD (yr)	46.4 ± 15	50.3 ± 17	0.27
Male sex, *n* (%)	20 (68.9)	63 (67)	0.84
Body mass index, mean ± SD (kg/m²)	29.9 ± 9.9	26.4 ± 6.8	0.03
Race, *n* (%)			0.82
White	16 (55)	55 (55.5)	
Black	2 (7)	6 (6)	
Asian or Indian/South Asian	2 (7)	8 (8.5)	
Native Pacific Islander	0 (0)	1 (1)	
More than one race	6 (20)	17 (18)	
Other	3 (10)	4 (4)	
Unknown	0	3 (3)	
Hispanic ethnicity, *n* (%)	9 (31)	32 (34)	0.76
Past medical history (yes, no), *n* (%)			
Cardiovascular history	14 (48.3)	56 (58.9)	0.29
Neurologic history	3 (10.3)	6 (6.3)	0.44
Pulmonary history	9 (31)	23 (24)	0.48
Chronic kidney disease	1 (3.4)	4 (4.2)	1.00
Diabetes	7 (24.1)	22 (23.2)	1.00
Liver disease	1 (3.4)	1 (1.1)	0.42
Connective tissue disease	1 (3.4)	7 (7.4)	0.68
Cancer history	3 (10.3)	11 (11.6)	1.00
Solid organ transplantation	2 (6.9)	7 (7.4)	1.00
Peripartum	0	2 (2.1)	1.00
Sequential Organ Failure Assessment score at ICU admission, mean ± SD	12.9 ± 4.4	11.3 ± 5.5	0.13
Respiratory ECMO Survival Prediction score, mean ± SD	2.3 ± 4.5	−0.2 ± 4.3	0.173
Survival After Venoarterial ECMO score, mean ± SD	−2.9 ± 5.4	−8.1 ± 6.9	0.007
Mechanical ventilation days prior to ECMO, median (interquartile range)	0 (0–1)	1 (1–3)	0.009
ECMO indication, *n* (%)			0.145
Circulatory shock	19 (65.5)	55 (58.5)	
Hypoxia or hypercapnia	7 (24.1)	36 (38.3)	
Extracorporeal cardiopulmonary resuscitation	2 (6.9)	2 (2.1)	
Intraoperative support	1 (3.4)	1 (3.4)	

ECMO = extracorporeal membrane oxygenation.

($p = 0.851$), gender ($p = 0.994$), and SAVE score for veno-arterial-ECMO patients ($p = 0.476$).

Nurse-run ECMO also had a noninferior rate of complications per ECMO-day compared with perfusionist-run ECMO ($p = 0.989$). Patients on venovenous-ECMO have significantly fewer complications per ECMO-day compared with venoarterial-ECMO ($p = 0.005$). Patients with higher BMI

TABLE 2.
Extracorporeal Membrane Oxygenation Program Outcomes

Variables	Perfusionist-Run Year (2017)	Nurse-Run Combined Years (2018 and 2019)
Total ECMO cases (venoarterial-ECMO), *n* (%)	30 (76.6)	99 (60.6)
ECMO days per patient, median (IQR)	5.5 (3.25–10.75)	6 (3–12)
Total ECMO days	220	808[a]
Days hospitalized, median (IQR)	23 (12.5–47.8)	25 (10.8–45.4)
Survival to discharge, total (%)	8/29 (27.5)	49/94 (52)
Survival to discharge venoarterial-ECMO, *n* (%)	4/23 (20.8)	26/60 (43)
Survival to discharge venovenous-ECMO, *n* (%)	4/6 (66)	23/34 (68)
Active infections (pre and during ECMO), *n* (%)		
No infections	16/29 (55.2)	46/94 (48.9)
1 infection	5/29 (17.2)	17/94 (18.1)
2 infections	3/29 (10.3)	8/94 (8.5)
3 infections	1/29 (3.4)	9/94 (9.6)
4 or more infections	4/29 (13.8)	14/94 (14.9)
Total ECMO complications by system, *n* (%)[b]	$n = 65$	$n = 177$
ECMO circuit	0	10 (5.6)
ECMO cannula associated	5 (7.7)	0
Hematologic (e.g., bleeding)	13 (20)	42 (23.7)
Neurologic	8 (12.3)	17 (9.6)
Pulmonary	7 (10.8)	16 (9)
Renal	21 (32.3)	56 (31.6)
Cardiac	5 (7.7)	28 (15.8)
Peripheral vascular	6 (9.2)	8 (4.5)
Total complications per ECMO run, mean ± SD	2.24 ± 1.66	1.88 ± 2.24
Total complications per ECMO run, median (IQR)	2 (1–4)	1 (0–3)
Total complications per ECMO day, mean ± SD	0.42 ± 0.52	0.34 ± 0.49
Total complication per ECMO day, median (IQR)	0.25 (0.13–0.41)	0.17 (0–0.49)

ECMO = extracorporeal membrane oxygenation, IQR = interquartile range.
[a]Four-hundred twenty-nine ECMO days in 2018, 329 ECMO days in 2019.
[b]ECMO complications were grouped by systems defined by the extracorporeal life support organization database requirements, see Figures S3 and S4 (http://links.lww.com/CCX/A661).
Outcomes of a perfusionist-run ECMO in 2017 compared with nurse-run ECMO in 2018 and 2019. The total amount of ECMO runs is greater than total patients in 2017 and 2018 due to some patients receiving multiple runs of ECMO.

has significantly more complications per ECMO-day ($p = 0.004$). There were no significant changes in complications per ECMO-day when adjusting for SOFA score ($p = 0.767$), length of intubation pre-ECMO ($p = 0.336$), age ($p = 0.887$), RESP score ($p = 0.69$), and SAVE score ($p = 0.353$). Male gender was associated with significantly fewer complications per ECMO day ($p = 0.011$); however, this effect was nonsignificant ($p = 0.53$) when adjusting for length of intubation pre-ECMO, RESP score, and SAVE score.

Subgroup analysis for patients on venoarterial-ECMO found that nurse-run ECMO did not have inferior survival to hospital discharge compared with perfusionist-run ECMO ($p = 0.106$). Patients who were younger ($p = 0.012$) and had lower BMI ($p = 0.009$) had improved survival to hospital discharge. There was no statistical difference found for gender (p = 0.852), SOFA score (p = 0.262), length of intubation pre-ECMO (p = 0.862), or SAVE score (p = 0.638). Complications per ECMO-day for patients on veno-arterial-ECMO were noninferior with nurse-run ECMO compared with perfusionist-run ECMO (p = 0.557). Patients with higher BMI had a significant increase in complications per ECMO-day (p = 0.008). Male gender was associated with significantly fewer complications per ECMO-day ($p < 0.001$), but this effect was nonsignificant when adjusting for length of intubation pre-ECMO and SAVE score (p = 0.143). Other covariates had no significant effect on complications per ECMO-day: SOFA score (p = 0.411), age (p = 0.296), SAVE score (p = 0.127), and length of intubation pre-ECMO (p = 0.341).

In the subgroup analysis of patients on venovenous-ECMO, there was noninferior survival to hospital discharge during nurse-run ECMO compared with perfusionist-run ECMO (p = 0.399). Patients with higher RESP score had a significant increase in survival to hospital discharge (p = 0.016). Patients with lower BMI also had significantly improved survival to hospital discharge (p = 0.031); however, this difference was not significant after adjusting for length of intubation pre-ECMO and RESP score (p = 0.396). Other covariates had no significant effect on survival to hospital discharge: SOFA score (p = 0.876), age (p = 0.282), gender (p = 0.944), and length of intubation pre-ECMO (p = 0.678). Complications per ECMO-day for patients on venovenous-ECMO were noninferior with nurse-run ECMO compared with perfusionist-run ECMO (p = 0.104). All other covariates had no significant effect on complications per ECMO-day: SOFA score (p = 0.67), age (p = 0.236), gender (p = 0.516), BMI (p = 0.114), RESP score (p = 0.64), and length of intubation pre-ECMO (p = 0.53).

The costs analysis of using perfusionists versus nurses as the ECMO specialists at bedside is shown in **Table 3**. The total cost for perfusionist-run ECMO in 2017 was $580,999 at a cost of $2,550 per ECMO-day. The total cost of the nurse-run ECMO program in 2018 and 2019 was $386,008 ($902 per ECMO-day)

TABLE 3.
Extracorporeal Membrane Oxygenation Program Costs

Variables	2017 Actual Perfusionist-Run Costs	2018 Actual Nurse-Run Costs	2018 Projected Perfusionist-Run Costs	2019 Actual Nurse-Run Costs	2019 Projected Perfusionist-Run Costs
Model of ECMO specialists at bedside	Perfusion	Nurse	Perfusion	Nurse	Perfusion
Total patient ECMO days, *n*	238	428	428	379	379
Number of nurses trained as ECMO specialists, *n*	0	46	0	56	0
Cost of staffing (ECMO specialists and operating room staff if necessary), USD	$606,957	$105,895	$1,057,615	$103,299	$557,299
Total educational costs, USD	$0	$118,980	$0	$83,920	$0
Total ECMO program cost per year (staffing, education, and ECMO coordinator), USD	$606,957	$388,008	$1,057,615	$351,173	$789,859
Costs per ECMO day, USD	$2,550	$907	$2,471	$927	$2,084
Cost savings per year with nurse specialist program compared with projected year of perfusionist-run, USD		$644,177		$438,686	

USD = U.S. dollars.

Cost analysis of using perfusionists vs nurses as the ECMO specialists at bedside. Costs of nurse training was spent in 2017 to prepare for nurse-run ECMO in 2018. However, these costs were included in 2018 for our analysis.

and $351,173 ($927 per ECMO-day), respectively. Based on projected costs, this amounted to an estimated costs savings of $646,177 and $438,686 in 2018 and 2019, respectively.

DISCU3SSION

The implementation of a nurse-run ECMO program at our institution was associated with 1) noninferior survival to discharge, 2) no difference in the rates of ECMO complications, 3) increased ECMO capacity, and 4) potential cost savings.

We found that nurse-run ECMO had noninferior survival to hospital discharge and complications per ECMO day compared with the perfusionist-run ECMO program. Although not statistically significant, our survival to hospital discharge increased over the 3-year study period. This may reflect several changes in our program, including provider education, standardizing practices, and patient selection/indications for ECMO (supplement, http://links.lww.com/CCX/A661). Although the majority of patient baseline characteristics were unchanged, during nurse-run ECMO, the patients had slightly lower BMI. We found that increasing BMI decreased survival to hospital discharge in our ECMO cohort; however, this has not been seen in other ECMO cohorts (13, 14). More patients were placed on venovenous-ECMO during nurse-run ECMO (year 2018 and 2019), which also has higher historical survival rates than venoarterial-ECMO, although we also accounted for the type of ECMO configuration in our analysis. Patients with acute respiratory distress syndrome on venovenous-ECMO had a survival rate of 63% in the Extracorporeal Membrane Oxygenation to Rescue Lung Injury in Severe Acute Respiratory Distress Syndrome trial, and 54% in a large retrospective cohort study from Germany (2, 10, 15).

Similar to other centers, the majority of the nurses at our institution who trained in ECMO were selected from a cardiovascular ICU and had prior knowledge, training, and experience with mechanical circulatory support devices, making them especially well-suited to learning ECMO concepts and troubleshooting (16). Perfusionists continue to be used during initiation/discontinuation of ECMO and circuit exchanges, furthermore, are always available by phone to provide expertise when needed. Perfusionists remain an integral part of our ECMO program; however, with adequate training and appropriate supervision, nurse-run ECMO may have several advantages compared with perfusionist-run ECMO.

Another goal of our nurse-run ECMO program was to expand capacity to at least six ECMO patients simultaneously. Previously relying on perfusionists for ECMO, capacity was more restricted and may have limited the number of surgical operations that required cardiopulmonary bypass support. We initially trained 46 nurses, with additional nurses further trained in the second year of our program because many transitioned from night to day shift. Fortuitously, these additional ECMO specialists have been instrumental to increasing capacity during the current coronavirus disease 2,019 pandemic, during which the institution has managed nine patients simultaneously on venovenous-ECMO with minimal perfusionist support. Due to increased nursing experience, our nurse ECMO specialists now care for up to three ECMO patients simultaneously (3:1 patient-to-nurse ratio), allowing our capacity to increase to nine ECMO patients. Care was also taken not to train too many nurse ECMO specialists, so that each could maintain adequate ECMO hours annually to assure proficiency. Furthermore, continuing education and annual examinations are performed by our perfusionists and ECMO coordinator and are required for our nurses to maintain their ECMO certification. Although we specifically trained nurses, we note that other centers have used respiratory therapists which can further expand capacity and decrease costs.

We report substantial cost savings with a nurse-run ECMO program compared with a perfusionist-run program. These findings are consistent with other reports when transitioning to a nurse-run ECMO program (17). The daily cost of ECMO was reduced by 65% ($2,550 to ~$900), even after including initial training costs, continuing education, and hiring an ECMO coordinator. Our staffing model includes one charge nurse and three staff nurses each day who are ECMO specialists. This required training approximately 46 staff nurses, at a total cost of $117,000. No nurses were hired to support the ECMO program, which would have increased the initial costs. By our calculations, it would be cost neutral to maintain a nurse-run ECMO specialist program with only 155 patient ECMO days annually. Any additional ECMO days beyond 155/yr would lead to cost savings with a nurse-run program. Although institutional ECMO specialists (perfusionist or nurse) have lower hourly costs than per diem perfusionists, the per diem perfusionists have flexible hours, and the institution may not be liable for further labor costs (i.e., benefits). Thus, for centers with limited ECMO cases, it may be more cost-effective to use per diem perfusionists. Overall, each institution planning to implement a nurse-run ECMO program should perform their own cost analysis based on their labor costs, ECMO census, and local resources, and our experience may serve as a model for these projections.

There are multiple limitations to our study. First, this is a single-center study, although our center is considered a large-volume ECMO center with greater than 30 patients annually (18). Second, due to our center providing specialized services such as heart and lung transplant and pulmonary thromboendarterectomy, there may be limited generalizability to other centers without these complex cardiac surgeries, which rely on ECMO backup. Third, this was a pre- and poststudy design, rather than a randomized control trial (RCT). Although an RCT would be ideal, implementation may be impractical due to the costs and complexity of staffing. Nurse and perfusion ECMO specialists have unique patient ratios, and maintaining consistent bedside ECMO specialists within a trial may be costly and logistically difficult. Furthermore, with an RCT, nurses would have decreased time as the bedside ECMO specialist, leading to less experience and potentially increasing complications.

Other changes over time might also explain improvement in our outcomes. Many aspects of ECMO care at our institution were standardized as we transitioned to nurse-run ECMO (supplement for details, http://links.lww.com/CCX/A661). Thus, it is theoretically possible that nurse-run ECMO could have had a detrimental effect which may have been offset by other beneficial program changes that occurred during the same time. Although outcomes may have been impacted, the cost savings were likely independent of these changes. There were aspects of our ECMO program that did not change after implementing nurse-run ECMO, such as program leadership (director, coordinator, perfusionist champions), ECMO equipment (Table S2 and **Figure S2**, http://links.lww.com/CCX/A661), and our patient population.

As described in the methods, complications were retrospectively assessed by chart review for patients on ECMO in 2017; however, in 2018 and 2019, complications were documented daily by the bedside nurse ECMO specialists and reported to our ECMO coordinator. Despite these different methods of reviewing complications, the systematic capture of complications in 2018–2019 would likely have been more sensitive to complications with nurse-run ECMO. This change would be expected to favor a lower complication rate in the perfusionist-run ECMO program; however, this was not observed in our study. Due to limited sample size and complication rates, we totaled all of our complications for our analysis and standardized them by ECMO days. Thus, we cannot draw any conclusions for any of the rarer complications defined by ELSO. Our analysis also does not account for the severity of the complications, for example, an intracerebral hemorrhage or limb amputation is much more clinically significant, albeit rarer, compared with an elevated creatinine from 1.5 to 3.0 (online supplement, Figures S3 and S4, http://links.lww.com/CCX/A661). As such, larger studies are needed to draw conclusions about rarer and more devastating complications. Finally, the cost analysis was based on salaries and reimbursement at our center in Southern California, which are likely to be different in other geographic locations within or outside the United States.

CONCLUSIONS

In this single-center before/after analysis, noninferior survival to discharge and complication rates were observed after implementation of a nurse-run ECMO program. Nurse-run ECMO may also increase ECMO capacity, while substantially decreasing costs. Perfusionist support remains essential for training, continuing education, and clinical backup for a nurse-run ECMO program.

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