Original Article

Trends in Patient Characteristic, Cost, and Mortality Among Mechanically Ventilated Adult Patients With Congenital Heart Disease in the United States

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ABSTRACT

Background: There is an increasing number of adults with congenital heart disease (ACHD), but critically ill patients with ACHD remain understudied. The objective of this study was to evaluate patient characteristics and trends in mortality of mechanically ventilated patients with ACHD.

Methods: We evaluated ACHD with an ICD-9 procedure code for mechanical ventilation using the National Inpatient Sample (NIS), a public all-payer inpatient United States database, from 2005 to 2014. Primary and secondary outcomes were evaluated using multivariable logistic regression.

RÉSUMÉ

Introduction : Il existe un nombre croissant d'adultes atteints d'une cardiopathie congénitale (CC), mais peu d'études portent sur les patients gravement atteints d'une CC. L'objectif de la présente étude était l'évaluation des caractéristiques des patients et des tendances de la mortalité des patients atteints d'une CC sous ventilation mécanique.

Méthodes : Nous avons évalué les patients atteints d'une CC sous ventilation mécanique (VM, code ICD-9) à l'aide de l'échantillon national des patients hospitalisés (NIS, *National Inpatient Sample*), une base de données sur les patients hospitalisés des États-Unis accessible au public, de 2005 à 2014. Nous avons évalué les critères

With more than 90% of patients with congenital heart disease (CHD) surviving into adulthood, adults with congenital heart disease (ACHD) represent a rapidly growing cohort of patients.[1] Correspondingly, hospitalizations for ACHD have also increased rapidly.[2,3] Although many ACHD hospitalizations are secondary to cardiac issues,[4] admissions for chronic medical conditions are playing a larger role as ACHD survive longer.[2]

Many ACHD have lower pulmonary reserve, which makes them particularly vulnerable during critical illness.[5,6] Decreased tolerance to exercise and abnormal ventilatory patterns secondary to chronic heart failure and pulmonary

hypertension have been cited as reasons for risk of decompensation in ACHD.[5] As a result, ACHD have demonstrated higher rates of admission to intensive care units than the non-ACHD cohort.[6] Mechanical ventilation (MV) is a cornerstone of critical care. ACHD who require MV are of particular interest, as they represent the sickest group of patients who require life-sustaining measures to support them through their underlying illness. Several review articles have pointed out the potential difficulties with MV in ACHD, including abnormal or altered airway anatomy, poor restrictive pulmonary mechanics, and decreased oxygen reserve.[4,5,7] Unfortunately, data on MV in the ACHD cohort are lacking, and management relies heavily on experience and expert opinion.[5] The outcomes and mortality rates of such measures are unknown.

What is also unknown is the cost associated with mechanically ventilated ACHD. Compared with non-ACHD, ACHD have been associated with longer hospital length of stay and higher costs.[6] In MV ACHD, who are the most

Results: There were 10,962 of 77,334,704 discharges, representing 52,876 (0.6%) hospitalizations that were for patients with ACHD who required mechanical ventilation (MV). Mean age was 59 years (interquartile range: 45-71); 45.3% were female patients. The number of patients with ACHD requiring MV increased over the years (2342 to 7775, $P < 0.001$). Age and comorbidities of this cohort also increased (55 to 59, $P < 0.001$; 1 to 2, $P < 0.001$). Case-fatality ratio remained stable over the years (0.254 to 0.259, $P = 0.42$). Median cost of hospital stay was USD $49,583 and remained stable over the study period ($P = 0.42$), whereas total cost increased from $115 million to $564 million ($P < 0.001$).

Conclusions: The number of mechanically ventilated ACHD has increased over the years. Remarkably, despite an increase in the age and comorbidity burden in this cohort, case-fatality ratio of these patients and the cost per patient remained stable. Nonetheless, there is a growing need for health care resources in the management of this cohort of patients. Further studies will need to be conducted to evaluate the underlying physiological impact and prognosis of MV in specific subsets of ACHD.

de jugement principal et secondaire à l'aide de la régression logistique multivariée.

Résultats : Les 10 962 sorties d'hôpital sur 77 334 704, soit 52 876 (0,6 %) hospitalisations, concernaient des patients atteints d'une CC qui avaient nécessité une VM. L'âge moyen était de 59 ans (écart interquartile : 45-71); 45,3 % étaient des femmes. Le nombre de patients atteints d'une CC qui avaient nécessité une VM augmentait au fil des années (de 2 342 à 7 775, $P < 0,001$). L'âge et les comorbidités de cette cohorte augmentaient aussi (de 55 à 59, $P < 0,001$; de 1 à 2, $P < 0,001$). Le taux de létalité restait stable au fil des années (de 0,254 à 0,259, $P = 0,42$). Le coût médian des séjours à l'hôpital était de 49 583 $ US et restait stable au cours de la période de l'étude ($P = 0,42$), alors que le coût total passait de 115 M$ à 564 M$ ($P < 0,001$).

Conclusions : Le nombre de patients atteints d'une CC sous VM a augmenté au fil des années. Étonnamment, en dépit d'une augmentation de l'âge et du fardeau des comorbidités dans cette cohorte, le taux de létalité de ces patients et le coût par patient demeurait stable. Néanmoins, il existe un urgent besoin de ressources de soins de santé pour la prise en charge de cette cohorte de patients. Il sera nécessaire de mener d'autres études pour évaluer les effets physiologiques sous-jacents et le pronostic des patients sous VM dans des sous-ensembles spécifiques de CC.

critically ill, the requirements for specialist consultations, investigations, and interventions are even higher, particularly in those with lesions of moderate or great severity.[8] The purpose of this study is to better characterize ACHD who require MV and to evaluate the trends of both in-hospital mortality and health care costs associated with these patients over a 10-year period. The results will help inform practices and policies to facilitate higher quality and more efficient care.

Methods

Data source

We used data from the 2005 to 2014 National Inpatient Sample (NIS) from the Healthcare cost and Utilization Project (HCUP). The NIS is the largest publicly available all-payer inpatient care database in the United States and includes data on approximately 8 million discharges per year. The NIS contains a stratified sample of approximately 20% of US community hospitals, which cover greater than 97% of the US population. This database has been used previously to study trends and health care utilization of ACHD.[2,3,9]

Study population and variables

All patients greater than 18 years of age who had International Classification of Diseases, Ninth Edition (ICD-9) diagnosis codes of CHD (745, 746, 747.0, 747.1, 747.2, 747.3, and 747.4) and the procedure codes of MV (96.04, 96.70, 96.71, and 96.72) were identified. These diagnosis codes have been validated previously in administrative datasets, with high specificity.[10,11]

Baseline characteristics—including age, gender, race, median household income based on patients' ZIP codes, and health insurance status—were recorded. Clinical data included primary and secondary diagnoses (ICD-9 codes for type of

CHD, medical comorbidities, etc), elective vs emergency admission, and hospital characteristics (size, teaching status, and geographic region). The type of CHD defect was categorized into simple, moderate, and great complexity,[12] based on specific diagnoses and using the Bethesda classification (Supplemental Table S1). ICD-9 codes used for identifying each medical condition or procedure are listed in Supplemental Tables S1-S3.

As the data from NIS represent a collection of scattered hospital clusters, analyses need to account for a complex sampling design.[13] In the NIS database, each hospital admission has an associated "discharge weight" and "trend weight" used to calculate national estimates after accounting for the hierarchical structure of the data set.[13] The annual population-based hospitalization rate was determined, using the number of weighted discharges in the NIS and the corresponding annual adult population count from US census data, and expressed as hospitalizations per 100,000 US adult population.

Outcomes

The primary outcome was the trend in the in-hospital case fatality ratio of mechanically ventilated ACHD between 2005 and 2014. Secondary outcomes included patient characteristics (age, comorbidity, and CHD defect), hospital cost, and length of hospital stay. Hospital costs were calculated using total charges (TOTCHG) and the all-payer cost-to-charge (APICC) ratio using the cost-to-charge (CCR) documentation and method[13] and reflect the actual expenses incurred in the production of hospital services such as wages, supplies, and utility costs. Hospital costs were adjusted for inflation based on the 2014 US Bureau of Labor Consumer Price Index.[14] Total annual hospitalization costs were estimated by totaling the hospital costs for all invasive MV hospitalizations.
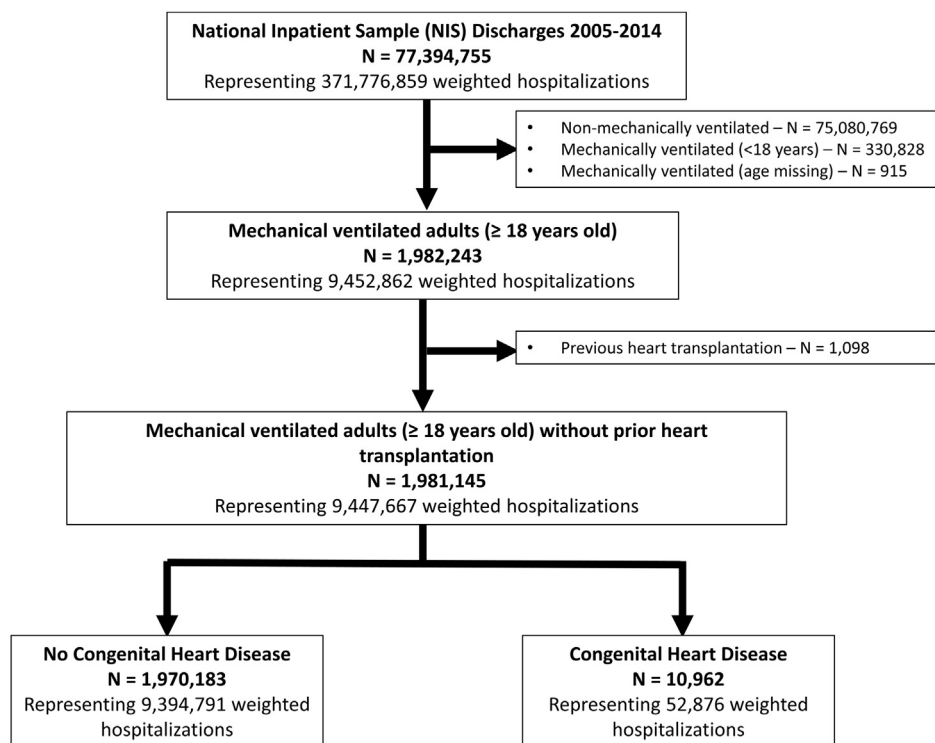
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Figure 1. Flowchart of mechanically ventilated adults with congenital heart disease.

Statistical analysis

All analyses were performed using STATA/MP 15.1 (StataCorp LLC, College Station, TX). Categorical data were presented as counts and weighted percentages. Continuous data were expressed as medians and interquartile (IQR) ranges. Estimates were obtained using complex survey methods to account for the NIS survey design, using the appropriate weights.

Temporal trends were evaluated using the Cochran-Armitage test for categorical variables and survey-specific linear regression for continuous variables. For continuous variables, these variables were additionally log-transformed, as they were not normally distributed, and analyses of trend were performed using the geometric means. Annual percent change was calculated using a linear model on the log of the age-standardized rates.[15]

For the analyses of trend of the in-hospital case-fatality ratio, we used a survey-specific generalized linear model with modified Poisson regression with Huber-White robust errors to estimate the associated yearly annual percent change and associated 95% confidence interval (CI). For the analyses of trend of hospital length of stay and hospital costs, we estimated the annual percent change by using survey-specific linear regression on the log-transformed outcomes.

Next, we performed a risk-adjusted analysis of case-fatality ratio by using survey-specific multivariable logistic regression. We estimated the adjusted odds ratio (OR) of case-fatality ratio and associated 95% CI for each year, using 2005 as the reference year. We adjusted for year (categorical variable, 2005 reference), age (continuous variable), biologic sex (categorical), race (categorical, including missing), insurance status (categorical), household income quartile (categorical),

hospital region (categorical), hospital bedsize (categorical), hospital teaching status and location (categorical), elective admission status (categorical), Charlson comorbidity index (CCI) category (categorical, 0, 1, 2, or 3+ comorbidities. All statistical tests were 2-tailed, and a P value less than 0.05 was considered significant.

Subgroup and sensitivity analyses

We performed 2 subgroup analyses to investigate our findings further by dividing patients by complexity of their CHD and by dividing patients by hospital size. A risk-adjusted analysis of in-hospital mortality by ACHD complexity was performed using survey-specific multivariable regression, adjusting for ACHD complexity (categorical variable), year (categorical variable, 2005 reference), age (continuous variable), biologic sex (categorical), race (categorical, including missing), insurance status (categorical), household income quartile (categorical), hospital region (categorical), hospital size (categorical), hospital teaching status and location (categorical), elective admission status (categorical), CCI category (categorical, 0, 1, 2, or 3+ comorbidities. Next, we performed 2 separate sensitivity analyses to investigate our findings by first excluding patients with elective admissions to capture the most critically ill ACHD population and, second, by excluding patients with ostium secundum atrial septal defects to increase the specificity of true CHD.[16]

Results

A total of 77,394,755 discharges, representing 371,776,859 hospitalizations, were evaluated using the NIS

Table 1. Baseline characteristics, comorbidities among hospitalized adult patients with CHD receiving mechanical ventilation from 2005 to 2014

Patient characteristic	2005 N = 494	2006 N = 619	2007 N = 638	2008 N = 1088	2009 N = 1227	2010 N = 1270	2011 N = 1408	2012 N = 1273	2013 N = 1390	2014 N = 1555	Total N = 10,962	P value for trend[‡]
Weighted hospitalizations	2342	2918	3053	5103	5792	6145	6433	6365	6950	7775	52,876	< 0.001
Hospitalizations per 100,000 US adult population	1.05	1.30	1.34	2.22	2.49	2.61	2.71	2.65	2.87	3.18	-	< 0.001
Female, N (%)	240 (48.5)	286 (46.2)	306 (48.0)	513 (47.0)	556 (45.5)	568 (44.8)	630 (44.6)	562 (44.2)	606 (43.6)	697 (44.8)	4964 (45.3)	0.02
Age, median years (IQR)	55 (37-69)	57 (40-71)	56 (40-70)	58 (45-72)	59 (45-72)	59 (46-71)	60 (47-72)	59 (46-70)	60 (47-70)	60 (47-71)	59 (45-71)	< 0.001
Race, N (%)												
White	281 (56.9)	369 (59.6)	320 (50.4)	633 (57.8)	727 (59.5)	815 (64.0)	899 (64.0)	831 (65.3)	910 (65.5)	1049 (67.5)	6834 (62.4)	< 0.001
Black	31 (6.2)	46 (7.5)	71 (11.3)	107 (9.6)	87 (6.8)	156 (12.6)	163 (11.4)	160 (12.6)	161 (11.6)	185 (11.9)	1167 (10.7)	< 0.001
Hispanic	41 (8.2)	37 (5.8)	57 (8.6)	83 (7.7)	97 (8.1)	77 (6.1)	104 (7.5)	103 (8.1)	117 (8.4)	113 (7.3)	829 (7.6)	0.80
Other	21 (4.3)	33 (5.3)	32 (5.0)	57 (5.4)	85 (7.1)	74 (5.8)	98 (7.1)	79 (6.2)	97 (7.0)	101 (6.5)	677 (6.2)	0.04
Missing	120 (24.4)	134 (21.8)	158 (24.7)	208 (19.4)	231 (18.6)	148 (11.5)	144 (10.0)	100 (7.9)	105 (7.6)	107 (6.9)	1455 (13.1)	< 0.001
Insurance status, N (%)												
Medicare	212 (42.9)	280 (45.2)	283 (44.4)	498 (45.9)	579 (47.1)	594 (46.2)	700 (49.8)	581 (45.8)	695 (50.3)	752 (48.5)	5174 (47.2)	0.004
Medicaid	75 (15.4)	90 (14.6)	85 (13.2)	143 (13.2)	173 (14.3)	207 (16.5)	203 (14.4)	185 (14.6)	193 (14.0)	280 (18.1)	1634 (15.0)	0.08
Private	165 (33.3)	207 (33.4)	215 (34.2)	354 (32.6)	371 (30.4)	351 (27.8)	386 (27.7)	391 (30.8)	373 (27.0)	420 (27.1)	3233 (29.6)	< 0.001
Self-pay	25 (5.0)	21 (3.5)	38 (5.9)	61 (5.7)	62 (5.1)	71 (5.7)	67 (4.9)	63 (5.0)	65 (4.7)	62 (4.0)	535 (4.9)	0.29
No charges	—	—	—	—	—	14 (1.1)	12 (0.9)	—	13 (0.9)	—	65 (0.6)	0.70
Other	14 (2.8)	17 (2.7)	16 (2.2)	28 (2.3)	37 (2.9)	33 (2.7)	33 (2.3)	40 (3.2)	44 (3.2)	34 (2.2)	296 (2.7)	0.87
Median household income quartile*, N (%)												
0%-25% (lowest income)	130 (26.6)	147 (23.8)	139 (22.4)	263 (25.1)	299 (25.1)	344 (28.3)	360 (25.6)	330 (26.7)	370 (27.1)	435 (28.5)	2817 (26.3)	0.05
26%-50%	114 (23.7)	128 (21.3)	158 (25.4)	282 (26.9)	321 (26.5)	361 (29.3)	353 (25.8)	318 (25.7)	375 (27.5)	439 (28.8)	2849 (26.7)	0.01
51%-75%	131 (26.7)	153 (24.9)	168 (26.8)	259 (24.6)	313 (26.3)	306 (24.8)	377 (27.8)	311 (25.1)	341 (25.0)	364 (23.8)	2723 (25.4)	0.37
76%-100% (highest income)	112 (23.1)	181 (30.0)	152 (26.4)	249 (23.5)	258 (22.2)	216 (17.6)	286 (20.8)	278 (22.5)	279 (20.4)	289 (18.9)	2300 (21.6)	0.002
Charlson score, median score (IQR)	1 (0-2)	1 (0-2)	1 (1-3)	1 (1-3)	2 (1-3)	2 (1-3)	2 (1-3)	2 (1-3)	2 (1-3)	2 (1-4)	2 (1-3)	< 0.001
CHD lesion complexity, N (%)[†]												
Simple	343 (69.5)	479 (77.5)	468 (74.2)	869 (79.9)	1000 (81.4)	1028 (81.8)	1140 (81.1)	1039 (81.6)	1123 (80.8)	1280 (82.3)	8769 (80.2)	< 0.001
Moderate	157 (31.7)	154 (24.8)	183 (28.0)	236 (21.7)	252 (20.8)	265 (20.1)	289 (20.3)	259 (20.4)	281 (20.2)	301 (19.4)	2377 (21.5)	< 0.001
Severe	30 (6.3)	15 (2.7)	20 (3.0)	38 (3.5)	23 (1.8)	38 (3.0)	45 (3.4)	42 (3.3)	33 (2.4)	36 (2.3)	320 (2.9)	0.08
Comorbidities, N (%)												
Smoker	63 (12.6)	96 (15.6)	83 (12.8)	131 (12.0)	206 (16.3)	271 (21.5)	337 (24.1)	304 (23.9)	351 (25.3)	436 (28.0)	2278 (20.9)	< 0.001
Previous myocardial infarction	18 (3.7)	20 (3.3)	18 (2.8)	28 (2.6)	59 (4.8)	47 (3.8)	90 (6.4)	73 (5.7)	57 (4.1)	73 (4.7)	483 (4.4)	0.001
Pulmonary hypertension	78 (15.9)	105 (17.0)	101 (15.8)	162 (14.7)	234 (18.9)	242 (19.3)	283 (20.0)	236 (18.5)	302 (21.7)	309 (19.9)	2052 (18.7)	< 0.001
Atrial fibrillation	135 (27.3)	172 (28.2)	171 (26.7)	236 (21.7)	349 (28.2)	322 (25.5)	412 (29.4)	368 (28.9)	386 (27.8)	472 (30.4)	3023 (27.6)	0.007
Congestive heart failure	196 (39.9)	211 (33.8)	215 (33.4)	350 (31.9)	440 (35.7)	457 (36.3)	573 (40.6)	502 (39.4)	603 (43.4)	640 (41.2)	4187 (8.2)	< 0.001
Stroke	40 (8.0)	70 (11.4)	80 (12.4)	167 (15.3)	190 (15.8)	243 (19.2)	252 (18.0)	234 (18.4)	231 (16.6)	288 (18.5)	1795 (16.5)	< 0.001

%, weighted percentage; -, not applicable; CHD, congenital heart disease; IQR, interquartile range; N, unweighted number.

* Median income quartile for patient ZIP code.

[†] According to the Bethesda classification.

[‡] P value for linear trend. A P value of <0.05 indicates statistical significance.

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trend weights between 2005 and 2014; 10,962 of these discharges, representing 52,876 hospitalizations (0.6% of weighted hospitalizations), were ACHD who required MV. See Figure 1 for the selection process of the MV weighted hospitalizations from all the weighted hospitalizations and the further separation of MV-weighted hospitalizations into ACHD and non-ACHD.

The median age was 59 years (IQR: 45-71) and 4964 patients (45.3%) were female. Ethnicities of patients included 6834 White (62.4%), 1167 Black (10.7%), 829 Hispanic (7.6%), and 677 other (n = 6.2%), with 1455 unknown (13.1%). Of the 10,962 patients, 8769 (80.2%), 2377 (21.5%), and 320 (2.9%) had simple, moderate, and severe defects, respectively. The median CCI was 2 (IQR: 1-3). Of the admissions involving MV, 2577 (23.1%) were elective admissions, and 8385 (76.9%) were nonelective, with 745 (6.8%), 2269 (20.7%), and 7936 (72.4%) admitted to small, medium, and large hospitals, respectively. The geographic distribution of MV hospitalizations included 1940 (17.7%) Northeast, 2795 (25.5%) Midwest, 3749 (34.2%) South, and 2488 (22.7%) West.

Of the 10,962 admissions, 6327 (57.8%) were admitted with the Angus definition of severe sepsis and septic shock, 6876 (63.0%) had acute respiratory distress syndrome (ARDS), and 4056 (37.2%) had an acute kidney injury (AKI). Other diagnoses included cardiogenic shock (n = 1313; 12.1%), and acute coronary syndrome (n = 1517; 13.9%). Baseline characteristics of the study population are listed in Table 1.

Trends in outcomes over time

Of the 52,876 weighted ACHD MV hospitalizations between 2005 and 2014, there were 2342 ACHD (4.43%) requiring MV in 2005 compared with 7775 (14.70%) in 2014 ($P < 0.001$), showing a drastic rise in the incidence of MV ACHD over this decade (Fig. 2). Over the 10-year span, the age of ACHD patients requiring MV increased ($P < 0.001$) from 55 years old (IQR: 37-69) in 2005 to 59 (IQR: 45-71) in 2014, with the largest increment within the first 4 years. The median CCI also increased from 1 (IQR: 0-2) in 2005 to 2 (IQR: 1-3) in 2014 ($P < 0.001$). The prevalence of individual comorbidities also showed a significant increase over the 10-year study period. The percentage of patients who have smoked showed a steady increase from 63 (12.6%) in 2005 to 436 (28.0%) in 2014 ($P < 0.001$). The percentage of patients with pulmonary hypertension also steadily increased from 78 (15.9%) in 2005 to 309 (19.9%) in 2014 ($P < 0.001$). The percentage of patients who have had previous myocardial infarction, atrial fibrillation, and congestive heart failure also showed a significant overall increase over the study period but demonstrated more fluctuations in prevalence, with transient increases and decreases from year to year (Table 1).

Simple CHD defects increased as a greater proportion of all ACHD patients requiring MV ($P < 0.001$) from 343 (69.5%) in 2005 to 1280 (82.3%) in 2014, whereas a smaller absolute rise was seen in moderate complexity CHD defects ($P < 0.001$), with 157 (31.7%) in 2005 to 301 (19.4%) in 2014. The proportion of patients with great-complexity CHD defects remained stable over this time period, with 30 (6.3%)

patients in 2005 and 36 (2.3%) patients in 2014 ($P = 0.08$). The incidence trend of CHD by severity from 2005 and 2014 can be seen in Figure 3. Rates of severe septic shock steadily increased from 225 (46.0%) in 2005 to 974 (62.6%) in 2014 ($P < 0.001$). Similarly, rates of ARDS increased from 239 (48.3%) to 1180 (75.9%) ($P < 0.001$) as well as rates of AKI (100 to 722; 20.2 to 46.4%, $P < 0.001$).

Overall, 2729 (24.9%) patients died in hospitals. Although the absolute number of deaths increased over the study period (0.27 to 0.82 per 100,000 US population, $P < 0.001$) (Fig. 2), reflecting a parallel increase in the number of ACHD admissions, the in-hospital case fatality ratio remained stable (0.254 to 0.259, $P = 0.42$). Median length of stay was 12 days (IQR: 6-21). There was a statistically significant rise in the length of hospital stay over the 10-year study period ($P = 0.002$). Median in-hospital cost per patient was USD $49,583 (IQR: $25,762-$88,029). The hospital cost per patient remained stable over the study period ($P = 0.42$) (Table 3). The total cost increased from $114 million in 2005 to $564 million in 2014 (394.9% relative increase), with an average annual percent increase of 14.7%. Overall, 727 (6.7%) patients required mechanical support including intra-aortic balloon pump, ventricular assist device, or extracorporeal membrane oxygenation. There was no significant change in the need for mechanical support over time ($P = 0.18$). A summary of the trends in clinical outcomes and associated costs over the 10-year span are shown in Tables 2 and 3.

Discussion

We retrospectively reviewed 52,876 hospitalizations of mechanically ventilated ACHD patients from 2005 to 2014 to explore trends in patient characteristics, complexity of disease, length of stay, hospitalization costs, and in-hospital mortality. Our principal finding was that although there was an increase in overall incidence, comorbidities, and length of stay in this patient population, hospitalization costs and—most importantly—case-fatality ratios remained stable.

There has been a dramatic increase in ACHD admissions over the last decade.[2,3,9] Our study is in keeping with the previously published data showing an increase in hospitalizations for ACHD. However, this is the first study that explicitly demonstrates a significant increase in the number of ACHD admissions requiring MV. This cohort of patients represent ACHD who were the most critically ill. Severe sepsis and ARDS were the most common admission diagnoses, with a significant increase over the 10-year study period. The physiological consequences of abnormal or altered cardiac anatomy affect beyond the cardiovascular system and may hamper the ability of ACHD to cope with a systemic insult such as sepsis or ARDS, necessitating such life-saving measures as MV. MV, in turn, has been shown to be a significant risk factor of mortality in ACHD hospitalized for heart failure.[17]

In addition to the rise in incidence of ACHD requiring MV over the decade, this study also demonstrated a significant increase in both age and comorbidities. The review by Agarwal et al. showed a similar finding of overall hospitalizations in ACHD from 2003 to 2012.[2] With an aging ACHD population, the burden of medical comorbidities also increased.[2] They also noted that, although cardiac-specific
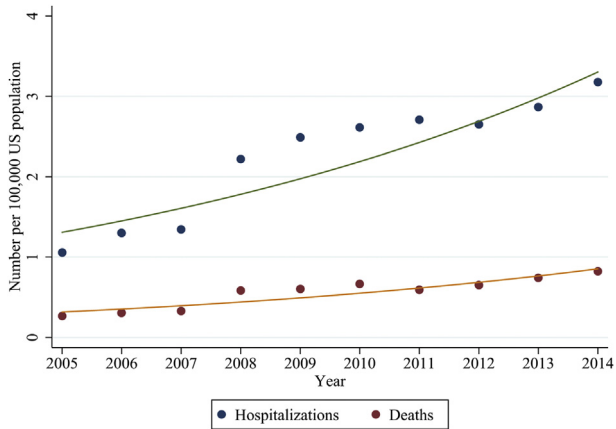
Figure 2. Trend in incidence of adult patients with congenital heart disease in hospitalizations and death.

conditions—such as CHF, arrhythmias, and valvular diseases—were common reasons for hospitalizations, noncardiac conditions—such as respiratory conditions and pregnancies—also accounted for a significant number of admissions.[2] Although the target populations between the 2 studies differed (general hospital admissions vs critically ill patients requiring MV), our study similarly demonstrated an increase over time of noncardiac conditions as the primary and secondary diagnoses. The median length of hospital stay was 12 days, which increased over the study period by an average of 1.38% from 2005 to 2014 ($P = 0.002$). The increasing complexity of ACHD admissions—necessitating more investigations, interventions, and consultations—could explain the increasing length of hospital stay over the study period.[2]

Despite an increase in the absolute number of deaths in MV ACHD, case-fatality ratio remained stable from 2005 to 2014. This is remarkable, given the older and more comorbid ACHD patient population over the years, which would lead one to believe that mortality would increase. Given the overall improvement in critical care management over time, data from the general population have demonstrated a similar trend. This has been attributed to the improved management of mechanically ventilated patients through increased
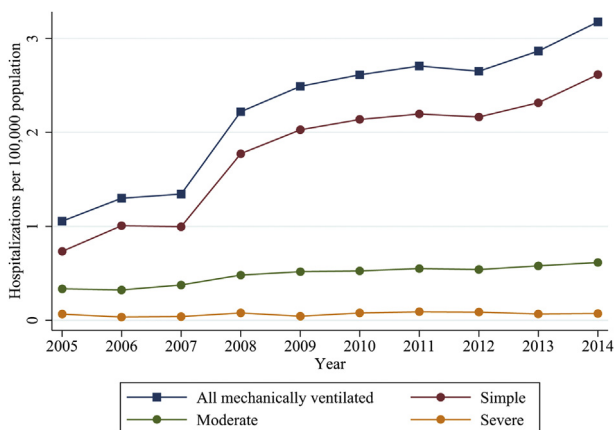
knowledge of ventilator settings[18,19] and the incorporation of weaning protocols.[20,21] Other potential contributors include better long-term outcomes from enhanced medical and surgical approaches as well as clinicians' increased comfort and familiarity in managing ACHD, particularly at established centres of excellence.[22]

Within the limitations of this study's methodology, the cost per ACHD requiring MV remained stable over the 10-year span ($P = 0.42$). This was a surprising result, given the increasing age and comorbidity burden in this patient cohort. A potential explanation is that although there were more patients requiring MV, thanks to improvements in critical care management and protocols to facilitate early weaning from the ventilator, the duration of MV likely decreased over time. A Cochrane review and meta-analysis by Blackwood et al.[23] demonstrated a 25% reduction in the duration of MV when a weaning protocol was implemented vs usual care. This could explain the relatively stable hospital cost per ACHD patient during the study period. A thorough understanding of the utilization and outcomes of MV in ACHD is crucial, as the financial and resource burden of intensive medical care is enormous. In the United States, a significant portion of the health care cost is attributed to inpatient care.[24] The intensive care unit, in particular, comprises nearly one-third of total inpatient costs despite accounting for less than 10% of the beds in US hospitals.[25] Given the growing population of ACHD, we have already seen a significant increase in health care spendings in this cohort.[2,3] In the ACHD population, the mean cost of a MV ACHD was USD $77,671, compared with the mean cost of $34,257 reported for a MV patient from the general population.[26] Other literature has found similar findings, with elevated costs for patients with ACHD.[2,3] This higher cost may be secondary to the high requirements for cardiovascular and respiratory investigations and interventions as well as the need for interdisciplinary input in the care of this cohort.[2] Therefore, although—reassuringly—we did not see an increase per ACHD patient requiring MV over time, this population does place a higher financial burden on the system than the non-ACHD subset.

This study is the first to evaluate the epidemiology, outcomes, and costs of ACHD requiring MV. The strengths of the study include a large sample size from a diverse population, as well as the use of multivariate analysis to minimize interference from patient and clinical variables.

Limitations

Limitations of this study include its retrospective methodology, which precludes more definitive conclusions to be made. We identified CHD diagnoses and MV use using ICD-9 diagnosis and procedure codes. Although previous studies have validated the use of these codes in hospitalized patients, we cannot rule out misclassification or potential biases in coding by physicians. This is relevant for the ICD-9 procedure codes for MV, which has been found to have high specificity but low sensitivity, particularly in patients with surgical admissions.[11] A contributing factor is a reimbursement model that deprioritize the inclusion of MV in surgical

Figure 3. Incidence trend of congenital heart disease by severity.

Table 2. Admission diagnoses, procedures, and outcomes among hospitalized patients with adult congenital heart disease receiving mechanical ventilation from 2005 to 2014

Patient characteristic	2005 N = 494	2006 N = 619	2007 N = 638	2008 N = 1088	2009 N = 1227	2010 N = 1270	2011 N = 1408	2012 N = 1273	2013 N = 1390	2014 N = 1555	Total N = 10,962	P value for trend[‡]
Diagnoses: primary and secondary, N (%)												
Cardiogenic shock	24 (4.9)	51 (8.1)	47 (7.3)	110 (10.2)	138 (11.5)	146 (11.6)	192 (13.7)	157 (12.3)	215 (15.5)	233 (15.0)	1313 (12.1)	< 0.001
Acute kidney injury	100 (20.2)	137 (22.1)	144 (23.0)	357 (33.0)	459 (37.5)	470 (37.2)	564 (40.0)	499 (39.2)	604 (43.5)	722 (46.4)	4056 (37.2)	< 0.001
Acute coronary syndrome	62 (12.6)	80 (12.8)	74 (11.9)	147 (13.5)	157 (13.2)	184 (14.4)	187 (13.4)	179 (14.1)	198 (14.2)	249 (16.0)	1517 (13.9)	0.01
Sepsis	225 (46.0)	270 (43.1)	321 (50.8)	589 (54.1)	710 (57.7)	774 (61.1)	862 (61.3)	770 (60.5)	832 (59.9)	974 (62.6)	6327 (57.8)	< 0.001
ARDS	239 (48.3)	290 (46.5)	339 (53.3)	589 (54.6)	650 (53.2)	760 (59.7)	859 (61.0)	954 (74.9)	1016 (73.1)	1180 (75.9)	6876 (63.0)	< 0.001
Elective admission, N (%)	138 (28.4)	170 (26.6)	152 (23.5)	280 (25.3)	330 (25.7)	290 (22.2)	349 (24.2)	280 (22.1)	271 (19.6)	317 (20.4)	2577 (23.1)	< 0.001
Procedures, N (%)												
Tracheostomy	41 (8.4)	51 (8.4)	71 (11.2)	133 (12.4)	168 (13.8)	137 (11.0)	176 (12.8)	130 (10.2)	162 (11.7)	183 (11.8)	1252 (11.5)	0.26
Renal replacement therapy	31 (6.3)	41 (6.9)	38 (6.0)	106 (9.6)	110 (8.9)	125 (9.8)	134 (9.5)	110 (8.6)	129 (9.3)	141 (9.1)	965 (8.8)	0.02
Mechanical circulatory support	36 (7.3)	39 (6.2)	38 (5.9)	68 (6.3)	68 (5.6)	86 (6.4)	89 (6.4)	86 (6.8)	106 (7.6)	111 (7.1)	727 (6.7)	0.18
Outcomes, N (%)												
In-hospital case fatality ratio	129 (25.6)	146 (23.7)	156 (24.6)	287 (26.4)	296 (24.2)	327 (25.6)	312 (21.9)	313 (24.6)	360 (25.9)	403 (25.9)	2729 (24.9)	0.65
In-hospital mortality, adjusted OR[*]	1.0 (Reference)	0.84 (0.62-1.14)	0.81 (0.60-1.09)	0.91 (0.71-1.17)	0.77 (0.59-0.99)	0.79 (0.61-1.02)	0.62 (0.48-0.81)	0.74 (0.57-0.95)	0.77 (0.59-1.00)	0.77 (0.60-0.99)	-	-
Hospital costs,[†] median USD (IQR)	42,001 (22,311-82,394)	45,239 (23,580-73,822)	48,810 (23,637-83,832)	52,683 (28,192-93,860)	55,919 (29,369-93,325)	48,859 (25,249-86,184)	52,273 (27,714-89,558)	46,454 (24,798-84,824)	47,315 (25,035-87,739)	49,695 (25,033-90,198)	49,583 (25,762-88,029)	0.42
Hospital length of stay, median days (IQR)	9 (5-17)	10 (5-18)	10 (5-20)	12 (6-21)	13 (7-23)	12 (6-20)	12 (7-21)	11 (6-20)	12 (6-20)	12 (6-22)	12 (6-21)	0.002

%, weighted percentage; ARDS, acute respiratory distress syndrome; IQR, interquartile range; N, unweighted number; OR, odds ratio.

[*] Adjusted for year (categorical variable), age, sex, race, income quartile, insurance status, hospital location and teaching status, hospital bedsize, hospital region.

[†] Charlson comorbidity index, and elective admission status. C-statistic = 0.77. [d]Adjusted for inflation to 2014 US dollars.

[‡] P value for linear trend. A P value of <0.05 indicates statistical significance.

Table 3. Temporal changes among mechanically ventilated patients with adult congenital heart disease

Outcome	Relative change from 2005 to 2014, %	Annual percent change (95% CI)	P value
Case fatality ratio, % change			
All patients	1.33	0.31 (−1.04; 1.69)	0.45
By lesion complexity			
Simple	6.9	0.71 (−0.86; 2.30)	0.38
Moderate	−13.4	−0.75 (−3.34; 1.94)	0.58
Severe	11.5	0.06 (−5.95; 6.47)	0.98
By hospital size			
Small	13.9	1.56 (−2.86; 6.19)	0.49
Medium	3.7	1.24 (−1.47; 4.02)	0.38
Large	−1.3	−0.10 (−1.76; 1.58)	0.90
Mean hospital costs per patient, % change			
All patients	17.6	0.45 (−0.65; 1.56)	0.42
By lesion complexity			
Simple	17.5	0.30 (−0.80; 1.42)	0.59
Moderate	1.7	0.30 (−1.59; 2.23)	0.76
Severe	55.4	0.01 (−5.37; 5.68)	1.00
By hospital size			
Small	−2.0	−1.67 (−4.81; 1.57)	0.31
Medium	−4.0	−0.78 (−3.02; 1.51)	0.50
Large	28.6	1.23 (−0.08; 2.56)	0.07
Total hospital costs among all hospitalized patients, % change			
All patients	394.9	14.7 (9.2; 20.4)	< 0.001
By lesion complexity			
Simple	478.1	15.7 (9.3; 22.4)	< 0.001
Moderate	162.8	9.8 (7.0; 12.6)	< 0.001
Severe	105.7	10.0 (3.4; 16.9)	0.01
By hospital size			
Small	1301.6	17.5 (9.6; 26.1)	0.001
Medium	409.4	16.5 (11.4; 21.9)	< 0.001
Large	366.2	14.3 (8.3; 20.6)	< 0.001
Mean hospital length of stay, % change			
All patients	21.6	1.38 (0.52; 2.25)	0.002
By lesion complexity			
Simple	22.9	1.17 (0.26; 2.09)	0.01
Moderate	4.4	1.06 (−0.62; 2.77)	0.22
Severe	102.0	2.09 (−2.19; 6.57)	0.34
By hospital size			
Small	37.5	0.42 (−2.52; 3.45)	0.78
Medium	11.8	0.82 (−0.79; 2.44)	0.32
Large	28.2	1.83 (0.78; 2.89)	0.001

CI, confidence interval.

patients,[11] which could have introduced selection bias in our study. By using NIS data, certain details regarding the hospitalizations of this ACHD cohort were unavailable for analysis. As the data could not be traced to unique patient's hospitalizations, ACHD patients' surgical or interventional histories were not taken into account. The indications surrounding the hospitalizations, whether surgical or nonsurgical, were also not included. In addition, our anatomic classification scheme for the severity of CHD has been shown to be less predictive of outcomes when compared with the new classification scheme that incorporates physiological severity, which may explain why we did not see much difference in outcomes between the groups.[27] As outlined in the 2018 American Heart Association/American College of Cardiology (AHA/ACC) Guideline for Management of ACHD, a combination of anatomic and physiological features is now recommended when grading severity of ACHD. Finally, treatment cost is a complex matter, involving calculations of many different factors. A thorough cost analysis was, unfortunately, beyond the scope of this study. However, the findings of this study surrounding treatment cost may be hypothesis generating for future studies.

Conclusions

Our data showed an increasing burden of episodes of severe illness leading to MV in ACHD. Furthermore, the patient population was increasing in age and had a higher burden of medical comorbidities over the study period. Although the length of hospital stay increased over time, mortality and hospital cost per patient remained stable over the study. Future research will be needed to describe prognostic factors for ACHD requiring MV in more detail by using the newly combined anatomic and physiological severity-classification system. This will help us to better understand the physiological impact and prognosis of MV in specific subsets of patients with ACHD, thereby helping both the patient and the health care team make an informed decision about MV in these critically ill ACHD subsets.

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Disclosures

The authors have no conflicts of interest to disclose.

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Supplementary Material

To access the supplementary material accompanying this article, visit *CJC Open* at https://www.cjcopen.ca/ and at https://doi.org/10.1016/j.cjco.2021.09.024.