EuroIntervention 2018;13:e2152-e2159 published online February 2018 ■ published online e-edition April 2018

National trends, predictors of use, and in-hospital outcomes in mechanical circulatory support for cardiogenic shock

Jordan B. Strom[1], MD; Yuansong Zhao[1], MA; Changyu Shen[1], PhD; Mabel Chung[1,2], MD; Duane S. Pinto[1], MD, MPH; Jeffrey J. Popma[1], MD; Robert W. Yeh[1]*, MD, MSc

1. Richard A. and Susan F. Smith Center for Outcomes Research in Cardiology, Division of Cardiovascular Medicine, Beth Israel Deaconess Medical Center, Boston, MA, USA; 2. Department of Anesthesia, Critical Care, and Pain Medicine, Massachusetts General Hospital, Boston, MA, USA

This paper also includes supplementary data published online at: http://www.pcronline.com/eurointervention/133rd_issue/356

KEYWORDS

- cardiogenic shock
- IABP
- ventricular assist device

Abstract

Aims: Despite rising rates of cardiogenic shock (CS), data on trends and in-hospital outcomes of short-term non-durable mechanical circulatory support (MCS) are limited. Thus, we aimed to identify recent national trends in MCS utilisation in the USA, patient-level predictors of MCS use, and in-hospital outcomes in CS inclusive of extracorporeal membrane oxygenation (ECMO).

Methods and results: Hospitalisations of US adults with a discharge diagnosis of CS, from January 2004 to December 2014, in the National Inpatient Sample were included. Rates of MCS were stratified by device type and clinical presentation. Outcomes included in-hospital mortality, hospitalisation costs, and number of procedures. A total of 183,516 hospitalisations with CS (47,636 [25.9%] involving MCS) were included. MCS recipients were younger, less frequently female, received more procedures, had higher costs, and more frequently presented with MI (MCS vs. non-MCS: 71.6% vs. 42.9%; p<0.0001). Growth in CS hospitalisations (214.4%) outpaced annual MCS use (160.0%), with relative declines in intra-aortic balloon pump use starting in 2008. Right heart catheterisation rates for both groups remained low (MCS vs. non-MCS: 5.9% vs. 3.3%; p<0.0001). In-hospital mortality declined but remained high in both groups (MCS vs. non-MCS [2014]: 32.7% vs. 41.5%; p<0.0001).

Conclusions: In-hospital mortality for CS has declined but remains high. Rates of CS have outpaced MCS utilisation which remains uncommon in non-MI hospitalisations with shock. MCS is associated with utilisation of other procedures during hospitalisation.

**Corresponding author: Richard A. and Susan F. Smith Center for Outcomes Research in Cardiology, Beth Israel Deaconess Medical Center, 375 Longwood Ave, Fourth Floor, Boston, MA 02215, USA. E-mail: ryeh@bidmc.harvard.edu*

SUBMITTED ON 19/10/2017 - REVISION RECEIVED ON 1st 30/11/2017 / 2nd 25/01/2018 - ACCEPTED ON 26/01/2018

DOI: 10.4244/EIJ-D-17-00947

Abbreviations

CS	cardiogenic shock
ECMO	extracorporeal membrane oxygenation
IABP	intra-aortic balloon pump
ICD-9-CM	International Classification of Diseases, Ninth Revision, Clinical Modification
MCS	mechanical circulatory support
MI	myocardial infarction
ND-MCS	non-durable mechanical circulatory support
NSTEMI	non-ST-elevation myocardial infarction
PCPS	percutaneous cardiopulmonary support
STEMI	ST-elevation myocardial infarction

Introduction

Cardiogenic shock (CS), the inability to maintain adequate perfusion due to failure of the heart's pumping mechanism, is present in 3.5% of patients presenting with acute heart failure and in 6.6% of those presenting with myocardial infarction (MI), with in-hospital mortality rates as high as 70%[1,2]. The recent availability of temporary mechanical circulatory support (MCS) has led to a redefinition of therapeutic options for CS, allowing circulatory support as a bridge to recovery or transplantation[3]. While durable MCS devices such as left ventricular assist devices and the total artificial heart are utilised selectively, the recent availability and rapid expansion of use of percutaneous short-term MCS devices, such as Impella® (Abiomed, Danvers, MA, USA) devices and veno-arterial extracorporeal membrane oxygenation (ECMO), have permitted more widespread availability of circulatory support for CS.

There is a paucity of data on trends in utilisation and outcomes of MCS use in CS[3], incorporating recent technological improvements in therapies. Also, the extent to which changes in MCS use have paralleled overall rates of CS is unknown. Thus, we aimed to identify recent national trends in MCS utilisation in the USA, patient-level predictors of MCS use, and in-hospital outcomes in CS inclusive of ECMO.

Editorial, see page 2099

Methods

STUDY POPULATION

All hospitalisations of adults (≥18 years old) with a diagnosis of CS (International Classification of Diseases, Ninth Revision, Clinical Modification [ICD-9-CM], code 785.51) in any position in the National Inpatient Sample (NIS) from January 2004 up to December 2014 were included. The NIS is the largest publicly available all-payer inpatient healthcare database in the USA, representing a 20% sample of all US hospital discharges[4]. Studies in the NIS are exempt from Institutional Review Board approval at the Beth Israel Deaconess Medical Center.

EXPOSURES AND OUTCOME

The primary exposures of interest **(Supplementary Table 1)** were short-term non-durable MCS (ND-MCS), intra-aortic balloon pump (IABP), centrally cannulated extracorporeal membrane oxygenation (ECMO), and peripherally cannulated ECMO or percutaneous cardiopulmonary support (PCPS), collectively defined as MCS. ND-MCS would typically include percutaneous devices (TandemHeart™ [CardiacAssist Inc., Pittsburgh, PA, USA] and Impella® devices [Abiomed]), as well as non-percutaneous devices (Thoratec paracorporeal ventricular assist device [Thoratec Inc., Pleasanton, CA, USA], AB5000 [Abiomed], BVS 5000 [Abiomed], and CentriMag® [Thoratec Inc.])[3].

Outcomes **(Supplementary Table 1)** included the proportion of CS hospitalisations using MCS, costs, receipt of coronary angiography, percutaneous coronary intervention (PCI), coronary artery bypass grafting (CABG), left heart catheterisation, and right heart catheterisation, rates of cardiac arrest, major bleeding, cerebrovascular accident, and in-hospital mortality[5-7]. Direct in-hospital costs were analysed in aggregate and stratified annually using Healthcare Cost and Utilization Project (HCUP) cost-to-charge ratios, adjusted for inflation using the consumer price index inpatient hospital services inflation multiplier with 2014 as the base year. Hospitalisation for CS was the primary unit of analysis with unweighted discharge estimates presented.

COVARIATES

Patient-level covariates included age, sex, hospital bed size, and 18 clinical and procedural variables previously associated with mortality in CS **(Supplementary Table 2)**[3,8-17]. We stratified hospitalisations by comorbid discharge diagnoses clinically associated with CS, including non-ST-segment elevation MI (NSTEMI), ST-segment elevation MI (STEMI), myocarditis, pulmonary embolism, hypertrophic cardiomyopathy, and infective endocarditis. We additionally determined the top ten primary discharge diagnoses associated with MCS utilisation in CS by device type. Stratification by states or regions was not examined, due to annual variation in sampling of hospitals within states prior to 2012 in the NIS.

STATISTICAL ANALYSIS

We evaluated rates of MCS use over the study period overall and stratified by type of device and comorbid discharge diagnoses. Patient characteristics by MCS receipt were compared via t-tests and chi-square tests. The Mantel-Haenszel trend test was used to assess temporal trends in MCS utilisation by device type. Total direct hospitalisation costs were determined in 2014 US dollars, stratified by type of therapy, using the HCUP cost-to-charge ratio. A multivariable marginal model, accounting for the complex sampling design in the NIS, was used to determine predictors of in-hospital mortality in MCS recipients using all available variables and a logit link. All analyses were carried out with SAS version 9.4 (SAS Institute Inc., Cary, NC, USA) at a two-tailed p-value <0.05.

Results

OVERALL RESULTS

A total of 183,516 hospitalisations (906,382 weighted to national estimates) with CS were included, of which 47,636 (235,048 [25.9%] weighted) received MCS **(Table 1)**. MCS recipients were

younger and less frequently female. More than two thirds (71.6%) of MCS recipients had a diagnosis of MI versus fewer than half (42.9%) of non-recipients (p<0.0001). Among comorbid diagnoses evaluated, rates of MCS use were highest for STEMI (49.6%) followed by myocarditis (41.0%), NSTEMI (26.9%), infective endocarditis (18.7%), hypertrophic cardiomyopathy (17.8%) and pulmonary embolism (12.1%). Most (68.1-73.3%) CS hospitalisations occurred at large hospitals regardless of MCS receipt. The frequency of hospitalisations for CS increased by 214.4% (11,421 to 24,489), disproportionate to MCS use (3,193 to 5,110 [160.0%]). Correspondingly, MCS as a proportion of CS hospitalisation declined starting in 2008 (29.5% to 20.9%).

TYPE OF DEVICE

IABP was the most commonly used device (91.3% of MCS), followed by ND-MCS (5.4%), ECMO (3.2%) and PCPS (0.1%) **(Table 2)**. While the overall number of devices increased across all categories **(Figure 1)**, relative IABP utilisation declined as a proportion of overall MCS use **(Figure 2)**, starting in 2008, concomitant with a rise in other MCS use (ND-MCS, IABP, ECMO: p-value for trend <0.0001; PCPS: p-value for trend=0.2035). Growth of MCS was highest for ECMO (1,421.4%), followed by ND-MCS (1,229.2%), PCPS (216.7%), and IABP (140.5%). Within the ND-MCS category, rates of increase were highest for percutaneous devices (5,830.0%) versus non-percutaneous devices

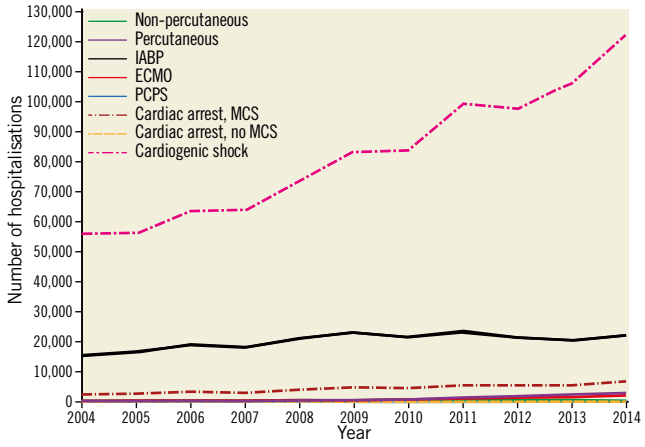


Figure 1. *National estimates of the utilisation of mechanical circulatory support devices in individuals with cardiogenic shock, stratified by device type, 2004-2014. Numbers are weighted at the level of hospitalisation to reflect national estimates of utilisation. Cardiac arrest, MCS: rates of cardiac arrest in individuals receiving MCS; Cardiac arrest, no MCS: rates of cardiac arrest in individuals not receiving MCS; ECMO: centrally cannulated extracorporeal membrane oxygenation; IABP: intra-aortic balloon pump; Non-percutaneous: non-percutaneously implanted non-durable mechanical circulatory support device; PCPS: peripherally cannulated extracorporeal membrane oxygenation; Percutaneous: percutaneously implanted non-durable mechanical circulatory support device*

Table 1. Characteristics of cardiogenic shock patients by receipt of MCS.

Variable		Received MCS (N=47,636)	Did not receive MCS (N=135,880)
Age, years, mean (SD)		65.2±13.1	68.9±14.7
Female sex, n (%)		15,901 (33.4)	58,467 (43.0)
Coronary artery disease, n (%)		31,282 (65.7)	57,800 (42.5)
Receipt of PCI, n (%)		24,243 (50.9)	16,829 (12.4)
Receipt of CABG, n (%)		13,032 (27.4)	9,777 (7.2)
Total revascularisation, n (%)		37,275 (78.2)	26,606 (19.6)
Receipt of haemodialysis, n (%)		3,378 (7.1)	14,287 (10.5)
Chronic kidney disease, n (%)		7,888 (16.6)	36,889 (27.2)
Atrial fibrillation, n (%)		12,990 (27.3)	45,264 (33.3)
Diabetes mellitus, n (%)		14,113 (29.6)	40,628 (29.9)
Heart failure, n (%)		26,390 (55.4)	74,957 (55.2)
Receipt of mechanical ventilation, n (%)		23,959 (50.3)	72,489 (53.4)
Multi-organ system failure, n (%)		4,082 (8.6)	24,897 (18.3)
Prior stroke, n (%)		2,376 (5.0)	9,267 (6.8)
Chronic obstructive pulmonary disease, n (%)		9,283 (19.5)	34,243 (25.2)
Acute kidney injury, n (%)		19,950 (41.9)	65,586 (48.3)
Peripheral arterial disease, n (%)		2,905 (6.1)	10,492 (7.7)
Hospital bed size, n (%)			
Small (<300 beds)		3,189 (6.7)	12,984 (9.6)
Medium (300-499 beds)		9,479 (20.0)	30,164 (22.3)
Large (>500 beds)		34,805 (73.3)	92,147 (68.1)
Comorbid discharge diagnosis of cardiogenic shock, n (%)[a]			
Non-ST-elevation MI (N=51,654; MCS rate 26.9%)		13,920 (29.2)	37,734 (27.8)
ST-elevation MI (N=40,798; MCS rate 49.6%)		20,231 (42.4)	20,567 (15.1)
Myocarditis (N=781; MCS rate 41.0%)		320 (0.7)	461 (0.3)
Pulmonary embolism (N=5,294; MCS rate 12.1%)		639 (1.3)	4,655 (3.4)
Hypertrophic cardiomyopathy (N=192; MCS rate 17.8%)		34 (0.1)	158 (0.1)
Infective endocarditis (N=2,105; MCS rate 18.7%)		393 (0.8)	1,712 (1.3)
Year of evaluation	**Total, n (%)**		
2004	11,421 (6.2)	3,193 (27.9)	8,228 (72.0)
2005	11,519 (6.3)	3,452 (30.0)	8,067 (70.0)
2006	13,084 (7.1)	3,952 (30.2)	9,132 (69.8)
2007	12,980 (7.1)	3,758 (29.0)	9,222 (71.0)
2008	14,883 (8.1)	4,388 (29.5)	10,495 (70.5)
2009	16,720 (9.1)	4,811 (28.8)	11,909 (71.2)
2010	16,742 (9.1)	4,470 (26.7)	12,272 (73.3)
2011	20,837 (11.4)	5,209 (25.0)	15,628 (75.0)
2012	19,583 (10.7)	4,669 (23.8)	14,914 (76.2)
2013	21,258 (11.6)	4,624 (21.8)	16,634 (78.2)
2014	24,489 (13.3)	5,110 (20.9)	19,379 (79.1)

[a]Percentages represent proportion of MCS or non-MCS hospitalisations with comorbid discharge diagnosis. All *p*-values for comparisons less than 0.0001 except diabetes mellitus (p=0.0794) and hypertrophic cardiomyopathy (p=0.0083). MCS: mechanical circulatory support

Table 2. Rates of MCS use and type of device used in National Inpatient Sample.

Year of evaluation	Type of device used		IABP	ECMO	PCPS
	ND-MCS (percutaneous)	ND-MCS (non-percutaneous)			
Total, N (%)	1,990 (4.1%)	716 (1.4%)	45,188 (91.2%)	1,568 (3.2%)	71 (0.1%)
2004 (N=3,231 [6.5%])	1 (0.0%)	47 (1.4%)	3,149 (97.5%)	28 (0.9%)	6 (0.2%)
2005 (N=3,504 [7.1%])	9 (0.2%)	45 (1.3%)	3,423 (97.7%)	24 (0.7%)	3 (0.1%)
2006 (N=3,998 [8.0%])	11 (0.3%)	51 (1.3%)	3,913 (97.9%)	19 (0.5%)	4 (0.1%)
2007 (N=3,815 [7.7%])	16 (0.4%)	49 (1.3%)	3,717 (97.4%)	30 (0.8%)	3 (0.1%)
2008 (N=4,483 [9.0%])	37 (0.8%)	86 (2.0%)	4,282 (95.5%)	69 (1.5%)	9 (0.2%)
2009 (N=4,972 [10.4%])	93 (1.9%)	94 (1.9%)	4,660 (93.7%)	120 (2.4%)	5 (0.1%)
2010 (N=4,648 [9.4%])	139 (3.0%)	70 (1.5%)	4,306 (92.5%)	129 (2.9%)	4 (0.1%)
2011 (N=5,508 [11.1%])	280 (5.1%)	93 (1.7%)	4,930 (89.5%)	202 (3.7%)	3 (0.1%)
2012 (N=4,955 [10.0%])	371 (7.5%)	65 (1.3%)	4,260 (86.0%)	251 (5.0%)	8 (0.2%)
2013 (N=4,933 [10.0%])	450 (9.1%)	55 (1.2%)	4,123 (83.6%)	298 (6.0%)	7 (0.1%)
2014 (N=5,486 [11.0%])	583 (10.6%)	61 (1.1%)	4,425 (80.7%)	398 (7.3%)	19 (0.3%)
Rate of increase, n (%)	582 (5,830.0%)	14 (129.8%)	1,276 (140.5%)	370 (1,421.4%)	13 (216.7%)
Comorbid diagnosis associated with cardiogenic shock, n (%)[a]	**ND-MCS (percutaneous)**	**ND-MCS (non-percutaneous)**	**IABP**	**ECMO**	**PCPS**
Non-ST-elevation MI (N=14,342)	616 (4.3%)	119 (0.8%)	13,326 (92.9%)	271 (1.9%)	10 (0.1%)
ST-elevation MI (N=20,810)	671 (3.2%)	198 (0.9%)	19,657 (94.0%)	267 (1.3%)	17 (0.1%)
Myocarditis (N=363)	42 (11.6%)	26 (7.2%)	243 (66.9%)	52 (14.3%)	0 (0%)
Pulmonary embolism (N=685)	29 (4.2%)	20 (3.0%)	528 (77.0%)	106 (15.5%)	2 (0.3%)
Hypertrophic cardiomyopathy (N=38)	2 (5.2%)	2 (5.2%)	28 (73.8%)	6 (15.8%)	0 (0%)
Infective endocarditis (N=430)	6 (1.4%)	17 (3.9%)	362 (84.2%)	45 (10.5%)	0 (0%)

[a]Percentages represent proportion of patients with comorbid diagnosis and cardiogenic shock with type of device. All *p*-values for trend test for device type by year less than 0.0001 except PCPS (*p* for trend=0.2035). ECMO: extracorporeal membrane oxygenation; IABP: intra-aortic balloon pump; ND-MCS: non-durable mechanical circulatory support; PCPS: percutaneous cardiopulmonary support

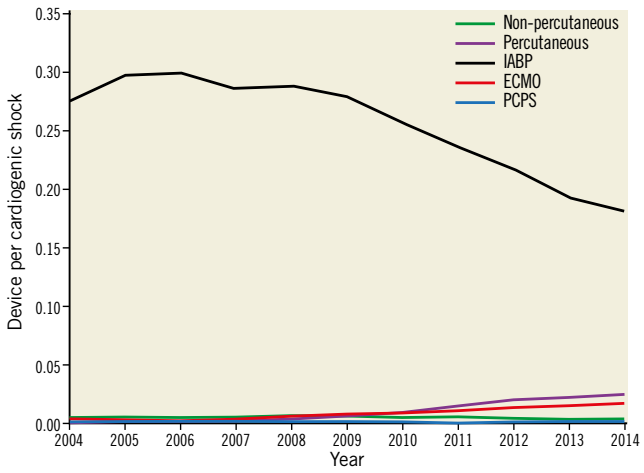


Figure 2. *Proportion of cardiogenic shock hospitalisations receiving mechanical circulatory support by device type, 2004-2014. ECMO: centrally cannulated extracorporeal membrane oxygenation; IABP: intra-aortic balloon pump; Non-percutaneous: non-percutaneously implanted non-durable mechanical circulatory support device; Percutaneous: percutaneously implanted non-durable mechanical circulatory support device; PCPS: peripherally cannulated extracorporeal membrane oxygenation*

(129.8%). IABP was the most commonly used device in MI, utilised in 92.9% of CS with concomitant non-ST-elevation MI (NSTEMI) diagnosis and 94.0% with STEMI. NSTEMI (ICD-9-CM 410.71) represented the most common discharge diagnosis associated with MCS (18.9% of hospitalisations using IABP, 17.3% using ND-MCS, 7.5% using ECMO, and 2.8% using PCPS) **(Supplementary Table 3)**.

UNADJUSTED OUTCOMES

Rates of concomitant cardiac procedures were higher in MCS recipients **(Table 3)**, with half (50.9%) receiving PCI and one quarter (27.4%) receiving CABG. Right heart catheterisation rates were low (MCS vs. non-MCS 5.9% vs. 3.3%; p<0.0001). Cardiac arrest (21.1%) and major bleeding (14.9%) were more common in MCS recipients. There were no significant differences in rates of stroke between MCS (3.2%) and non-MCS recipients (3.1%; p=0.77). There were 15,558 in-hospital deaths in the MCS group versus 56,428 in the non-MCS group (in-hospital mortality 32.7% vs. 41.5%, respectively; p<0.0001). In-hospital mortality declined in both groups from a peak of 37.6% in 2004 for MCS recipients and 52.1% for non-MCS recipients to 33.5% and 38.9% in 2014 for MCS vs. non-MCS recipients, respectively **(Supplementary Figure 1)**.

ADJUSTED OUTCOMES

Multivariable predictors of in-hospital mortality in the subgroup receiving MCS are presented in **Supplementary Figure 2**. Age was associated with a 35% increase in odds of in-hospital mortality per decade (adjusted odds ratio [AOR] 1.35, 95% CI: 1.32-1.37, p<0.0001). Female gender was associated with a 15% increase in odds for in-hospital mortality (AOR 1.15, 95% CI: 1.10-1.20, p<0.0001). The highest risk conditions were cardiac arrest (AOR 2.05, 95% CI: 1.94-2.16, p<0.0001) and receipt of mechanical ventilation (AOR 1.89, 95% CI: 1.80-2.00, p<0.0001). The adjusted odds of in-hospital mortality for patients receiving MCS (using year 2004 as reference) declined until 2008 and were constant thereafter **(Supplementary Figure 3)**.

COSTS OF HOSPITALISATION

Overall direct hospitalisation costs for MCS patients were $23,530 higher (MCS vs. non-MCS median [IQR] cost in 2014 US dollars: $48,059 [29,148-79,722] vs. $24,529 [11,811-48,098]; p<0.0001) **(Table 3)**. This relationship remained constant over the study period.

Table 3. Outcomes of cardiogenic shock patients by receipt of MCS.

Outcome	Received MCS (N=47,636)	Did not receive MCS (N=135,880)
Direct hospital costs ($), median (IQR)	48,059 (29,148-79,722)	24,529 (11,811-48,098)
In-hospital mortality, n (%)	15,558 (32.7%)	56,428 (41.5%)
Cardiac arrest, n (%)	10,053 (21.1%)	24,959 (18.4%)
Major bleeding, n (%)	7,081 (14.9%)	15,814 (11.6%)
Cerebrovascular accident, n (%)	1,499 (3.2%)	4,239 (3.1%)
Receipt of procedure, n (%)		
Coronary angiography	38,647 (81.1%)	35,885 (26.4%)
PCI	24,243 (50.9%)	16,829 (12.4%)
CABG	13,032 (27.4%)	9,777 (7.2%)
Total revascularisation	37,275 (78.2%)	26,606 (19.6%)
Left heart catheterisation	25,776 (54.0%)	23,024 (16.9%)
Right heart catheterisation	2,815 (5.9%)	4,419 (3.3%)

All *p*-values for comparisons <0.0001. IQR: interquartile range; MCS: mechanical circulatory support; PCI: percutaneous coronary intervention

Discussion

Despite rising rates of hospitalisation for CS, recent national trends in MCS use have not been evaluated. Our study demonstrates that CS hospitalisations increased faster than MCS utilisation. Additionally, there was a decline in IABP use relative to other forms of MCS starting in 2008. Over two thirds of MCS recipients had a concomitant diagnosis of MI. Procedures were more common in MCS recipients, though rates of right heart catheterisation remained under 6%, regardless of therapy. Hospitalisation costs were greater for MCS recipients and remained stable. In-hospital mortality for CS declined over the study period, with greater declines in MCS recipients, remaining above 30%.

These data suggest that physicians may be using MCS less frequently in CS, or that CS admissions are increasing faster than the current capacity to place MCS devices. Additionally, physicians are increasingly selecting ND-MCS, particularly percutaneous devices, and ECMO in lieu of IABP. The observed relative decline in utilisation may reflect growing uncertainty about the importance of IABP in CS, given the publication of multiple trials from 2007-2012 suggesting the lack of efficacy of IABP in patients presenting with MI complicated by CS[18-20]. As a result, the 2017 European Society of Cardiology guidelines for management of patients with acute myocardial infarction (AMI) downgraded IABP use to class III for use in CS[21]. Regardless, it remained the most common MCS device, with usage rates nearly sevenfold higher than the next most common device. While the majority of CS hospitalisations were managed at large hospitals, it remains unclear whether the observed relative decline in utilisation of MCS is due to a hospital's inability to offer MCS to individuals presenting with CS. This merits further research.

Second, while safety and efficacy have been demonstrated previously for multiple aetiologies[22-25], utilisation of MCS for CS outside of MI was less common, with rates of use of 41.0% in myocarditis and 12.1% in pulmonary embolism complicated by shock. The Extracorporeal Life Support Organization (ELSO) multicentre registry has reported survival to hospital discharge as high as 67% in myocarditis patients receiving ECMO, suggesting an expanded role for ECMO in short-term support[26,27]. Data are more limited to support its use in pulmonary embolism[28]. The infrequent utilisation of MCS in these settings may suggest an opportunity to improve upon the haemodynamic support of patients with non-MI conditions and shock, though optimal use needs to be further defined.

Third, MCS recipients had lower rates of comorbidities and more frequently received cardiac procedures. While this finding may reflect an appropriate response to the perceived futility of such interventions for the highest acuity patients, it suggests that MCS patients receive more aggressive care overall as part of a "procedural bundle". Thus, the lower in-hospital mortality seen in MCS patients may not only reflect the underlying selection of healthier patients for more aggressive treatment but also the impact of other interventions. Hospitalisation costs were $23,530 higher in MCS recipients, which may reflect differences in patient and hospital characteristics, the costs of the MCS device, and concomitant interventions. Of note, right heart catheterisation was uncommon with overall rates <6%. This finding may possibly reflect emergent MCS implantation or scepticism about the role of right heart catheterisation[29-31]. Whether more routine use of right heart catheterisation in this setting would improve overall shock outcomes is unknown and warrants further evaluation.

Fourth, despite improvements in CS care[22,32], survival remains very low, with over 30% of patients dying prior to discharge regardless of receipt of MCS. While in-hospital mortality declined in both MCS and non-MCS recipients, survival plateaued after 2008. The proportional decrease in mortality over this time period may be due to secular trends in the management of cardiogenic shock patients. The high and stable mortality in this population, regardless of receipt of MCS, reflects the acuity of this condition and suggests the urgent need for new management strategies.

Limitations

There are several limitations of the current study. First, the study is retrospective and included a limited number of variables, which are probably related, and causality cannot be inferred. Second, the timing of MCS relative to other diagnoses noted on discharge cannot be discerned. Third, inaccuracies in coding may reduce precision and interpretation of the results. Fourth, as the hospitals sampled in the NIS differ annually, no hospital level comparisons could be made across years and may not fully reflect national trends. Lastly, as costs were derived from hospital charges, they may not represent the total direct or induced costs or cost-effectiveness of MCS therapy.

Conclusions

Despite improvements in survival for CS over time, in-hospital mortality remains high. Relative utilisation of IABP has declined since 2008, though continues to increase in volume. Hospitalisations for CS have outpaced increases in overall MCS use. MCS use remains uncommon outside of MI presentations and is associated with an overall increase in the rates of concomitant procedures and costs during hospitalisation for CS.

Impact on daily practice

Rates of cardiogenic shock have outpaced MCS utilisation. MCS use remains uncommon outside myocardial infarction with high mortality (32.7%) and high utilisation of other procedures.

Funding

This work was supported by an investigator-initiated grant from Abiomed, Danvers, MA, USA. Members of the study team are additionally supported by funding from the National Heart, Lung, and Blood Institute (1F32HL1407-11 to J.B. Strom, R01HS024520-01 to C. Shen and 1R01HL136708-01 to R.W. Yeh). The funding organisations had no role in the final edits or submission of this manuscript.

Conflict of interest statement

J. Popma reports grants from Medtronic, Abbott Vascular, and Direct Flow Medical and personal fees from Boston Scientific, Cordis, and Direct Flow Medical, outside the submitted work. D. Pinto reports personal fees from Medtronic, The Medicines Company, Medicure, and Abiomed, outside the submitted work. R. Yeh reports investigator-initiated grant funding from Abiomed related to the conduct of the study, grant support from Boston Scientific, and consulting fees from Abbott, Medtronic, and Teleflex, outside the submitted work. The other authors have no conflicts of interest to declare.

References

1. Adams KF Jr, Fonarow GC, Emerman CL, LeJemtel TH, Costanzo MR, Abraham WT, Berkowitz RL, Galvao M, Horton DP; ADHERE Scientific Advisory Committee and Investigators. Characteristics and outcomes of patients hospitalized for heart failure in the United States: rationale, design, and preliminary observations from the first 100,000 cases in the Acute Decompensated Heart Failure National Registry (ADHERE). *Am Heart J.* 2005; 149:209-16.

2. Babaev A, Frederick PD, Pasta DJ, Every N, Sichrovsky T, Hochman JS; NRMI Investigators. Trends in management and outcomes of patients with acute myocardial infarction complicated by cardiogenic shock. *JAMA.* 2005;294:448-54.

3. Stretch R, Sauer CM, Yuh DD, Bonde P. National trends in the utilization of short-term mechanical circulatory support: incidence, outcomes, and cost analysis. *J Am Coll Cardiol.* 2014;64: 1407-15.

4. Healthcare Cost and Utilization Project (HCUP). 2006-2014. Agency for Healthcare Research and Quality. http://www.hcup-us.ahrq.gov/databases.jsp (accessed 6 October 2017).

5. Strom JB, McCabe JM, Waldo SW, Pinto DS, Kennedy KF, Feldman DN, Yeh RW. Management of Patients With Cardiac Arrest Complicating Myocardial Infarction in New York Before and After Public Reporting Policy Changes. *Circ Cardiovasc Interv.* 2017 May;10(5).

6. Foy AJ, Liu G, Davidson WR Jr, Sciamanna C, Leslie DL. Comparative effectiveness of diagnostic testing strategies in emergency department patients with chest pain: an analysis of downstream testing, interventions, and outcomes. *JAMA Intern Med.* 2015;175:428-36.

7. Wiener RS, Welch HG. Trends in the use of the pulmonary artery catheter in the United States, 1993-2004. *JAMA.* 2007;298: 423-9.

8. Elixhauser Comorbidity Software. Healthcare Cost and Utilization Project (HCUP). Rockville, MD: Agency for Healthcare Research and Quality; 2008. Available from: http://www.hcup-us.ahrq.gov/toolssoftware/comorbidity/comorbidity.jsp (accessed 6 October 2017).

9. Hasdai D, Holmes DR Jr, Califf RM, Thompson TD, Hochman JS, Pfisterer M, Topol EJ. Cardiogenic shock complicating acute myocardial infarction: predictors of death. GUSTO Investigators. Global Utilization of Streptokinase and Tissue-Plasminogen Activator for Occluded Coronary Arteries. *Am Heart J.* 1999;138:21-31.

10. Holmes DR Jr, Berger PB, Hochman JS, Granger CB, Thompson TD, Califf RM, Vahanian A, Bates ER, Topol EJ.

Cardiogenic shock in patients with acute ischemic syndromes with and without ST-segment elevation. *Circulation.* 1999;100:2067-73.

11. Katz JN, Stebbins AL, Alexander JH, Reynolds HR, Pieper KS, Ruzyllo W, Werdan K, Geppert A, Dzavik V, Van de Werf F, Hochman JS; TRIUMPH Investigators. Predictors of 30-day mortality in patients with refractory cardiogenic shock following acute myocardial infarction despite a patent infarct artery. *Am Heart J.* 2009;158:680-7.

12. Crenshaw BS, Ward SR, Granger CB, Stebbins AL, Topol EJ, Califf RM. Atrial fibrillation in the setting of acute myocardial infarction: the GUSTO-I experience. Global Utilization of Streptokinase and TPA for Occluded Coronary Arteries. *J Am Coll Cardiol.* 1997;30:406-13.

13. Lin MJ, Chen CY, Lin HD, Wu HP. Prognostic Analysis for Cardiogenic Shock in Patients with Acute Myocardial Infarction Receiving Percutaneous Coronary Intervention. *Biomed Res Int.* 2017;2017:8530539.

14. Reynolds HR, Hochman JS. Cardiogenic shock: current concepts and improving outcomes. *Circulation.* 2008;117:686-97.

15. Pöss J, Köster J, Fuernau G, Eitel I, de Waha S, Ouarrak T, Lassus J, Harjola VP, Zeymer U, Thiele H, Desch S. Risk Stratification for Patients in Cardiogenic Shock After Acute Myocardial Infarction. *J Am Coll Cardiol.* 2017;69:1913-20.

16. Wakabayashi K, Gonzalez MA, Delhaye C, Ben-Dor I, Maluenda G, Collins SD, Syed AI, Gaglia MA Jr, Torguson R, Xue Z, Suddath WO, Satler LF, Kent KM, Lindsay J, Pichard AD, Waksman R. Impact of chronic obstructive pulmonary disease on acute-phase outcome of myocardial infarction. *Am J Cardiol.* 2010;106:305-9.

17. Figueras J, Baneras J, Pena-Gil C, Barrabes JA, Rodriguez Palomares J, Garcia Dorado D. Hospital and 4-Year Mortality Predictors in Patients With Acute Pulmonary Edema With and Without Coronary Artery Disease. *J Am Heart Assoc.* 2016 Feb 16;5(2).

18. Thiele H, Zeymer U, Neumann FJ, Ferenc M, Olbrich HG, Hausleiter J, Richardt G, Hennersdorf M, Empen K, Fuernau G, Desch S, Eitel I, Hambrecht R, Fuhrmann J, Böhm M, Ebelt H, Schneider S, Schuler G, Werdan K; IABP-SHOCK II Trial Investigators. Intraaortic balloon support for myocardial infarction with cardiogenic shock. *N Engl J Med.* 2012;367:1287-96.

19. Prondzinsky R, Lemm H, Swyter M, Wegener N, Unverzagt S, Carter JM, Russ M, Schlitt A, Buerke U, Christoph A, Schmidt H, Winkler M, Thiery J, Werdan K, Buerke M. Intra-aortic balloon counterpulsation in patients with acute myocardial infarction complicated by cardiogenic shock: the prospective, randomized IABP SHOCK Trial for attenuation of multiorgan dysfunction syndrome. *Crit Care Med.* 2010;38:152-60.

20. Sjauw KD, Engström AE, Vis MM, van der Schaaf RJ, Baan J Jr, Koch KT, de Winter RJ, Piek JJ, Tijssen JG, Henriques JP. A systematic review and meta-analysis of intra-aortic balloon pump therapy in ST-elevation myocardial infarction: should we change the guidelines? *Eur Heart J.* 2009;30:459-68.

21. Ibanez B, James S, Agewall S, Antunes MJ, Bucciarelli-Ducci C, Bueno H, Caforio ALP, Crea F, Goudevenos JA, Halvorsen S, Hindricks G, Kastrati A, Lenzen MJ, Prescott E, Roffi M, Valgimigli M, Varenhorst C, Vranckx P, Widimsky P; ESC Scientific Document Group. 2017 ESC Guidelines for the management of acute myocardial infarction in patients presenting with ST-segment elevation: The Task Force for the management of acute myocardial infarction in patients presenting with ST-segment elevation of the European Society of Cardiology (ESC). *Eur Heart J.* 2018;39:119-77.

22. Spratt JR, Raveendran G, Liao K, John R. Novel percutaneous mechanical circulatory support devices and their expanding applications. *Expert Rev Cardiovasc Ther.* 2016;14:1133-50.

23. Brown JL, Estep JD. Temporary Percutaneous Mechanical Circulatory Support in Advanced Heart Failure. *Heart Fail Clin.* 2016;12:385-98.

24. Agrawal H, Aggarwal K. Mechanical Circulatory Support in Percutaneous Coronary Interventions: Expanding the Possibilities. *J Invasive Cardiol.* 2016;28:243-5.

25. Miller L. Cardiogenic Shock in Acute Myocardial Infarction: The Era of Mechanical Support. *J Am Coll Cardiol.* 2016;67:1881-4.

26. Paden ML, Rycus PT, Thiagarajan RR; ELSO Registry. Update and outcomes in extracorporeal life support. *Semin Perinatol.* 2014;38:65-70.

27. Diddle JW, Almodovar MC, Rajagopal SK, Rycus PT, Thiagarajan RR. Extracorporeal membrane oxygenation for the support of adults with acute myocarditis. *Crit Care Med.* 2015;43:1016-25.

28. Harjola VP, Mebazaa A, Celutkiene J, Bettex D, Bueno H, Chioncel O, Creso-Leiro MG, Falk V, Filippatos G, Gibbs S, Leite-Moreira A, Lassus J, Masjip J, Mueller C, Mullens W, Naeije R, Nordegraaf AV, Parissis J, Riley JP, Ristic A, Rosano G, Rudiger A, Ruschitzka F, Seferovic P, Sztrymf B, Viellard-Baron A, Yilmaz MB, Konstantinides S. Contemporary management of acute right ventricular failure: a statement from the Heart Failure Association and the Working Group on Pulmonary Circulation and Right Ventricular Function of the European Society of Cardiology. *Eur J Heart Fail.* 2016;18:226-41.

29. Binanay C, Califf RM, Hasselblad V, O'Connor CM, Shah MR, Sopko G, Stevenson LW, Francis GS, Leier CV, Miller LW; ESCAPE Investigators and ESCAPE Study Coordinators. Evaluation study of congestive heart failure and pulmonary artery catheterization effectiveness: the ESCAPE trial. *JAMA.* 2005;294:1625-33.

30. Khera R, Pandey A, Kumar N, Singh R, Bano S, Golwala H, Kumbhani DJ, Girotra S, Fonarow GC. Variation in Hospital Use and Outcomes Associated With Pulmonary Artery Catheterization in Heart Failure in the United States. *Circ Heart Fail.* 2016 Nov;9(11).

31. Pandey A, Khera R, Kumar N, Golwala H, Girotra S, Fonarow GC. Use of Pulmonary Artery Catheterization in US Patients With Heart Failure, 2001-2012. *JAMA Intern Med.* 2016;176:129-32.

32. Lim HS. Cardiogenic Shock: Failure of Oxygen Delivery and Oxygen Utilization. *Clin Cardiol*. 2016;39:477-83.

Supplementary data

Supplementary Table 1. Administrative codes used to define exposures, major covariates, and outcomes.

Supplementary Table 2. Comorbid conditions adjusted for in the regression model and representative administrative codes.

Supplementary Table 3. Top ten primary discharge diagnoses in hospitalisations involving mechanical circulatory support and cardiogenic shock by device type.

Supplementary Figure 1. Proportion of hospitalisations resulting in death by receipt of mechanical circulatory support, 2004-2014.

Supplementary Figure 2. Multivariable predictors of in-hospital mortality in the subgroup receiving mechanical circulatory support.

Supplementary Figure 3. Adjusted odds ratio for likelihood of in-hospital mortality by year in patients receiving mechanical circulatory support.

The supplementary data are published online at: http://www.pcronline.com/eurointervention/133rd_issue/356

Supplementary data

Supplementary Table 1. Administrative codes used to define exposures, major covariates, and outcomes.

Variable name	ICD-9-CM code
ND-MCS	
Percutaneous	37.68
Non-percutaneous	37.60
IABP	37.61
ECMO	39.65
PCPS	39.66
Coronary angiography	37.21, 37.22, 37.23, 88.52, 88.53, 88.54, 88.55, 88.56, 88.57
PCI	00.66, 17.55, 36.01, 36.02, 36.05, 36.06, 36.07
CABG	36.10-36.17, 36.19
Left heart catheterisation	37.22
Right heart catheterisation	37.21
Cardiac arrest	427.5
Major bleeding	998.11, 998.12, 530.82, 531.37, 531.0-537.0, 562.0, 578.X, 599.7, 430.X, 431.X, 432.0, and 432.9
Cerebrovascular accident	433.X1, 434.X1, and 436.0
Non-ST-elevation MI	410.71 and 410.91
ST-elevation MI	410.11-410.61 and 410.81
Myocarditis	429.0, 422.90, and 422.91
Pulmonary embolism	415.1X
Hypertrophic cardiomyopathy	425.11
Infective endocarditis	421.0, 421.1, 421.9

Supplementary Table 2. Comorbid conditions adjusted for in the regression model and representative administrative codes.

Variable name	ICD-9 code
Coronary artery disease	414.01, 414.3-4, 434.06, 410.X
Receipt of PCI	00.66, 17.55, 36.01, 36.02, 36.05, 36.06, and 36.07
Receipt of CABG	36.10-36.17, 36.19
Receipt of haemodialysis	39.95
History of chronic kidney disease	585.1-5, 585.6, 585.81, 585.9, 403.9
Atrial fibrillation	427.31-32
Diabetes mellitus	250.X
Heart failure	402.01, 402.11, 402.91, 404.01, 404.03, 404.13, 404.91, 404.93, 428.0, 428.1, 428.2X, 428.3X, 428.4X
Receipt of mechanical ventilation	96.7X, 96.04
Multi-organ system failure	995.92
Prior stroke or TIA	V12.54, V15.52, 438.0-9, 434.11, 434.91, 435.9X, 434.01, 437.1-2, 997.02, 432.9, 348.89, 437.9
Chronic obstructive pulmonary disease	490-492.8, 493.00-493.92, 494-494.1, 495.0-505, 506.4
Acute kidney injury	584.5-584.9
Peripheral arterial disease	443.9, 250.7, 443.81, 440.2X
NSTEMI	410.71 and 410.91
ST-elevation MI	410.11-410.61, and 410.81
Myocarditis	429.0, 422.90, and 422.91
Pulmonary embolism	415.1X
Hypertrophic cardiomyopathy	425.11
Infective endocarditis	421.0, 421.1, 421.9

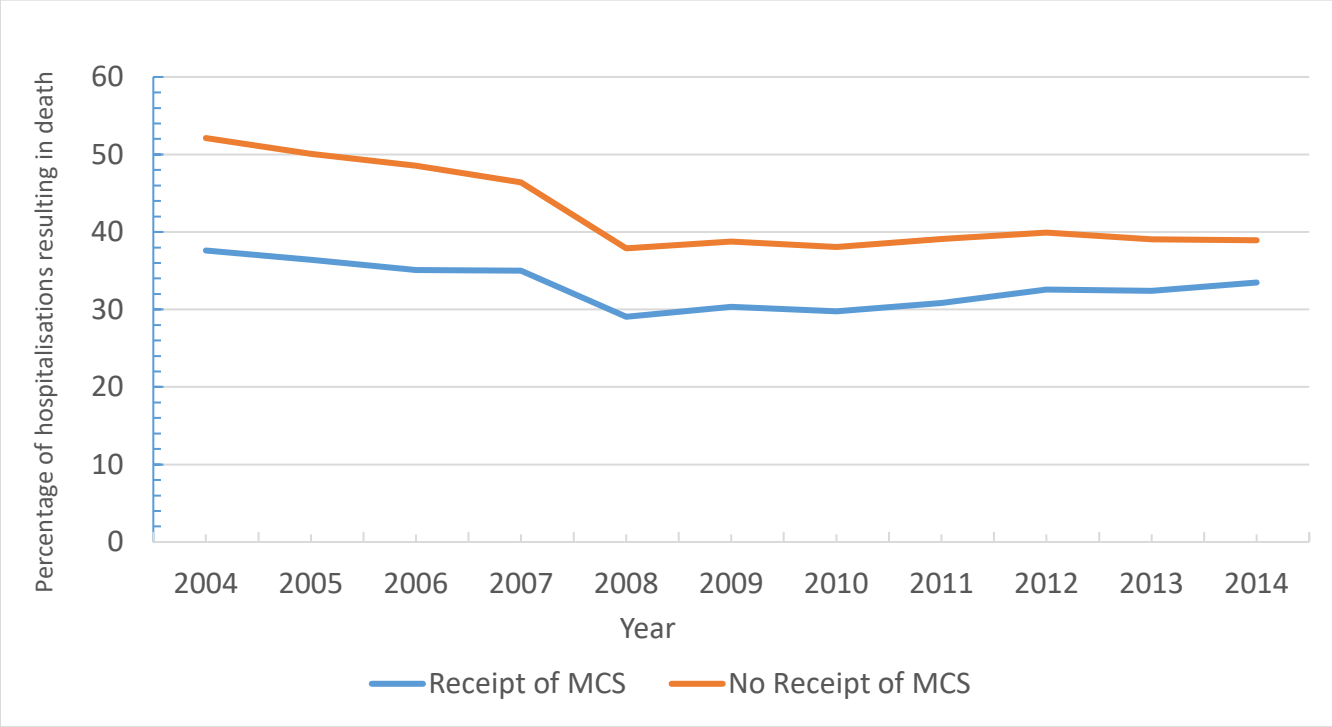
Supplementary Table 3. Top ten primary discharge diagnoses in hospitalisations involving mechanical circulatory support and cardiogenic shock by device type.

	Type of device used			
	ND-MCS (N=2,674)		**IABP (N=45,188)**	
	Diagnosis (ICD-9-CM code)	**Frequency (%)**	**Diagnosis (ICD-9-CM code)**	**Frequency (%)**
1	Non-ST-elevation MI (410.71)	462 (17.3%)	Non-ST-elevation MI (410.71)	8,561 (18.9%)
2	Acute anterior MI (410.11)	400 (15.0%)	Acute anterior MI (410.11)	8,177 (18.1%)
3	Atherosclerosis of coronary arteries (414.01)	180 (6.7%)	Acute inferior MI (410.41)	5,613 (12.4%)
4	Acute inferior MI (410.41)	179 (6.7%)	Atherosclerosis of coronary arteries (414.01)	3,089 (6.8%)
5	Acute anterolateral MI (410.01)	143 (5.3%)	Acute anterolateral MI (410.01)	2,845 (6.3%)
6	Acute on chronic systolic HF (428.23)	101 (3.8%)	Acute MI, unspecified site (410.91)	1,932 (4.3%)
7	Acute MI, unspecified site (410.91)	92 (3.4%)	Acute inferolateral MI (410.21)	1,279 (2.8%)
8	Ventricular tachycardia (427.1)	75 (2.8%)	Acute inferoposterior MI (410.31)	1,106 (2.4%)
9	Heart failure, unspecified (428.0)	73 (2.7%)	Heart failure, unspecified (428.0)	888 (2.0%)
10	Aortic valve disorders (424.1)	71 (2.7%)	Aortic valve disorders (424.1)	789 (1.7%)
	ECMO (N=1,568)		**PCPS (N=71)**	
	Diagnosis (ICD-9-CM code)	**Frequency (%)**	**Diagnosis (ICD-9-CM code)**	**Frequency (%)**
1	Non-ST-elevation MI (410.71)	117 (7.5%)	Aortic valve disorders (424.1)	11 (15.5%)
2	Acute anterior MI (410.11)	104 (6.6%)	Atherosclerosis of coronary arteries (414.01)	9 (12.7%)
3	Aortic valve disorders (424.1)	83 (5.3%)	Acute anterior MI (410.11)	8 (11.3%)
4	Acute inferior MI (410.41)	65 (4.1%)	Mitral valve disorders (424.0)	4 (5.6%)
5	Atherosclerosis of coronary arteries (414.01)	65 (4.1%)	Dissection of aorta, thoracic (441.01)	3 (4.2%)

6	Acute on chronic systolic HF (428.23)	51 (3.3%)	Acute anterolateral MI (410.01)	2 (2.8%)
7	Septicaemia, unspecified (038.9)	47 (3.0%)	Acute inferior MI (410.41)	2 (2.8%)
8	Heart failure, unspecified (428.0)	46 (2.9%)	Non-ST-elevation MI (410.71)	2 (2.8%)
9	Complications of transplanted heart (996.83)	46 (2.9%)	Acute MI, not elsewhere classified (410.81)	2 (2.8%)
10	Acute respiratory failure (518.81)	41 (2.6%)	Pulmonary embolism (415.19)	2 (2.8%)

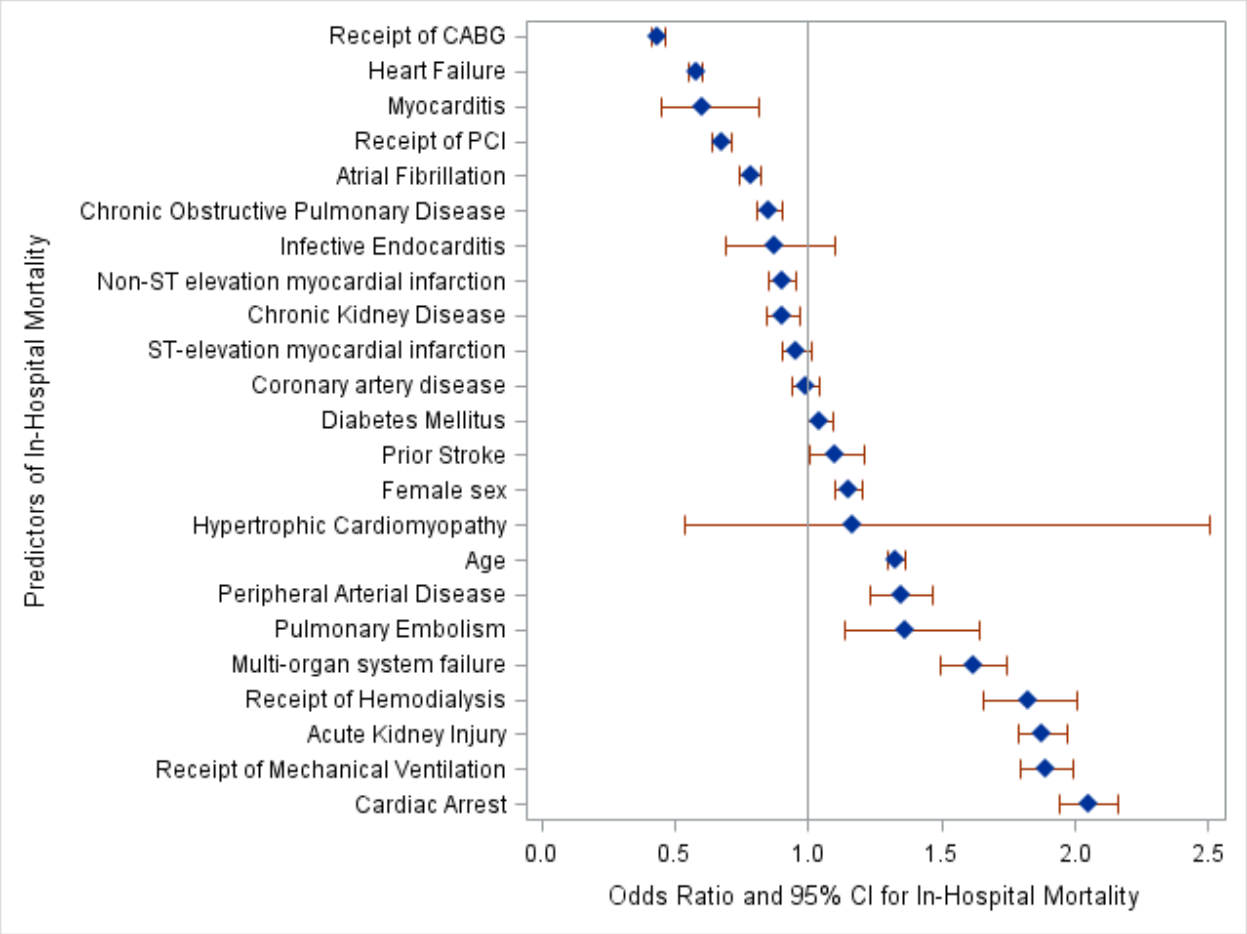
ECMO: centrally cannulated extracorporeal membrane oxygenation; IABP: intra-aortic balloon pump; ICD-9-CM: International Classification of Diseases, Ninth Revision, Clinical Modification; ND-MCS: non-durable mechanical circulatory support device; PCPS: peripherally cannulated extracorporeal membrane oxygenation

Supplementary Figure 1. Proportion of hospitalisations resulting in death by receipt of mechanical circulatory support, 2004-2014.



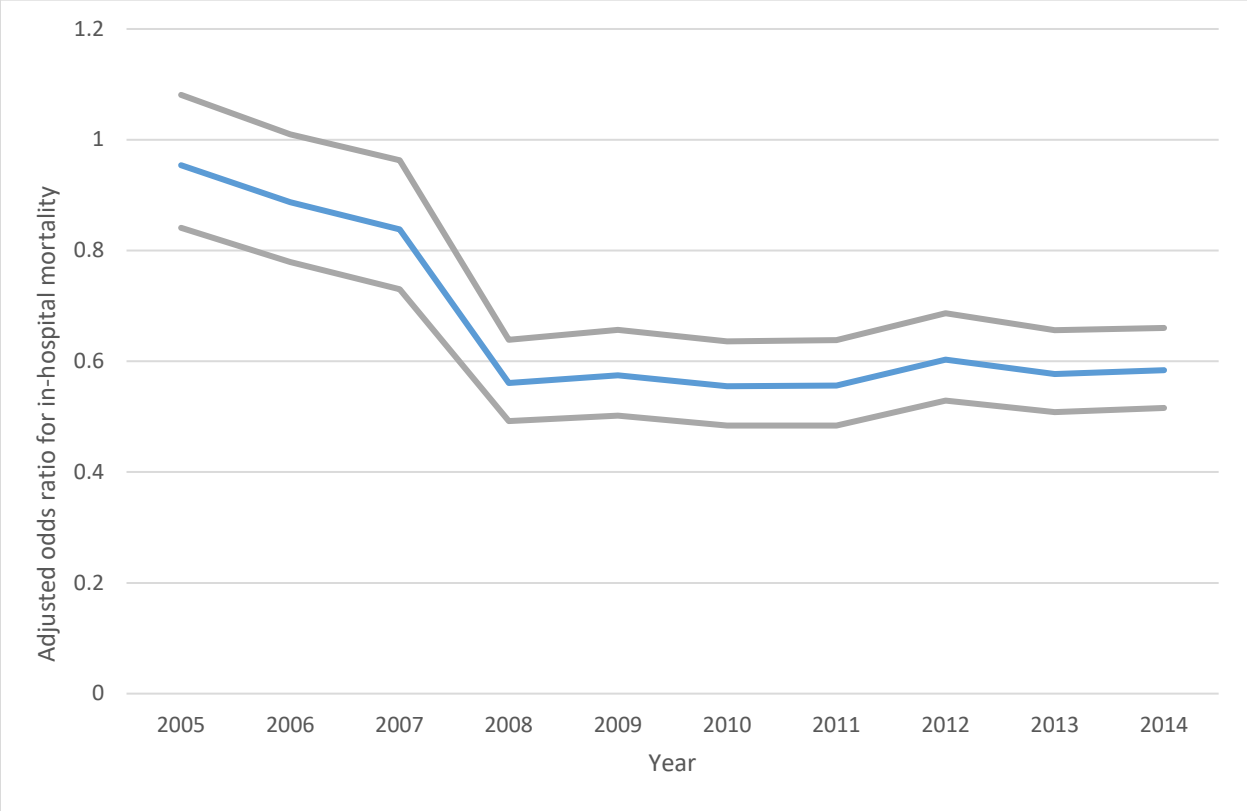
MCS: mechanical circulatory support

Supplementary Figure 2. Multivariable predictors of in-hospital mortality in subgroup receiving mechanical circulatory support.



CI: confidence interval; MCS: mechanical circulatory support

Supplementary Figure 3. Adjusted odds ratio for likelihood of in-hospital mortality by year in patients receiving mechanical circulatory support.



Blue line: adjusted odds ratio estimates with 2004 as the comparison year.
Grey lines: lower and upper 95% confidence limits. Year treated as categorical variable in model.