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Research article

Pulmonary artery catheter receipt among cardiac surgery patients from the national inpatient sample (1999–2019): Prevalence, predictors and hospitalization charges

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ABSTRACT

Despite limited evidence to support its efficacy, use of pulmonary artery catheter (PAC), a relatively expensive medical device, for monitoring clinical status and guiding therapeutic interventions, has become standard of care in many settings, and especially during and after cardiac surgery. We examined the prevalence and predictors of PAC use and its association with hospitalization charges among cardiac surgery patients generally and for each selected subgroup of high-risk or complex surgical procedures. We conducted an analysis on 1,442,528 records from the National Inpatient Sample (1999–2019) that included cardiac surgery patients ≥18 years of age. Subgroups were categorized based on the presence of specific disorders like tricuspid or mitral valve disease, pulmonary hypertension, heart failure, or cardiac surgery combinations. Multivariable regression models were constructed to assess predictors of PAC use as well as PAC use as a predictor of $\log_e$ hospitalization charges controlling for patient and hospital characteristics. Based on International Classification of Diseases procedure codes, PAC use was prevalent among 7.15 % of cardiac surgery hospitalizations, and hospitalization charges were estimated at $191,345, with no differences according to PAC use. Overall, being female, having Charlson comorbidity index (CCI) > 0, and non-payer (versus Medicare) status were independently associated with PAC use. Among the subgroup with the selected conditions, being female, having CCI>0, and being a Medicaid (versus Medicare) recipient were independently associated with PAC use, whereas elective admission was inversely related to PAC use. Among the subgroup without the selected conditions, having a CCI >0, elective admission, and non-payer (vs. Medicare) status were independently associated with PAC use. PAC use was not independently related to hospitalization charges overall or among subgroups. In conclusion, approximately 7 % of cardiac surgery hospitalizations received a PAC, with no differences in charges according to PAC use and disparities in PAC use driven by sex, elective admission, CCI and health insurance status. Large randomized trials are required to characterize the safety, efficacy, and cost-effectiveness of PAC use among distinct groups of patients undergoing cardiac surgery.

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1. Introduction

Since its introduction in the 1970s, pulmonary artery catheter (PAC) use has steadily increased to become the standard of care in many clinical settings, despite the paucity of evidence to support efficacy in monitoring clinical status and guiding therapeutic interventions, especially during or after cardiac surgery [1–3]. A PAC is a costly medical device that can measure various direct and indirect hemodynamic parameters, and it has previously been doubted whether these data are accurate or clinically relevant [4–6]. For example, estimates of measured cardiac output (CO) are prone to technical and miscalculation errors, as well as those related to organ-level abnormalities and a patient's posture. Indeed, some studies suggest that CO must increase or decrease by at least 25 % for such a change to be reflected in PAC measurements [7].

Current evidence from randomized controlled trials and observational studies remains inconclusive regarding clinical risks and benefits linked to PAC use among cardiac surgery patients. A limited number of studies examining PAC use in relation to mortality during hospitalization, length of hospital stay (LOS), intensive care unit (ICU) LOS, mechanical ventilation duration, inotropic medication use, acute kidney injury (AKI), infections and other complications have yielded inconsistent results [8–16]. There is still insufficient research on PAC within subgroups of cardiac surgery patients having pulmonary hypertension, congestive heart failure, mitral/tricuspid valve disease, or combined operations [9]. Furthermore, it remains uncertain whether utilization of PAC in cardiac surgery is cost-effective, since the few studies examining resource use linked to PAC insertion either relied on small, non-representative, samples or were not focused on cardiac surgeries [17,18]. Accordingly, in this cross-sectional study, we analyzed existing data from 1999 to 2019 National Inpatient Sample (NIS) to examine the prevalence and predictors of PAC use as well as PAC's association with hospitalization charges among patients who underwent cardiac surgery before and after stratifying by specific conditions that may be considered high-risk including pulmonary hypertension, heart failure, mitral/tricuspid valve disease, or that are considered complex cases such as combined cardiac surgical procedures. We hypothesized that specific conditions exist that can influence whether a PAC would be utilized in patients receiving cardiac surgery, and that hospitalization charges would differ according to PAC use.

2. Methods

Data source: The NIS data were analyzed for January 1, 1999 until December 31, 2019. The NIS remains the biggest all-payer inpatient care database of community hospitals in the United States that is accessible to the public. Since 1988, it has been compiling a sample of up to 8 million discharge records annually from 1000 hospitals. Based on hospital ownership/control, bed capacity, teaching status, location, and region, a 20 % stratified probability sampling of hospitals (before 2012) or discharge records (since 2012) is executed annually from participating states. Sampling weights were included in the NIS database and can be used to produce national estimates for all years, accounting for modifications in sampling design in 2012. Patient demographics, up to fifteen diagnoses, fifteen procedures, hospital course, and outcomes were included in the NIS database. It was decided that this research at Fort Belvoir Community Hospital did not involve human beings. A list of all ICD-9-CM/ICD-10 codes used to specify eligibility requirements and to define variables may be found in **Supplemental Material 1**. Notably, the first three quarters of 2015 and the years 1999 through 2014 employed ICD-9-CM codes. In contrast, the fourth quarter of 2015 and the years 2016–2019 were coded using ICD-10 codes.

Study participants: After applying pre-established eligibility criteria, data elements from the NIS databases were used to create variables related to patient and hospital characteristics. Hospital discharge records from the 1999–2019 NIS database that satisfied the following inclusion requirements were included in the study population: [1] Age more than eighteen; [2] At least one of the first fifteen procedure variables (PR1–PR15) included a cardiac surgery-related ICD-9-CM/ICD-10 code. Additionally, hospital discharge records that satisfied one or more of the following requirements were excluded: [1] $<$ 2 procedure codes; [2] lacking information on patient or hospital attributes as explained below.

Study variables: The final analytic sample of cardiac surgery hospitalizations was stratified by subgroup status, when examining PAC prevalence and hospitalization charges (overall and according to PAC receipt), predictors of PAC receipt as well as PAC receipt as a predictor for hospitalization charges, before and after adjustment for patient and hospital attributes. Patient characteristics were determined by sex, age, race/ethnicity, Charlson comorbidity index (CCI), elective admission, quarter of admission, weekend admission status, and primary payer. The study calculates the CCI score using 15 ICD-9-CM/ICD-10 diagnostic codes, indicating the cumulative increase in one-year mortality likelihood due to comorbidities' severity. Hospital characteristics, including region, control, location, teaching status, and bed size, were defined in the NIS database. For qualifying hospitalizations in the 1999–2019 NIS database, a detailed list of ICD-9–CM/ICD-10 procedure codes corresponding to PAC receipt was generated. As a result, hospital discharge records were divided into two categories: [1] PAC recipient; and [2] PAC non-receiver. Primary and secondary procedure variables (PR1–PR15) were used to generate these codes, and hospital-level rates of PAC use were determined and grouped as $<$ 5 %, 5-$<$10 %, 10-$<$20 %, 20-$<$40 %, 40-$<$60 % and $\geq$60 %. Subgroups of patients were defined based on the presence (subgroup 1) or absence (subgroup 2) of at least one ICD-9-CM or ICD-10 code for the following conditions: "pulmonary hypertension,", "heart failure," "mitral or tricuspid valve disease," and "combined surgery," as indicated in **Supplemental Material 1**. Diagnostic (DX1-DX15) and procedure (PR1-PR15) variables were used to define subgroups of patients. The Consumer Price Index (https://www.bls.gov/data/inflation_calculator.htm) was used to modify the total hospitalization costs, expressed in US dollars ($), for rates of inflation ranging from 1999 to 2019. The 1999 calendar year was used as a baseline. Due to its skewed distribution, this continuous outcome variable was first examined without transformation and then underwent $\log_e$-transformation.

Statistical analysis: Stata version 17 (StataCorp, College Station, TX) was used for statistical analyses taking suggestions and complex sampling design into account [19]. Tests for normality were applied to determine if parametric or non-parametric tests are needed. For continuous variables, summary statistics were provided as mean (± standard error [SE]) and for categorical variables, frequencies with percentages. When appropriate, design-based F-tests and uncorrected Chi-square were applied to investigate bivariate relationships. Binary logistic regression models were designed to evaluate unadjusted or adjusted odds ratios with 95 % confidence intervals (CI) for patient and hospital factors as predictors for PAC use, while stratifying by subgroup status. Interaction terms were included within unadjusted logistic regressions to examine effect modification by subgroup status for PAC use in relation to each patient or hospital characteristic. While stratifying by subgroup status, linear regression models were built to determine unadjusted and adjusted beta coefficients with 95 % CI for PAC use as predictor for $\log_e$-transformed hospitalization charges. Sensitivity analyses included: [1] an examination of PAC rates by year of admission and subgroup status, and [2] an examination of age group as a predictor of PAC use in simple and multivariable logistic regression models before and after stratifying by subgroup status. Complete subject analyses were carried out following analysis of missingness patterns. Two-sided tests were examined at an overall significance level of 0.10 for interaction effects and 0.05 for other analyses, taking multiple testing into consideration with the use of familywise Bonferroni correction, as appropriate.

3. Results

Study flowchart: According to Fig. 1, of the 158,971,760 hospitalization records in the 1999–2019 NIS database, 132,916,882 were linked to patients who were at least 18 years old. Among them, 1,477,041 had procedure codes associated with heart procedures. The final analytic sample consisted of 1,442,528 records (437,654 in subgroup 1 and 1,004,874 in subgroup 2) whereby hospitalized cardiac surgery patients ≥18 years of age had at least two procedure codes and non-missing information on the selected patient and hospital variables. Within subgroup 1, 141,483 were diagnosed with congestive heart failure, 63,007 were diagnosed with pulmonary hypertension, 190,618 were diagnosed with mitral/tricuspid valve disease, and 189,028 had surgery combinations. By contrast, subgroup 2 had none of these conditions.

Descriptive statistics: The prevalence rate of PAC use in the overall study population was estimated at 7.15 %, with a significantly higher rate among subgroup 1 (8.01 %) versus subgroup 2 (6.78 %) (cOR = 1.19, 95 % CI: 1.13, 1.27). As shown in Table S1 in the supplemental material and Fig. 2, the PAC rate was relatively stable throughout the 1999–2019 study period for subgroup 2 of cardiac surgeries ($P_{trend} = 0.26$) but varied on an annual basis for subgroup 1 ($P_{trend} = 0.046$), with variations occurring mainly between 2010 and 2019. Similarly, the distribution of hospital-level PAC rates was skewed, with nearly 70 % of hospitalizations occurring in hospitals with PAC rates less than 5 %, and significant difference in PAC rate distribution between the two subgroups (Supplemental Material; Figure S1 and Table S2). Furthermore, the mean [SE] for total hospitalization charges per cardiac surgery patient was estimated (in U. S. dollars) at $191,345 [2279] in the overall study population, $192,761 [6229] among PAC recipients and $191,236 [2882] among non-PAC recipients. Overall, an excess of $89,112 in hospitalization charges was observed in subgroup 1 versus subgroup 2, with non-significant differences in hospitalization charges according to PAC use irrespective of subgroup status. We obtained consistent results in for stratified analyses by specific groups (Table 1).

Relationship of patient characteristics with PAC use: Unadjusted logistic models for patient variables are shown in Table 2 as indicators of inpatient cardiac surgery patients' usage of PACs, both overall and according to subgroup status. Age, female, weekend admission, elective admission, and health insurance all showed significant interactions, suggesting that the relationships between these factors and PAC usage varied by subgroup. In the general population as well as within subgroups, there was no discernible difference in the mean [SE] age by PAC receipt. By contrast, PAC rates were significantly higher among older age groups, with 2–3 fold higher PAC rates among patients ≥30 years when compared to patients <30 years, and significantly stronger associations between PAC use and age

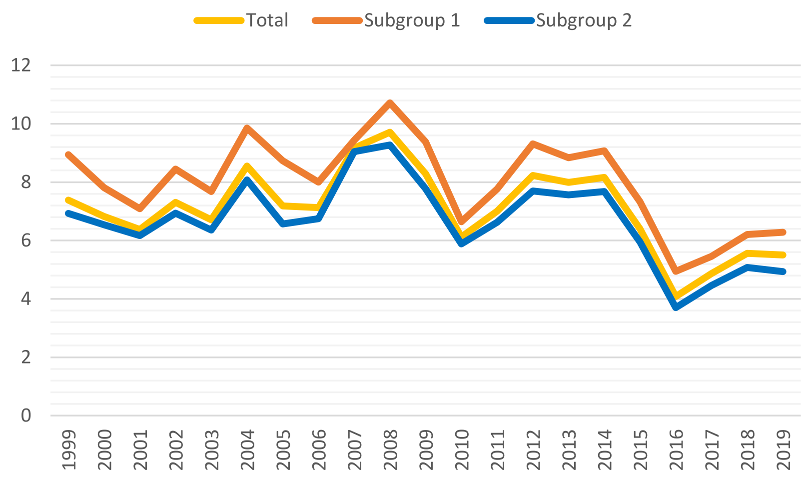

Fig. 1. Pulmonary artery catheter use by year of admission and perioperative risk status – National Inpatient Sample (1999–2019).

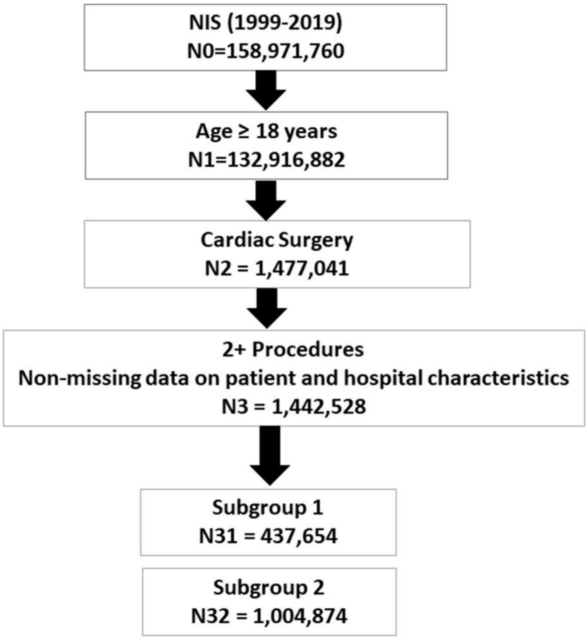

Fig. 2. Study flowchart – national inpatient sample (1999–2019).

group among subgroup 1 versus subgroup 2 (Supplemental Material; Table S3). Also, female patients were more frequently PAC recipients among subgroup 1, but not among subgroup 2. In subgroup 2, African American patients were less likely than their White counterparts to receive a PAC. Similarly, weekend admissions were more likely to receive a PAC and elective admissions were less likely to receive a PAC among subgroup 1 only. Among subgroup 2, self-payers and those having private insurance were less likely to receive a PAC as compared to Medicare recipients.

Relationship of hospital characteristics with PAC use: Table 3 presents unadjusted logistic models for hospital variables as predictors of PAC use in hospitalized cardiac surgery patients, in general, and by subgroup. Results suggested a significant interaction effect between subgroup status and hospital region in relation to PAC use. However, there were no significant differences in PAC use according to region, location, teaching status or bed capacity.

Predictors of PAC use: Multivariable logistic regression models are presented in Table 4 for patient and hospital variables as predictors of PAC use in hospitalized cardiac surgery patients, before and after stratifying by subgroup status. Overall, being female (aOR = 1.02), having a CCI = 1 (aOR = 1.08) or CCI = 2+ (aOR = 1.16) as opposed to CCI = 0, and being a non-payer (aOR = 1.48) as opposed to Medicare recipient were associated with PAC receipt. Among subgroup 1, being female (aOR = 1.04), having a CCI = 1 (aOR = 1.09) or CCI = 2+ (aOR = 1.10) as opposed to CCI = 0, and being a Medicaid (aOR = 1.09) as opposed to Medicare beneficiary were associated with PAC receipt, whereas elective admission was inversely related to PAC receipt (aOR = 0.90). Among subgroup 2, having a CCI = 1 (aOR = 1.08) or CCI = 2+ (aOR = 1.17) as opposed to CCI = 0, having an elective admission (aOR = 1.06) and being a non-payer as opposed to Medicare beneficiary (aOR = 1.68) were associated with PAC use. In multivariable logistic regression models, age group was an independent predictor of PAC use, with 80 % higher PAC rates among subgroup 1 patients ≥30 years versus <30 years, and 2.5 times higher PAC rates among subgroup 2 patients ≥30 years versus <30 years (Supplemental Material; Table S3).

Relationship of PAC use with hospitalization charges: Table 5 presents PAC use as a predictor for $\log_e$-transformed hospitalization charges among cardiac surgery patients, overall and in each subgroup. Both unadjusted and adjusted models suggest that PAC use was not associated with hospitalization charges in the overall study population and among subgroups.

4. Discussion

4.1. Key findings

We conducted secondary analyses of available data on over 1.4 million adult heart surgery patient records from the 1999–2019 NIS database in this cross-sectional investigation. Specifically, we examined the prevalence and predictors of PAC use in addition to relationship of PAC use with hospitalization charges in patients who underwent cardiac surgery overall and within subgroups. Based on ICD procedure codes, we found a relatively stable PAC rate of approximately 7 % across different groups defined by patient and hospital characteristics, although it was higher among female patients, those with CCI >0 as well as those having Medicaid or no health insurance as opposed to Medicare, with interactive effects between subgroup status and elective admission. Female sex is independently related to poor outcome post-cardiac surgery, and these patients have a higher rate of diastolic dysfunction, potentially driving the increased PAC use. Similarly, patients in subgroup 1 were more likely to receive a PAC and had greater hospitalization charges than

Table 1
Pulmonary Artery Catheter Receipt and Hospitalization Charges Among Cardiac Surgery Patients, Overall and by Subgroup status – National Inpatient Sample (1999–2019) (n = 1,442,528).

	Total (n = 1,442,528)	Subgroup Status *		
		1 (n = 437,654)	2 (n = 1,004,874)	OR/β (95 % CI)
OVERALL:				
PAC receipt (%)	7.15 %	8.01 %	6.78 %	1.19 (1.13, 1.27)
Hospitalization charges ($)				
Overall, Mean [SE]	191,345 [2279]	253,365 [3522]	164,253 [2427]	89,112 (85,802–92,422)
PAC recipients, Mean [SE]	192,761 [6229]	254,309 [6896]	160,972 [5530]	93,337 (86,258–100,416)
Non-PAC recipients, Mean [SE]	191,236 [2882]	253,283 [3648]	164,491 [2521]	88,791 (85,393–92,189)
P [PAC recipients vs. non-PAC recipients]	0.81	0.88	0.54	
CONGESTIVE HEART FAILURE:				
PAC use (%)	7.15 %	7.72 %	7.08 %	1.09 (1.01, 1.19)
Hospitalization charges ($)				
Overall, Mean [SE]	191,345 [2279]	321,451 [3958]	177,156 [2611]	144,294 (138,828–149,761)
PAC recipients, Mean [SE]	192,761 [6229]	336,467 [8696]	175,685 [5705]	160,782 (147,348–174,215)
Non-PAC recipients, Mean [SE]	191,236 [2882]	320,194 [4006]	177,267 [2711]	142,295 (137,444–148,406)
P [PAC recipients vs. non-PAC recipients]	0.81	0.73	0.91	
PULMONARY HYPERTENSION:				
PAC receipt (%)	7.15 %	10.14 %	7.01 %	1.09 (1.01, 1.19)
Hospitalization charges ($)				
Overall, Mean [SE]	191,345 [2279]	219,593 [3716]	190,053 [2769]	29,539 (24,750–34,330)
PAC recipients, Mean [SE]	192,761 [6229]	227,706 [7466]	190,451 [6242]	37,259 (26,704–47,804)
Non-PAC recipients, Mean [SE]	191,236 [2882]	218,678 [3802]	190,023 [2873]	28,654 (23,806–35,503)
P [PAC recipients vs. non-PAC recipients]	0.81	0.44	0.91	
VALVE DISEASE:				
PAC receipt (%)	7.15 %	8.60 %	6.92 %	1.26 (1.19, 1.34)
Hospitalization charges ($)				
Overall, Mean [SE]	191,345 [2279]	205,127 [3385]	189,247 [2748]	15,879 (12,532–19,227)
PAC recipients, Mean [SE]	192,761 [6229]	212,494 [6047]	189,029 [6376]	23,464 (16,097–30,831)
Non-PAC recipients, Mean [SE]	191,236 [2882]	204,432 [3514]	189,263 [2848]	15,169 (11,711–18,627)
P [PAC recipients vs. non-PAC recipients]	0.81	0.23	0.99	
COMBINED SURGERIES:				
PAC receipt (%)	7.15 %	7.68 %	7.07 %	1.09 (1.02, 1.16)
Hospitalization charges ($)				
Overall, Mean [SE]	191,345 [2279]	275,950 [3998]	178,548 [2597]	97,401 (93,554–101,248)
PAC recipients, Mean [SE]	192,761 [6229]	275,279 [8080]	179,210 [5918]	96,068 (86,055–106,081)
Non-PAC recipients, Mean [SE]	191,236 [2882]	276,006 [4140]	178,498 [2694]	97,508 (93,561–101,454)
P [PAC users vs. non-PAC users]	0.81	0.89	0.88	

Abbreviations: β = Slope; CI = Confidence Interval; OR = Odds Ratio; PAC = Pulmonary Artery Catheter; * Subgroups were defined based on presence (subgroup 1) or absence (subgroup 2) of selected conditions, namely, heart failure, pulmonary hypertension, mitral or tricuspid valve disease, and/or any combined cardiac surgical procedure.

those in subgroup 2, with no significant differences in hospitalization charges in recipients versus non-recipients of PAC. Finally, patients who were at least 30 years of age were more likely to receive a PAC as compared to those less 30 years of age, especially in subgroup 2. Examining specific groups of patients, such as those with pulmonary hypertension, heart failure, mitral/tricuspid valve disease, and/or combined operations, did not reveal any differences in the study conclusions. The finding that hospitalization charges did not differ according to PAC use might suggest that the use of a PAC is not useful for reducing perioperative complications among cardiac surgery patients, or that expenses linked to PAC use are counterbalanced by cost-savings.

4.2. Relationship to previous studies

The relatively low PAC rate of 7 % estimated from this nationally representative sample is consistent with the idea that the use of an expensive medical device such as PAC is not routine practice in cardiac surgery without high-quality data originating from large, randomized, trials for balancing its risks against its benefits. In fact, the safety, efficacy, and effectiveness of PAC use among cardiac surgery patients remain uncertain. Shaw et al. conducted a multicenter retrospective study on 6842 patients undergoing a range of cardiac surgeries and found that PAC use was independently associated with a lower risk of a composite of cardiopulmonary adverse outcomes, reduced hospital LOS, and a lower risk of AKI, but an increased risk of serious infection [20]. A systematic review by Joseph et al. identified six articles focusing on PAC in the context of cardiac surgery – including coronary artery bypass grafting (CABG) – and concluded that PAC use was not linked to worse outcomes [1]. Specifically, there was no variation in mortality among PAC recipients and non-recipients, except for high-risk patients, and ICU length of stay was similar by PAC receipt in the context of CABG. By contrast, total LOS >30 days was more frequent among cardiac surgery patients and hospitalization costs were higher among CABG patients who were recipients versus non-recipients of PAC [1]. Finally, complication rates did not differ between recipients of PAC and central

Table 2
Unadjusted Logistic Regression Models for Patient Characteristics as Predictors of Pulmonary Artery Catheter Receipt Among Hospitalized Cardiac Surgery Patients, Overall and by Subgroup status – National Inpatient Sample (1999–2019) (n = 1,442,528).

	PAC receipt (% Yes)					
	Total (n = 1,442,528)		Subgroup status			
			1 (n = 437,654)		2 (n = 1,004,874)	
Patient Characteristics:	**%**	**OR (95 % CI)**	**%**	**OR (95 % CI)**	**%**	**OR (95 % CI)**
Age (years):		0.80 (0.55, 1.05)		1.00 (1.00, 1.00)		1.00 (1.00, 1.00)
Mean ± SEM (PAC user)		65.59 ± 0.12		66.97 ± 0.15		64.87 ± 0.12
Mean ± SEM (PAC non-user)		64.76 ± 0.08		66.38 ± 0.10		64.07 ± 0.08
				$P_{interaction} < 0.0001$		
Sex:						
Male	7.07	Ref.	7.88	Ref.	6.76	Ref.
Female	7.32	1.04 (1.02, 1.06)	8.22	1.05 (1.02, 1.08)	6.81	1.01 (0.98, 1.03)
				$P_{interaction} = 0.027$		
Race/Ethnicity:						
White	7.13	Ref.	7.94	Ref.	6.77	Ref.
African-American	6.46	0.90 (0.80, 1.00)	7.54	0.94 (0.86, 1.03)	5.84	0.85 (0.74, 0.98)
Hispanic	6.95	0.97 (0.78, 1.20)	7.78	0.98 (0.81, 1.18)	6.57	0.97 (0.77, 1.22)
Other	7.04	0.98 (0.85, 1.15)	8.23	1.04 (0.92, 1.18)	6.50	0.96 (0.80, 1.14)
Unknown	7.52	1.06 (0.79, 1.41)	8.49	1.08 (0.82, 1.41)	7.17	1.06 (0.78, 1.44)
			$P_{interaction}$ (African-American) = 0.06			
			$P_{interaction}$ (Hispanic) = 0.87			
			$P_{interaction}$ (Other) = 0.17			
			$P_{interaction}$ (Unknown) = 0.89			
Charlson Comorbidity Index:						
0	6.52	Ref.	7.33	Ref.	6.23	Ref.
1	7.05	1.09 (1.05, 1.13)	8.05	1.10 (1.05, 1.16)	6.68	1.08 (1.04, 1.12)
2+	7.56	1.17 (1.10, 1.25)	8.26	1.14 (1.06, 1.22)	7.18	1.16 (1.09, 1.24)
			$P_{interaction}$ (1) = 0.27			
			$P_{interaction}$ (2+) = 0.77			
Elective admission:						
Yes	7.15	1.00 (0.94, 1.06)	7.66	0.90 (0.85, 0.95)	6.91	1.04 (0.97, 1.12)
No	7.15	Ref.	8.44	Ref.	6.64	Ref.
			$P_{interaction} < 0.0001$			
Admission Quarter:						
1st quarter	7.38	Ref.	8.21	Ref.	7.01	Ref.
2nd quarter	7.18	0.97 (0.95, 0.99)	8.02	0.97 (0.94, 1.01)	6.82	0.97 (0.94, 1.00)
3rd quarter	7.09	0.96 (0.93, 0.99)	7.99	0.97 (0.93, 1.01)	6.70	0.95 (0.92, 0.99)
4th quarter	6.94	0.94 (0.90, 0.97)	7.81	0.95 (0.90, 0.99)	6.56	0.93 (0.89, 0.97)
			$P_{interaction}$ (q2) = 0.82			
			$P_{interaction}$ (q3) = 0.37			
			$P_{interaction}$ (q4) = 0.47			
Weekend Admission:						
Yes	7.26	1.02 (0.97, 1.06)	8.45	1.07 (1.01, 1.13)	6.77	0.99 (0.95, 1.05)
No	7.14	Ref.	7.97	Ref.	6.78	Ref.
			$P_{interaction} = 0.011$			
Primary Payer:						
Medicare	7.36	Ref.	8.09	Ref.	6.97	Ref.
Medicaid	7.15	0.97 (0.90, 1.04)	8.23	1.02 (0.94, 1.09)	6.64	0.95 (0.87, 1.03)
Private	6.91	0.94 (0.89, 0.98)	7.86	0.97 (0.92, 1.02)	6.60	0.94 (0.90, 0.98)
Self-pay	6.31	0.85 (0.77, 0.93)	7.56	0.93 (0.83, 1.05)	5.87	0.83 (0.75, 0.92)
No Pay	8.95	1.24 (0.81, 1.88)	7.67	0.94 (0.64, 1.39)	9.46	1.39 (0.88, 2.18)
Other	6.71	0.91 (0.78, 1.05)	7.57	0.93 (0.82, 1.05)	6.41	0.91 (0.77, 1.09)
			$P_{interaction}$ (Medicaid) = 0.064			
			$P_{interaction}$ (Private) = 0.18			
			$P_{interaction}$ (Self-pay) = 0.028			
			$P_{interaction}$ (No pay) = 0.011			
			$P_{interaction}$ (Other) = 0.79			

Abbreviations: CI = Confidence Interval; OR = Odds Ratio; PAC = Pulmonary Artery Catheter; * Subgroups were defined based on presence (subgroup 1) or absence (subgroup 2) of selected conditions, namely, heart failure, pulmonary hypertension, mitral or tricuspid valve disease, and/or any combined cardiac surgical procedure.

venous lines [1].

Wide variations in PAC use exist in different clinical settings and countries, which could partly be explained by embedded local practices, clinical equipoise in low-to-moderate risk cases, and a scarcity of evidence from randomized trials guiding practice. Judge et al. conducted a survey through the Society of Cardiovascular Anesthesiologists to assess patterns of PAC utilization among cardiac anesthetists in the US, Canada, Europe, and Australia [21]. Amongst respondents, 68.2 % utilized a PAC in at least 75 % of cases

Table 3
Unadjusted Logistic Regression Models for Hospital Characteristics as Predictors of Pulmonary Artery Catheter Receipt Among Hospitalized Cardiac Surgery Patients, Overall and by Subgroup status – National Inpatient Sample (1999–2019) (n = 1,442,528).

	PAC receipt (% Yes)					
	Total (n = 1,442,528)		Subgroup status			
			1 (n = 437,654)		2 (n = 1,004,874)	
Hospital Characteristics:	**%**	**OR (95 % CI)**	**%**	**OR (95 % CI)**	**%**	**OR (95 % CI)**
Region:						
Northeast	7.02	Ref.	7.30	Ref.	6.88	Ref.
Midwest	8.78	1.27 (0.85, 1.91)	9.65	1.35 (0.95, 1.94)	8.40	1.24 (0.80, 1.92)
South	6.16	0.87 (0.56, 1.33)	7.08	0.96 (0.67, 1.39)	5.80	0.83 (0.52, 1.33)
West	7.37	1.05 (0.70, 1.58)	8.60	1.19 (0.83, 1.72)	6.78	0.98 (0.64, 1.51)
			$P_{interaction}$ (Midwest) = 0.25			
			$P_{interaction}$ (South) = 0.08			
			$P_{interaction}$ (West) = 0.006			
Location & Teaching status:						
Rural	9.14	Ref.	10.74	Ref.	8.62	Ref.
Urban – Non-Teaching	7.65	0.82 (0.55, 1.22)	8.48	0.77 (0.53, 1.12)	7.34	0.84 (0.55, 1.28)
Urban – Teaching	6.83	0.73 (0.50, 1.06)	7.73	0.69 (0.49, 0.99)	6.40	0.72 (0.48, 1.08)
			$P_{interaction}$ (Urban – Non-Teaching) = 0.47			
			$P_{interaction}$ (Urban –Teaching) = 0.70			
Bed Size:						
Small	6.33	Ref.	7.54	Ref.	5.80	Ref.
Medium	7.02	1.12 (0.84, 1.48)	7.78	1.04 (0.79, 1.36)	6.70	1.16 (0.86, 1.58)
Large	7.27	1.16 (0.88, 1.53)	8.12	1.08 (0.83, 1.42)	6.89	1.20 (0.89, 1.61)
			$P_{interaction}$ (Medium) = 0.16			
			$P_{interaction}$ (Large) = 0.19			

Abbreviations: CI = Confidence Interval; OR = Odds Ratio; PAC = Pulmonary Artery Catheter; * Subgroups were defined based on presence (subgroup 1) or absence (subgroup 2) of selected conditions, namely, heart failure, pulmonary hypertension, mitral or tricuspid valve disease, and/or any combined cardiac surgical procedure.

involving CABG [21]. These results suggest large variations in practice, and higher than expected PAC utilization despite recommendations to only consider PAC in selected high-risk cases [21].

Recently conducted studies provide evidence for a declining trend in PAC use [8,22] in favor of alternative flow-directed cardiac output monitoring [12,23–26]. The prevalence of PAC use based on small cohort studies involving cardiac surgery patients ranges between 25 % and 70 % [8,9,14,16,20,22,27], although a study by Handa et al. highlighted a decline in PAC use rates among cardiac surgery patients from 100 % in 1997 to 8.5 % in 2001 [22]. Ikuta et al. examined national trends of PAC use in the US Medicare beneficiaries between 1999 and 2013 [28], and reported a decline in PAC use for any indication of 67.8 % [(6.28/1000 in 1999 to 2.02/1000 in 2013; $P < 0.001$)] over the study period but did not report subgroup data for cardiac surgery patients or among specific groups of patients. Therefore, while the authors concluded that there is broad de-adoption of PAC use across a range of indications, little can be drawn about contemporary patterns of use in the cardiac surgery population from this study [28].

The finding that PAC insertion was significantly greater among the subgroup with specific conditions or complex cardiac surgeries and the independent association of PAC use with the comorbidity score corroborate the recommendation to consider a PAC only among selected high-risk patients, since at least some of these comorbidities might influence perioperative outcomes [21]. Gender disparities are consistent with previous studies reporting gender differences in risks and benefits from PAC use [29]. By contrast, the independent associations of elective admission and insurance type with PAC receipt requires in-depth evaluation although it may reflect health disparities given the potential for costly treatments associated with the PAC and the observed association of PAC use with hospital LOS [1,13,14,18,20,28].

In our study, estimated PAC rate was nearly 10 times higher in cardiac surgery patients when compared to a general population of 1993–2004 NIS hospitalizations [30] as well as NIS-based estimated PAC use in congestive heart failure [31–33] and aneurysmal subarachnoid hemorrhage [34] hospitalizations. However, the PAC rate was consistent with an analysis of acute myocardial infarction (MI) - cardiogenic shock patients using NIS (2000–2014) data in which PAC rate was estimated to be 8.1 % [18]. It was also substantially less than PAC rates found in cardiac surgery patients in cohort studies that relied on a wide range of data sources [8,9,14,16,20,22,27]. In a retrospective cohort study that relied on administrative data from 116,333 patients undergoing cardiac surgery at academic as well as community hospitals participating from the National Anesthesia Clinical Outcomes Registry, Brovman et al. reported a 34.4 % PAC rate [8]. In a retrospective cohort study, Ramsey et al. reported a PAC rate of 57.9 % among 13,907 non-emergent CABG surgery patients selected from 56 community-based hospitals from 26 states in 1997 [14]. In another retrospective cohort study, it was reported that 69.2 % of 2414 low-risk beating-heart surgery patients from a tertiary care teaching hospital received a PAC between 2000 and 2003 [27]. Similarly, Schwann et al. found that 53.6 % of 3123 CABG surgery patients from a prospective cohort study involving 70 centers (November 1996–June 2000) received a PAC [16]. A matched retrospective cohort study by Shaw et al. found that 25.8 % of 16,039 adult cardiac surgeries [isolated valve surgery, aortic surgery, isolated CABG, other complex non-valvular and multi-cardiac procedures, and/or heart transplant] from the Cerner Health Facts database (January 1, 2011–June 30, 2015)

Table 4
Multivariable Logistic Regression Models for Patient and Hospital Characteristics as Predictors of Pulmonary Artery Catheter receipt Among Hospitalized Cardiac Surgery Patients, Overall and by Subgroup status – National Inpatient Sample (1999–2019).

	Overall	Subgroup 1	Subgroup 2
	aOR (95 % CI)	aOR (95 % CI)	aOR (95 % CI)
Age:	1.00 (1.00, 1.00)	1.00 (1.00, 1.00)	1.00 (1.00, 1.00)
Sex:			
Male	Ref.	Ref.	Ref.
Female	1.02 (1.01, 1.05)	1.04 (1.02, 1.08)	0.99 (0.97, 1.02)
Race/Ethnicity:			
White	Ref.	Ref.	Ref.
African-American	0.95 (0.86, 1.07)	0.98 (0.90, 1.08)	0.92 (0.80, 1.05)
Hispanic	1.03 (0.84, 1.27)	1.00 (0.83, 1.21)	1.04 (0.83, 1.30)
Other	1.01 (0.87, 1.17)	1.04 (0.92, 1.19)	0.99 (0.83, 1.18)
Unknown	0.98 (0.73, 1.32)	0.98 (0.74, 1.31)	0.99 (0.72, 1.35)
Charlson Comorbidity Index:			
0	Ref.	Ref.	Ref.
1	1.08 (1.05, 1.12)	1.09 (1.03, 1.14)	1.08 (1.04, 1.12)
2+	1.16 (1.09, 1.24)	1.10 (1.02, 1.18)	1.17 (1.09, 1.25)
Elective admission:			
Yes	1.01 (0.95, 0.99)	0.90 (0.84, 0.96)	1.06 (1.04, 1.12)
No	Ref.	Ref.	Ref.
Admission Quarter:			
1st quarter	Ref.	Ref.	Ref.
2nd quarter	0.97 (0.94, 0.99)	0.97 (0.94, 1.01)	0.97 (0.94, 1.00)
3rd quarter	0.96 (0.93, 0.99)	0.97 (0.93, 1.01)	0.95 (0.92, 0.99)
4th quarter	0.94 (0.91, 0.97)	0.94 (0.90, 0.99)	0.93 (0.89, 0.97)
Weekend Admission:			
Yes	1.00 (0.96, 1.05)	1.01 (0.95, 1.08)	1.00 (0.95, 1.05)
No	Ref.	Ref.	Ref.
Primary Payer:			
Medicare	Ref.	Ref.	Ref.
Medicaid	1.07 (0.99, 1.16)	1.09 (1.01, 1.17)	1.06 (0.97, 1.16)
Private	1.02 (0.97, 1.07)	1.04 (0.99, 1.10)	1.02 (0.97, 1.07)
Self-pay	0.96 (0.86, 1.06)	0.99 (0.88, 1.13)	0.95 (0.84, 1.06)
No Pay	1.48 (1.03, 2.14)	1.09 (0.76, 1.55)	1.68 (1.13, 2.49)
Other	0.99 (0.85, 1.15)	0.98 (0.87, 1.12)	1.01 (0.84, 1.20)
Region:			
Northeast	Ref.	Ref.	Ref.
Midwest	1.26 (0.82, 1.94)	1.36 (0.93, 1.99)	1.22 (0.77, 1.93)
South	0.85 (0.55, 1.31)	0.95 (0.66, 1.38)	0.81 (0.51, 1.29)
West	1.02 (0.68, 1.52)	1.18 (0.82, 1.69)	0.94 (0.61, 1.44)
Location & Teaching status:			
Rural	Ref.	Ref.	Ref.
Urban – Non-Teaching	0.83 (0.56, 1.26)	0.77 (0.53, 1.11)	0.86 (0.55, 1.35)
Urban – Teaching	0.73 (0.49, 1.08)	0.70 (0.49, 1.00)	0.73 (0.48, 1.11)
Bed Size:			
Small	Ref.	Ref.	Ref.
Medium	1.16 (0.87, 1.55)	1.06 (0.81, 1.40)	1.21 (0.88, 1.66)
Large	1.15 (0.87, 1.52)	1.07 (0.82, 1.40)	1.19 (0.88, 1.61)

Abbreviations: aOR = Adjusted Odds Ratio; CI = Confidence Interval; * Subgroups were defined based on presence (subgroup 1) or absence (subgroup 2) of selected conditions, namely, heart failure, pulmonary hypertension, mitral or tricuspid valve disease, and/or any combined cardiac surgical procedure.

received a PAC [20]. Finally, Brown et al. conducted a matched analysis involving 11,820 open cardiac surgery patients from a prospective cohort study (2010–2018) and found that 38.9 % were PAC recipients [9].

The data source for the NIS is administrative in nature whereby databases were originally constructed for billing rather than research purposes. Furthermore, the NIS unit of analysis is the hospital stay rather than an individual patient, with a subset of these hospitalization stays being ICU admissions. Although none of these data sources is considered as the gold standard, the use of up to 15 procedure codes within the NIS may have resulted in a less sensitive but more specific definition of PAC use, with a greater chance of underestimating PAC use as compared to claims or registry data.

Consistent with some of the previously conducted studies, we found that hospitalization charges were similar among users and non-users of PAC, implying that, despite its expensive nature, a PAC insertion had no impact on costs associated with cardiac surgeries. PAC cost-effectiveness in the context of cardiovascular disease, ICU admissions and cardiac surgeries remains inconclusive [1,17,18,35]. The 2000–2014 NIS analyses by Vallabhajosyula et al. reported more in-hospital mortality, longer LOS, greater hospitalization costs, and fewer home discharges among MI-cardiogenic shock patients who were PAC recipients versus non-recipients, although in-hospital mortality became comparable between these groups after propensity score matching [18]. Rajaram et al. conducted a review of the literature that assesses PAC-related mortality, LOS in the ICU and hospital, as well as costs among adult ICU patients [13]. Four US

Table 5
Pulmonary Artery Catheter Receipt as a predictor for Log_e-transformed Hospitalization Charges Among Cardiac Surgery Patients, Overall and by Subgroup status – National Inpatient Sample (1999–2019) (n = 1,442,528).

	Total (n = 1,442,528)	Subgroup status **	
		1 (n = 437,654)	2 (n = 1,004,874)
OVERALL:			
Unadjusted:			
PAC receipt:			
No	Ref.	Ref.	Ref.
Yes	0.010 (−0.065, 0.087)	−0.0024 (−0.066, 0.061)	−0.0086 (−0.088, 0.071)
Adjusted: *			
PAC receipt:			
No	Ref.	Ref.	Ref.
Yes	0.0053 (−0.60, 0.070)	−0.011 (−0.066, 0.044)	−0.0063 (−0.075, 0.062)
CONGESTIVE HEART FAILURE:			
Unadjusted:			
PAC receipt:			
No	Ref.	Ref.	Ref.
Yes	0.010 (−0.065, 0.087)	0.011 (−0.050, 0.072)	0.0045 (−0.071, 0.080)
Adjusted: *			
PAC receipt:			
No	Ref.	Ref.	Ref.
Yes	0.0053 (−0.60, 0.070)	0.014 (−0.043, 0.071)	0.0013 (−0.064, 0.067)
PULMONARY HYPERTENSION:			
Unadjusted:			
PAC receipt:			
No	Ref.	Ref.	Ref.
Yes	0.010 (−0.065, 0.087)	0.027 (−0.042, 0.096)	0.0045 (−0.073, 0.082)
Adjusted: *			
PAC receipt:			
No	Ref.	Ref.	Ref.
Yes	0.0053 (−0.60, 0.070)	0.056 (−0.054, 0.065)	0.0019 (−0.065, 0.068)
VALVE DISEASE:			
Unadjusted:			
PAC receipt:			
No	Ref.	Ref.	Ref.
Yes	0.010 (−0.065, 0.087)	0.041 (−0.025, 0.11)	0.00040 (−0.078, 0.079)
Adjusted: *			
PAC receipt:			
No	Ref.	Ref.	Ref.
Yes	0.0053 (−0.60, 0.070)	0.020 (−0.036, 0.076)	−0.0016 (−0.069, 0.066)
COMBINED SURGERIES:			
Unadjusted:			
PAC receipt:			
No	Ref.	Ref.	Ref.
Yes	0.010 (−0.065, 0.087)	0.0046 (−0.065, 0.074)	0.0059 (−0.071, 0.083)
Adjusted: *			
PAC receipt:			
No	Ref.	Ref.	Ref.
Yes	0.0053 (−0.60, 0.070)	−0.014 (−0.074, 0.046)	0.0046 (−0.062, 0.070)

Abbreviations: β = Slope; CI = Confidence Interval; OR = Odds Ratio; PAC = Pulmonary Artery Catheter; * Linear regression models for PAC use as a predictor of log_e-transformed hospitalization charges were adjusted for age, sex, race/ethnicity, Charlson Comorbidity Index, elective admission, admission quarter, weekend admission, primary payer, hospital region, location, teaching status and bed size; ** Subgroups were defined based on presence (subgroup 1) or absence (subgroup 2) of selected conditions, namely, heart failure, pulmonary hypertension, mitral or tricuspid valve disease, and/or any combined cardiac surgical procedure.

studies reported costs according to hospitalization charges, which were higher in the PAC groups, on average, and two of these studies which qualified for analysis did not show significant cost differences [13]. A recent study by Stevens et al. evaluated PAC's short-term and mid-term economic impact among adult cardiac surgery patients [17]. They reported annualized acute care hospital savings of 61, 806 US dollars among PAC recipients versus non-recipients assuming 500 procedures/year and 34 % PAC adoption, with savings ranging between 12,361 and 185,418 US dollars with volumes of 100 and 1500 procedures per year [17].

4.3. Study implications

Current evidence remains inconclusive with respect to in-hospital outcomes linked to PAC receipt in hospitalized patients, in general, and particularly among cardiac surgery patients. An evaluation of the prevalence, predictors, and hospitalization charges of PAC receipt with respect to cardiac surgery and among distinct subgroups is a gap in the literature. Using a nationally representative sample, we found a low rate of PAC insertion during or after cardiac surgeries, with slightly higher PAC rates among high-risk and complex cases. The finding that hospitalization charges among cardiac surgeries did not vary according to PAC receipt at the national level necessitate further evaluation, given the expensive nature of PAC and its potential role in clinical outcomes such as mortality and LOS. Because of its descriptive nature, this study cannot be used to change clinical practice. However, given that evidence for or against use of PAC originates mainly from observational studies [1,8,10,16,17,20,21,35–44], it can provide insights for the future design and conduct of large randomized trials aimed at evaluating safety, efficacy, and cost-effectiveness of PAC use within this clinical population.

4.4. Strengths and limitations

This study has several strengths which include large sample size, representativeness of hospitalized patients within the US, availability of data on hospitalization charges, and ability to assess PAC use according to the presence or absence of specific conditions. However, given several limitations, these results should be regarded with caution. Firstly, the granularity and research variable definition of secondary studies based on administrative data are often restricted [11]. Unlike registries, the NIS database does not routinely gather thorough data on critical aspects of cardiac surgery patients, including personal and family history, concomitant medications, and anesthetic agents, among others. Moreover, over the course of the 20-year NIS period, prognostic indicators reflecting the severity of the disease were not regularly gathered. As a result, we relied on CCI to represent both the severity of disease and load of comorbidities. Furthermore, hospital readmissions cannot be determined because the NIS database only contains hospitalization records rather than unique patient information. Second, hospitalization charges were examined instead of hospitalization costs as the outcome of interest, since cost-to-charge ratios became available after 1999, and, therefore, could not be evaluated for the entire study population. Third, complete subject analyses were carried out with the possibility for selection bias due to missing data. Fourth, there may have been misclassification bias because of several variables being specified using ICD-9-CM/ICD-10 diagnosis and procedure codes. Additionally, the use of diagnostic and procedure codes may have led to an underestimating of prevalence rates because they were only applied in cases where they were specific to the condition of interest and had matching codes in ICD-9-CM and ICD-10. Similarly, the NIS database did not have data on timing of PAC placement, *i.e.* whether it was performed after anesthesia, peri-operatively, or within the ICU when the patient's hemodynamics tend to worsen. Fifth, considering the observational study design and the restricted availability of data items in the NIS database, residual confounding could not be completely ruled out as a possible reason for study findings. Lastly, the study findings could only be applied to hospitalized patients within the relevant time frame.

5. Conclusion

In conclusion, nearly 7 % of adult cardiac surgery patients received a PAC perioperatively, with disparities by subgroup as well as sex, CCI, elective admission, and health insurance. Total hospitalization charges, estimated at 191,345 US dollars per cardiac surgery patient, did not differ according to PAC utilization, after controlling for patient and hospital characteristics. These findings can be used to generate hypotheses and conduct more rigorously designed studies that can inform clinical practice. To validate and clarify these cross-sectional results, randomized trials and prospective cohort studies are required.

Data availability statement

The National Inpatient Sample databases are not publicly available and can only be accessed after signing a data sharing agreement. However, the data generated from this study can be made available by the lead author upon reasonable request.

Ethics declaration

Review and/or approval by an ethics committee was not needed for this study because it received an example status determination (#946404) at Fort Belvoir Community Hospital.

CRediT authorship contribution statement

Hind A. Beydoun: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **May A. Beydoun:** Writing – review & editing, Software, Resources, Project administration, Methodology, Funding acquisition. **Shaker M. Eid:** Writing – review & editing, Validation, Resources, Investigation. **Alan B. Zonderman:** Writing – review & editing, Supervision, Software, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e24902.

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