Brachial Arterial Pressure Monitoring during Cardiac Surgery Rarely Causes Complications

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ABSTRACT

Background: Brachial arterial catheters better estimate aortic pressure than radial arterial catheters but are used infrequently because complications in a major artery without collateral flow are potentially serious. However, the extent to which brachial artery cannulation promotes complications remains unknown. The authors thus evaluated a large cohort of cardiac surgical patients to estimate the incidence of related serious complications.

Methods: The institutional Society of Thoracic Surgeons Adult Cardiac Surgery Database and Perioperative Health Documentation System Registry of the Cleveland Clinic were used to identify patients who had brachial artery cannulation between 2007 and 2015. Complications within 6 months after surgery were identified by International Classification of Diseases, Ninth Revision diagnostic and procedural codes, Current Procedural Terminology procedure codes, and Society of Thoracic Surgeons variables. The authors reviewed electronic medical records to confirm that putative complications were related plausibly to brachial arterial catheterization. Complications were categorized as (1) vascular, (2) peripheral nerve injury, or (3) infection. The authors evaluated associations between brachial arterial complications and patient comorbidities and between complications and in-hospital mortality and duration of hospitalization.

Results: Among 21,597 qualifying patients, 777 had vascular or nerve injuries or local infections, but only 41 (incidence 0.19% [95% CI, 0.14 to 0.26%]) were potentially consequent to brachial arterial cannulation. Vascular complications occurred in 33 patients (0.15% [0.10 to 0.23%]). Definitely or possibly related infection occurred in 8 (0.04% [0.02 to 0.08%]) patients. There were no plausibly related neurologic complications. Peripheral arterial disease was associated with increased risk of complications. Brachial catheter complications were associated with prolonged hospitalization and in-hospital mortality.

Conclusions: Brachial artery cannulation for hemodynamic monitoring during cardiac surgery rarely causes complications. **(Anesthesiology 2017; 126:1065-76)**

INTRAARTERIAL pressure monitoring is routine for patients having cardiac surgery; however, the ideal site for arterial cannulation that best reflects central aortic pressure while minimizing line-associated complications is unclear. Radial arterial cannulation often is preferred because collateral circulation from the ulnar artery to the hand reduces the risk of ischemic injury.[1] However, radial arterial pressure often exaggerates central aortic pressures because of decreased arterial elasticity, amplification of harmonic resonance, and the water hammer effect, which describes a bounding and forceful pulse caused by the propagation of a pressure wave throughout the vasculature.[2] Furthermore, hemodilution or radial artery vasospasm during critical periods of cardiac surgery can cause radial arterial pressure to underestimate central aortic pressure.[3,4] Inaccurate pressure measurements even for brief periods of time may promote inappropriate hemodynamic management and possibly increase postoperative morbidity and mortality.[5]

What We Already Know about This Topic

- Brachial arterial catheters better estimate aortic pressure than radial arterial catheters but are used infrequently because of risk of complications in a major artery without collateral flow are potentially serious
- The present study evaluated a large cohort of cardiac surgical patients to estimate the incidence of brachial artery catheter complications

What This Article Tells Us That Is New

- Brachial artery cannulation for hemodynamic monitoring during cardiac surgery rarely causes complications

Brachial arterial monitoring, in contrast, closely reflects central aortic pressure even during complex cardiac surgical procedures with prolonged cardiopulmonary bypass support.[3] Brachial arterial pressure may thus better guide patient care and clinical management than radial arterial pressure

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monitoring.[6] However, brachial artery catheterization often is avoided because the brachial artery is the major blood supply to the forearm and hand. Thrombotic and ischemic complications related to brachial artery cannulation can therefore critically compromise blood flow. Other potentially serious complications include infections and injuries to the median nerve. Complications consequent to brachial artery cannulation may be especially common in patients with diabetes and peripheral vascular disease—who are especially likely to require cardiac surgery.

The incidence of complications related to brachial artery cannulation remains essentially unknown. Two recent reports, for example, each included fewer than 150 patients undergoing cardiac surgery,[7,8] making them roughly two orders-of-magnitude smaller than necessary to accurately characterize the incidence of complications, much less potential associations between comorbidities and cannulation-related complications.

We therefore evaluated vascular complications, nerve injury, and infections plausibly related to brachial arterial cannulation in patients undergoing cardiac surgery. Second, we examined whether patients with preexisting peripheral vascular disease, diabetes mellitus, carotid artery disease, coronary artery disease, or chronic kidney disease were at increased risk for complications from brachial arterial cannulation. Finally, we assessed the association between complications from brachial arterial cannulation and length of hospitalization and risk of in-hospital mortality.

Materials and Methods

With Cleveland Clinic Institutional review board (Cleveland Clinic, Cleveland, Ohio) approval and waiver of informed consent, we reviewed the electronic records of patients who underwent cardiac surgery between January 1, 2007, and March 31, 2015. Using our institutional Society of Thoracic Surgeons (STS) database and the Perioperative Health Documentation System (PHDS) registry of the Cleveland Clinic, we identified adults who had brachial arterial catheters inserted intraoperatively for hemodynamic monitoring during cardiac surgery. Patients who had previous surgery on the brachial artery or known brachial artery disease were excluded.

Cannulation of the left brachial artery for intraarterial pressure monitoring is considered standard of care for patients who present for cardiac surgery at the Cleveland Clinic. Arterial puncture is performed with a 20-gauge intravenous catheter; the Seldinger technique (catheter-over-the-wire) is then used to place a 5-inch, 20-gauge catheter for continuous arterial pressure monitoring.

Both registries were used to identify patients with potential brachial arterial catheter complications by detecting all documented vascular or nerve injury, loss of function, or infection within 6 months after the cardiac surgery. The International Classification of Diseases, Ninth Revision diagnostic and procedural codes and Current Procedural Terminology procedure codes that were used to identify potential brachial arterial catheter complications from the PHDS are listed in appendix 1. Potential complications related to brachial arterial cannulation also were identified by a search of the institutional STS database for noncardiac reoperations, limb ischemia, postoperative anticoagulation, postoperative infections involving an arm, septicemia, and neuroparalysis.

Among patients with potential brachial arterial complications, electronic medical records were reviewed individually to characterize complications as definitely related, possibly related, or unrelated to brachial arterial line cannulation. Initial chart reviews were performed by one of three anesthesia residents (A.S., B.B., B.J.W.). All definitely and possibly related complications were cross-validated by a second anesthesiology resident to confirm that the complication appeared related. All complications and any disagreements were adjudicated by an experienced attending cardiothoracic anesthesiologist (A.E.D.).

Complications were considered definitely or possibly related to brachial artery cannulation when (1) the complication occurred at the same site and after insertion of the brachial arterial catheter; (2) the daily intensive care unit (ICU) progress note, cardiac surgery progress note, vascular medicine/surgery consult note, neurology consult note, operative reports, or infectious disease consult notes stated that the complication was consequent to the brachial arterial line; and (3) the brachial arterial catheter was removed when the complication was identified. Once complications were deemed definitely or possibly related to brachial arterial cannulation, they were categorized as a vascular (brachial arterial injury, upper extremity ischemia, compartment syndrome), neurologic (median nerve injury, paresthesia), or infectious (local or systemic infection).

Brachial arterial injuries were further categorized as thrombotic, embolic, dissection, stricture, aneurysm, or other arterial injury. If compartment syndrome was identified, the site was recorded as upper arm, forearm, wrist, or hand. We recorded whether treatments were required, including surgical arterial repair, thrombectomy, fasciotomy (upper arm, forearm, wrist, hand), anticoagulation, or amputation.

Infectious complications were categorized as catheter-site infection, cellulitis, bloodstream infection, septicemia, or other infection. When bloodstream infection or septicemia was identified, we categorized the events as definitely or possibly related to the brachial arterial catheter. Infections were considered definitely related to arterial catheterization and thus the likely source of bloodstream infection or septicemia when one of the following criteria were met: (1) the organism identified from culture of the catheter tip matched the blood culture; (2) the ICU progress note or infectious disease note described a local infection at the site of brachial arterial cannulation; (3) the ICU daily progress

note or infectious disease consult note stated that the arterial catheter was the likely source of infection; (4) other sources of infection were considered unlikely (for example, there were no other intravascular catheters). It is routine at our institution to remove all intravascular catheters when bloodstream infection or septicemia is identified, even without direct evidence that a catheter was the source of infection. Infectious complications were thus labeled as possibly related to arterial catheterization if none of the aforementioned criteria for definitely related to brachial arterial catheterization were fulfilled. We recorded whether treatments were required, including cannulation-site debridement and antibiotic therapy.

Patient demographics, comorbidities (diabetes, peripheral vascular disease, carotid disease, coronary artery disease, chronic kidney disease), type of cardiac surgery, length of hospital stay, and in-hospital mortality also were obtained from the registries.

Carotid artery disease, which is evaluated routinely by carotid ultrasound before cardiac surgery at our institution, was defined by the STS (version 2.81) data specification as carotid stenosis 50% or greater. Diabetes and peripheral vascular disease also were defined according to the STS data specifications. Patients having coronary artery bypass grafting were considered to have coronary artery disease. Chronic kidney disease was defined as estimated glomerular filtration rate less than 30 ml · min^{-1} · 1.73 m^{-2} calculated *via* the Modification of Diet in Renal Disease estimated glomerular filtration rate formula based on serum creatinine, age, gender, and race.

Statistical Analysis

We summarized patient's demographic and medical baseline characteristics as well as procedure related details *via* standard univariable summary statistics as means ± SD, median [first quartile, third quartile], or n (%).

The incidence of complications related to the intraoperative brachial arterial line insertion, our primary outcome, was estimated along with the 95% CI, assessed *via* normal approximation theory.[9] The separate incidence of brachial artery vascular complications, neurologic complications, and infection along with 98.3% (correction for multiple outcomes) normality approximated CI also was reported.

Second, we reported the association between the presence of diabetes, peripheral vascular disease, carotid artery disease, chronic kidney disease and coronary artery disease, and the risk of complications from brachial arterial cannulation with multivariable logistic regression. The association between chronic kidney disease and risk for brachial complications was assessed *post hoc*. We considered brachial arterial complications as the binary outcome and the listed conditions as the explanatory factors. Given the low incidence of the outcomes, we limited the adjustment of the reported associations to preselected clinically relevant cofounders, which included patient's age, body mass index, sex, race, American Society of Anesthesiologists physical status, duration of surgery, surgery emergency status, number of simultaneous cardiac procedures, duration of cardiopulmonary bypass time, duration of myocardial ischemia, and duration of circulatory arrest. The Wald test *P* value and the adjusted odds ratio along with 99% (correction for multiple comparisons) CI were reported for each of the baseline condition.

For the tertiary outcomes, we examined whether a complication related to brachial arterial cannulation was associated with increased length of hospitalization *via* multivariable linear regression model with log-transformed (to satisfy model normality assumption) length of hospitalization as an outcome and status on brachial arterial complication as an exploratory factor. The Wald test *P* value and the adjusted ratio of geometric means along with 97.5% (correction for multiple comparisons) CI were reported. The association between in-hospital mortality and brachial arterial cannulation complications were examined *via* multivariable logistic regression models. We reported the Wald test *P* value and the adjusted odds ratio along with 97.5% (correction for multiple comparisons) CI. Both associations were adjusted for history of diabetes, peripheral vascular disease, carotid disease, coronary artery disease, and all the baseline and intraoperative factors listed for the secondary analysis adjustment.

To adjust for multiple reported comparisons, the Bonferroni correction was applied for the computed CIs and tests significance levels to maintain the Type I error rate at 5% on each primary, secondary and tertiary analysis. SAS 9.4 statistical software (SAS Institute Inc., USA) was used for all analysis.

Sample Size Consideration

We planned to use all available cases and anticipated approximately 3,000 eligible patients per year, total of 24,000 patients. With 24,000 patients, we have the following precision in estimating complication incidence (precision is described in terms of CI width): the width of 95% CI ranges from 0.06 to 0.12% for incidence ranging from 0.05 to 0.2%, respectively: CI width was estimated by use of exact binomial method.

Results

After review of the PHDS and STS registries, we identified 30,652 patients who had cardiac surgery between 2007 and 2015. In 6,000 patients, documentation for an arterial catheter was missing. Most of the surgeries with missing documentation occurred between 2007 and mid-2008 (and were related to design issues in the newly implemented electronic anesthesia record); these patients were therefore excluded from analysis. A total of 21,597 patients met our inclusion and exclusion criteria (fig. 1), with 777 coded as having some form of vascular injury, nerve injury, loss of function, or infection within 6 months after cardiac surgery. Manual review of the electronic medical records confirmed

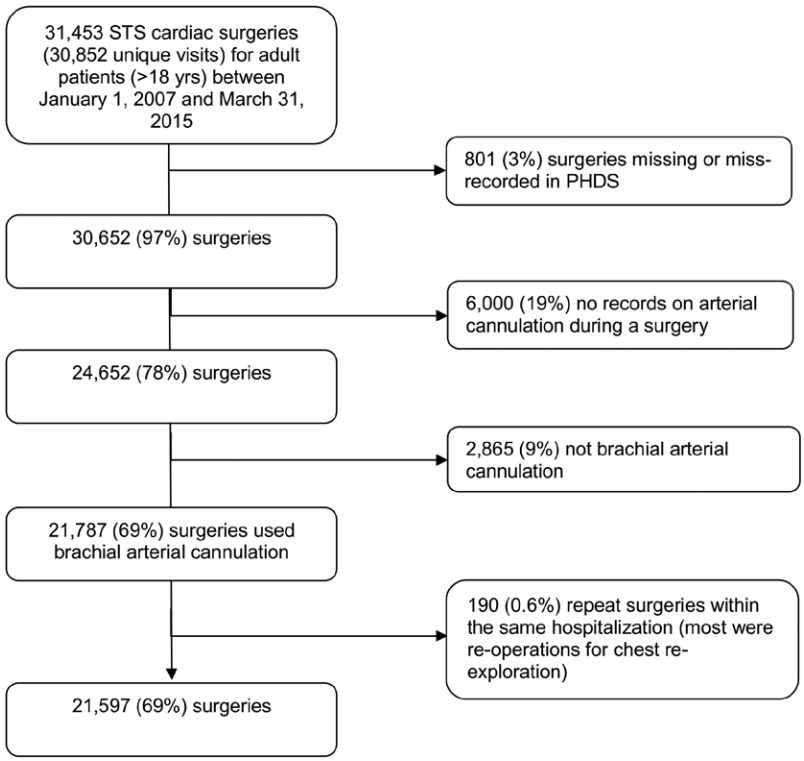

Fig. 1. Flowchart of patient selection. PHDS = Perioperative Health Documentation System; STS = Society of Thoracic Surgeons.

that 41 of 777 patients had complications that were definitely or possibly related to intraoperative brachial arterial catheter insertion. The corresponding incidence estimate (95% CI) for the combination of all three complications is 0.19% (0.14 to 0.26%).

Demographic and baseline characteristics of the study population and procedural details for patients with and without brachial arterial complications are shown in table 1.

Complications related to brachial arterial cannulations occurred between the day of surgery and the 30th postoperative day with the median [first, third quartile] day of complication on postoperative day 4 [2, 8]. Brachial artery vascular complications occurred in 33 (0.15% [0.10 to 0.23%]) patients, who had one or more of the following: upper extremity ischemia (21 patients), thrombosis (17 patients), embolism (2 patients), aneurysm (4 patients), compartment syndrome (1 patient), and other arterial injury (1 patient; table 2). No documented neurologic complications were found in any patient (estimated incidence 0.00% [0.00 to 0.03%]). Infection occurred in 8 (0.04% [0.02 to 0.08%]) patients. Five of eight infections were catheter-related sepsis. It was not possible to determine whether the infection originated from the arterial catheter or from coexistent central-venous catheters; thus, these complications were considered possibly related.

Treatment was required for 37 of the 41 patients who experienced complications (appendix 2). Treatment for vascular complications included repair of the brachial artery in 8 (22%) patients, thrombectomy in 18 (49%) patients, and fasciotomy in 1 (3%) patient. Other therapeutic interventions included anticoagulation in 17 (46%) patients, direct vascular compression in 3 (8%) patients, Rooke® Mitts (which promote vasodilation; Osborn Medical, USA) in 3 (8%), and thrombin injection in 1 patient (3%). All 8 cases of infection were treated with systemic antibiotic therapy.

Univariable and multivariable associations between the presence of diabetes, peripheral vascular disease, carotid disease, chronic kidney disease, coronary artery disease, and the risk of complications from brachial arterial cannulation are presented in table 3.

Postoperative complications and hospital events of patients who did and did not develop brachial arterial complications are presented in table 4. The incidence of cardiac arrest, requirement for extracorporeal membrane oxygenation support, use of intraaortic balloon counterpulsation, kidney failure, requirement for dialysis, prolonged ventilation, and multisystem organ failure was between 5 and 20 times greater in patients who had complications related to brachial arterial catheterization than in those who did not. Tertiary results on associations between brachial arterial catheter complication and length of hospitalization and in-hospital mortality using multivariate regression are shown in table 5. Patients with complications had median hospital stays of 22 days compared with 8 days for patients without complications. In-hospital mortality was 24% in patients with brachial arterial complications compared with 1.75% in patients without arterial complications.

Table 1. Summary of Patient Demographics, Baseline, and Procedural Characteristics (N = 21,597)

Variables	Definitive or Possible Brachial Artery Cannulation Complication (N = 41)		No Brachial Artery Cannulation Complication (N = 21,556)	
	No. Missing*	Summary Statistics	No. Missing*	Summary Statistics
Age, yr		64 ± 16		64 ± 14
Sex (male), n (%)		17 (41)		14,317 (66)
Race, n (%)	1		373	
White		30 (75)		19,169 (90)
African American		6 (15)		1,232 (6)
Others		4 (10)		782 (4)
Body mass index, kg/m^2		27.6 [23.4, 31.9]	8	27.7 [24.6, 31.6]
Medical history, n (%)				
Coronary artery disease		24 (59)		9,152 (42)
Myocardial infarction		9 (22)		4,071 (19)
Heart failure		17 (41)		5,361 (25)
Hypertension		28 (68)		14,750 (68)
Stroke or cerebral vascular accident		2 (5)		1,876 (9)
Diabetes mellitus		15 (37)		5,447 (25)
Carotid disease		0 (0)		202 (1)
Peripheral arterial disease		14 (34)		2,391 (11)
Chronic obstructive pulmonary disease		17 (41)		4,405 (20)
Endocarditis		6 (15)		1,254 (6)
Chronic kidney disease†		7 (17)	27	890 (4)
Dialysis		3 (7)		342 (2)
Atrial fibrillation/flutter	17	10 (42)	8,665	3,479 (27)
Complete heart block/pacer	17	0 (0)	8,668	566 (4)
Ventricular arrhythmia	17	5 (21)	8,668	958 (7)
Smoking		22 (54)		9,881 (46)
ASA physical status, n (%)			1	
1		0 (0)		1 (0)
2		0 (0)		50 (0)
3		2 (5)		3,570 (17)
4		39 (95)		17,678 (82)
5		0 (0)		254 (1)
6		0 (0)		2 (0)
New York Heart Association Functional Class, n (%)	4		3,044	
1		6 (16)		5,020 (27)
2		13 (35)		7,602 (41)
3		13 (35)		4,674 (25)
4		5 (14)		1,216 (7)
Preoperative laboratory values				
Blood urea nitrogen, mg/dl	0	18 [14, 27]	27	18 [15, 23]
Bilirubin, mg/dl	1	0.5 [0.4, 0.6]	213	0.6 [0.4, 0.8]
Creatinine, mg/dl		1.0 [0.9, 1.2]	27	1.0 [0.8, 1.2]
Hematocrit, %		37 [31, 39]	4	39 [34, 42]
HDL cholesterol, mg/dl	15	44 [37, 51]	4,633	46 [37, 58]
LDL cholesterol, mg/dl	15	81 [62, 104]	4,710	88 [67, 114]
Triglycerides, mg/dl	15	101 [78, 114]	4,632	101 [73, 144]
Surgical procedure, n (%)				
Coronary artery bypass grafting		21 (51)		7,145 (33)
Aortic valve replacement		16 (39)		7,947 (37)
Aortic valve repair		2 (5)		1,068 (5)
Mitral valve replacement		7 (17)		2,340 (11)
Mitral valve repair		9 (22)		5,172 (24)
Pulmonary valve repair/replacement		0 (0)		133 (2)
Tricuspid valve replacement		0 (0)		130 (1)

(*Continued*)

Table 1. (*Continued*).

Variables	Definitive or Possible Brachial Artery Cannulation Complication (N = 41)		No Brachial Artery Cannulation Complication (N = 21,556)	
	No. Missing*	Summary Statistics	No. Missing*	Summary Statistics
Tricuspid valve repair		7 (17)		2,153 (10)
Maze procedure		5 (12)		2,680 (12)
Any aortic root, ascending aortic, or aortic arch replacement procedure		12 (29)		3,510 (16)
Descending aorta replacement		2 (5)		393 (2)
Congenital ASD/PFO suture closure		1 (2)		372 (2)
Removal of atrial myxoma, cardiac tumors		0 (0)		108 (1)
Carotid endarterectomy		0 (0)		50 (0)
Pulmonary endarterectomy		1 (2)		88 (0)
Any congenital heart disease procedure		1 (2)		632 (3)
Left ventricular reconstructive procedure		1 (2)		116 (1)
Pericardiectomy		1 (2)		142 (1)
Septal myectomy		0 (0)		1,157 (5)
Heart transplant		1 (2)		260 (1)
Insertion of mechanical ventricular assist device		14 (34)		1,032 (5)
History of cardiothoracic surgical procedures, n (%)				
First surgery		26 (64)		16,292 (76)
First reoperative surgery		12 (29)		4,103 (19)
Second or more reoperative surgery		3 (7)		1,161 (5)
Emergent surgery, n (%)		3 (7)	1	816 (4)
Intraoperative				
Duration of surgery, min		494 [376, 557]		359 [298, 441]
Cardiopulmonary bypass time, min		129 [98, 182]		95 [69, 128]
Aortic cross-clamp time, min		87 [58, 107]		71 [50, 96]
Circulatory arrest, n (%)		6 (15)		1,125 (5)
Duration of circulatory arrest, min		41 ± 20		26 ± 21

Values are given as mean ± SD, median [first, third quartile], or n (%), as appropriate.

*The data that were not collected in the medical records marked as missing, which is mostly race, preoperative laboratory results, New York Heart Association Functional Class, and preoperative EKG. †Chronic kidney disease was identified if eGFR was less than 30 ml · min^{-1} · 1.73 m^{-2}; eGFR was calculated based on the MDRD equation.

ASA = American Society of Anesthesiologists; ASD = atrial septal defect; eGFR = estimated glomerular filtration rate; EKG = electrocardiogram; HDL = high-density lipoprotein; LDL = low-density lipoprotein; MDRD = Modification of Diet in Renal Disease; PFO = patent foramen ovale.

Discussion

In more than 21,500 patients who had brachial arterial catheterization for cardiac surgery, complications were infrequent, occurring in less than 0.2% of patients. This low incidence of complications is comparable with that reported for radial, femoral, and brachial arterial line cannulation in cardiac surgical, noncardiac surgical, and critically ill patients.[3,7,8,10] None of these other reports, however, included an adequate number of brachial arterial catheters to accurately assess the incidence of catheter-related complications of the brachial artery.[3,7,8]

Hypotension is associated with acute kidney and myocardial injury in (noncardiac) surgical patients,[5] and accurate measurement of arterial blood pressure may improve clinical outcomes. Radial arterial systolic pressure is higher than central aortic pressure because amplification occurs as distance from the heart increases,[11] although diastolic and mean arterial pressures decrease only slightly (about 1 to 4 mmHg).[11–13] Furthermore, radial artery pressure may underestimate central aortic pressure during and immediately after cardiopulmonary bypass[3,6,14] due in part to arterial spasm or thermoregulatory vasomotion.[14–17] If radial arterial pressure is inaccurate, patient care may be compromised by promoting administration of vasopressor or inotropic drugs, which may themselves worsen outcomes.[18] In patients having cardiac surgery, brachial arterial pressure measurements better estimate mean and systolic central aortic pressures than radial arterial pressures,[3,19] and those who require hypothermic circulatory arrest are at especially high risk for developing large and prolonged radial-to-aorta pressure gradients.[20] Use of the brachial artery for intraarterial pressure monitoring may thus provide a more accurate tool for hemodynamic monitoring.

The brachial artery is the main blood supply to the forearm and hand. Before the brachial artery bifurcates into the radial and ulnar arteries, several branches, including the deep brachial, humeral nutrient, superior and inferior

Table 2. Incidence of Definitely or Possibly Related Complications from Brachial Arterial Cannulation: Primary Results (N = 21,597)

	Cases, No.	Incidence (CI)*
Definitely or possibly related brachial arterial complications†	41	0.19% (0.14–0.26)
Brachial artery vascular complications	33	0.15% (0.10–0.23)
Upper extremity ischemia	21	
Thrombosis	17	
Embolism	2	
Aneurysm	4	
Compartment syndrome, forearm	1	
Other arterial injury	1	
Infection‡	8	0.04% (0.02–0.08)
Catheter-site infection	2	
Cellulitis	1	
Bloodstream infection/ septicemia	7	
Neurologic complications	0	0.00% (0.00–0.03)

*We reported 95% CIs for the estimate of the incidence of brachial arterial complications; for the specific complications, we reported 98.3% CI, which is Bonferroni adjusted (0.05/3 = 0.017) for multiple outcomes. †A patient might have more than one of the conditions in this list. ‡Five of eight cases of infection were line sepsis. These were identified as complications possibly related to brachial arterial cannulation, because it was not possible to determine whether the arterial catheter or a coexisting central venous catheter was the source of infection.

ulnar collateral artery, provide collateral blood flow to the elbow and upper arm. However, forearm and hand perfusion *via* these collaterals usually is insufficient if acute occlusion of the brachial artery occurs. Thus vascular compromise can cause ischemia to the arm and consequent catastrophic injury, and is an overwhelming concern of brachial arterial cannulation. As might be expected, nearly 80% of all the complications were related to vascular injury or occlusion. The overall incidence of vascular complications, however, was low at 0.15% (*i.e.*, less than 1 per 650 catheters).

Arterial catheters were removed immediately when complications were detected. Patients with brachial artery thrombosis received either thrombectomy or open repair of the brachial artery and postoperative anticoagulation. The remaining patients with upper extremity ischemia improved with intravenous anticoagulation. Ultrasound-guided compression was used to treat brachial arterial pseudoaneurysms.[21] With one exception,[7] other studies similarly reported that surgical and/or medical treatment was required for all vascular complications.[3,8,10]

Handlogten *et al.*[8] reported a slightly greater rate of complications compared with our results after brachial arterial catheterization, namely 0.35%; however, this estimate was based on 3 complications among 858 patients, a fragile result that would be altered substantially by the addition or subtraction of a single complication. Nuttall *et al.*[7] similarly reported a complication rate of 0.75% in cardiac surgical patients, which was also based on a single complication in 134 patients; however, their overall complication rate of 0.12% in approximately 1,600 patients was comparable with our report.

Although vascular complications after radial arterial cannulation recently were reported to be approximately 0.03% overall, complications were higher in patients undergoing cardiac surgery (approximately 0.07%).[7] Though our vascular complication rate in cardiac surgical patients of 0.15% was slightly greater,[7] the 95% CIs likely overlap. A direct comparison of safety between radial *versus* brachial arterial lines is not possible by comparing the results of separate reports because of confounding by differences in patient populations and risk factors.[7] Nonetheless, complications after brachial arterial cannulation may be slightly higher by perhaps 7 to 8 complications per 10,000 brachial catheters compared with radial arterial cannulation. The incidence

Table 3. The Association of Patient Comorbidities with Brachial Arterial Complications: Secondary Results (N = 21,597)

	Univariate Association		Multivariate Association†	
Baseline Comorbidities	OR (99% CI)*	*P* Value*	Adjusted OR (99% CI)*	*P* Value*
Diabetes	1.71 (0.74–3.94)	0.10	1.17 (0.45–3.03)	0.68
Peripheral arterial disease	4.16 (1.78–9.73)	<0.001	2.78 (1.11–7.01)	0.004
Carotid disease‡	N/A	N/A	N/A	N/A
Coronary artery disease	1.91 (0.84–4.33)	0.04	1.46 (0.59–3.59)	0.28
Chronic kidney disease§	4.78 (1.69–13.51)	<0.001	2.31 (0.70–7.65)	0.07

*The significance criteria for all five secondary tests were 0.01, which is Bonferroni adjusted for multiple comparisons (0.05/5 = 0.01) and corresponds to 99% CIs. †The association between the baseline condition (history of diabetes, peripheral vascular disease, carotid disease, coronary artery disease, chronic kidney disease) and postoperative brachial artery cannulation complication outcome was adjusted for patient's age, body mass index, sex, race, ASA status, duration of surgery, surgery emergency status, number of simultaneous cardiac procedures, duration of cardiopulmonary bypass time, duration of myocardial ischemia, and duration of circulatory arrest. ‡Carotid artery disease was identified if Doppler evaluation demonstrated ≥50% stenosis. There were no patients with carotid disease among 41 patients who experienced complications related to brachial artery cannulation. Therefore, we were not able to report the association between presence of carotid disease and risk of brachial artery cannulation complication. §Chronic kidney disease was identified if eGFR was less than 30 ml · min^{-1} · 1.73 m^{-2}; eGFR was calculated based on the MDRD equation.

ASA = American Society of Anesthesiologists; eGFR = estimate glomerular filtration rate; MDRD = Modification of Diet in Renal Disease; N/A = not applicable; OR = odds ratio.

Table 4. Postoperative Complications and Hospital Events in Patients with and without Brachial Arterial Cannulation Complication

Postoperative Complications	Definitive or Possible Brachial Artery Cannulation Complication (N = 41)	No Brachial Artery Cannulation Complication (N = 21,556)
Cardiac arrest	5 (12)	390 (2)
Atrial fibrillation	17 (41)	6,081 (28)
Extracorporeal membrane oxygenation	7 (17)	214 (1)
Left ventricular assist device	1 (2)	306 (1)
Intra/postoperative intraaortic balloon counterpulsation	6 (15)	527 (2)
Stroke	4 (10)	291 (1)
Transient ischemic attack	0 (0)	32 (0)
Coma/encephalopathy	1 (2)	220 (1)
Renal failure	13 (32)	1,018 (5)
Renal failure requiring dialysis	8 (20)	469 (2)
Prolonged ventilation: >24 h postoperatively	30 (73)	3,344 (16)
Pneumonia	4 (10)	273 (1)
Septicemia or bacteremia or sepsis	11 (27)	224 (1)
Gastrointestinal complication	3 (7)	767 (4)
Multisystem organ failure	4 (10)	87 (0)

Data are shown as n (%).

Table 5. The Association between Brachial Arterial Cannulation Complications and Length of Hospital Stay and In-hospital Mortality: Tertiary Results

	Raw Data		Univariate Association		Multivariate Association*	
Outcomes	Definitive or Possible Brachial Artery Cannulation Complication (n = 41)	No Brachial Artery Cannulation Complication (n = 21,556)	Estimate (97.5% CI)	*P* Value†	Estimate (97.5% CI)	*P* Value†
Length of hospitalization, d	22 [14, 30]	8 [6, 14]	2.29 (1.82–2.87)‡	<0.001	1.55 (1.28–1.89)‡	<0.001
In-hospital mortality	10 (24%)	378 (1.75%)	18.07 (7.93–41.18)§	<0.001	8.19 (3.08–21.78)§	<0.001

The raw data are reported as median [first, third quartiles] or n (%), as appropriate (N = 21,597).

*Multivariate linear regression was used to assess the ratio of geometric means of length of hospitalization comparing patients with brachial artery complication with those without complication along with 97.5% CI. Multivariate logistic regression was used to assess the odds ratio of in-hospital mortality comparing patients with brachial artery complication with those without complication. Both associations were adjusted for patient's age, body mass index, sex, race, ASA status, history of diabetes, peripheral vascular disease, carotid disease, coronary artery disease, duration of surgery, surgery emergency status, number of simultaneous cardiac procedures, duration of cardiopulmonary bypass time, duration of myocardial ischemia, and duration of circulatory arrest. †The Wald test *P*-value was reported; significance criteria were Bonferroni corrected for multiple testing and set to 0.05/2 = 0.025. ‡The ratio of geometric means along with 97.5% CI was reported. §The odds ratio along with 97.5% CI was reported.

ASA = American Society of Anesthesiologists.

of complications, however, may be higher at institutions in which brachial arterial cannulation is not routinely performed.

Patients having cardiac surgery may be at greater risk for complications from brachial arterial catheterization because they often have underlying vascular disease and experience perioperative hypoperfusion and low cardiac output state. Use of inotropic and vasopressor therapy may further jeopardize peripheral tissue perfusion. Alternatively, anticoagulation during cardiopulmonary bypass, perioperative platelet dysfunction or coagulopathy, and hypothermia impair coagulation[22] and might reduce thrombotic complications. Therefore, the extent to which our observed incidence in cardiac surgical patients can be extrapolated to patients having other types of surgery remains unknown. Although Nuttall *et al.*[7] reported more complications from brachial arterial cannulation for cardiac than noncardiac surgery, only a small number of patients were included, leaving the issue essentially unresolved.

Only 3 of 21,597 patients (0.01%) developed infectious complications definitely related to brachial arterial catheterization. Five additional patients developed catheter-related bloodstream infections, but definitive evidence that the arterial catheter was the source of infection was absent. Presumably, coexisting central venous catheters were the more likely source of infection.[23] We nonetheless conservatively included these five patients as possible infectious complications. Our incidence of infectious complications is less than

most reports, which range from 0.02 to 0.36%,[7,24] depending on site of arterial cannulation and patient population. Patients with infectious complications were treated with broad-spectrum intravenous antibiotics, whereas nearly one half required vasopressors infusion due to septic shock.

The median nerve runs close to the brachial artery in the antecubital fossa and paresthesia of the median nerve are common during brachial arterial cannulation. We thus expected some nerve injuries; however, we did not observe any reported nerve injury plausibly related to brachial artery cannulation among 21,597 patients. Previous studies also report no nerve injuries, although none were even remotely powered for this rare complication.[3,7,8] Injury to the median nerve during brachial arterial cannulation is thus exceedingly rare and does not cause persistent neurologic dysfunction. Fear of this complication should not guide selection of arterial cannulation site.

Unsurprisingly, patients with peripheral arterial disease had increased risk of complications from brachial arterial cannulation, possibly related to the presence of atheroma formation, calcification of the peripheral arteries, luminal narrowing, and reduced blood flow.[25] We note, however, that the overall incidence of complications even in these patients was low and that peripheral arterial disease is hardly a compelling reason to avoid brachial arterial catheterization if otherwise indicated. However, as mentioned previously, our low incidence of complications in cardiac surgical patients cannot be directly extrapolated to patients with peripheral vascular disease having noncardiac surgery, because perioperative management, such as systemic anticoagulation during cardiac surgery, may reduce risk of complications. Interestingly, patients with diabetes mellitus, coronary artery disease, and chronic kidney disease, all of which are associated with arterial compromise, were not at increased risk from brachial arterial cannulation. Safety of brachial arterial cannulation has significant future implications, especially in patients with kidney disease, who may later require vascular access for hemodialysis. We examined risk in patients with carotid disease, since this finding may indicate disease in other major arteries. However, none of the patients with brachial arterial line complications had preexisting carotid disease, suggesting that patients with carotid artery disease are not at increased risk, although we could not formally assess the association.

Patients with arterial line complications had prolonged hospital stays and greater in-hospital mortality. The postoperative course in these patients, however, was complicated by a much greater incidence of severe life-threatening postoperative complications, including cardiac arrest, kidney injury requiring dialysis, multiorgan failure, and use of extracorporeal membrane oxygenation for severe cardiac or pulmonary failure refractory to conventional management. It seems obvious that these serious postoperative complications were not directly consequent to brachial arterial cannulation. Instead, it is more likely that prolonged cannulation and monitoring of the brachial artery was required in these critically ill patients who suffered from a low cardiac output state, required high-dose vasopressor therapy or mechanical circulatory support, or had compromised systemic and peripheral perfusion. Thus, these serious postoperative complications likely predisposed patients to brachial arterial line complications, rather than the possibility that brachial arterial cannulation caused life-threatening complications, a prolonged hospital stay, or greater in-hospital mortality. Although the overall incidence of complications is low, increased clinical suspicion for vascular complications and appropriate consideration for alternative arterial line sites are suggested for critically ill patients who require prolonged high-dose pharmacologic or mechanical circulatory support.

Our observational analysis has the limitations inherent to its retrospective design. As in all retrospective studies, our findings rely on accurate recording of arterial line catheterization, comorbidities, and postoperative complications, and thus there is the possibility of underreporting of complications. We were not able to report minor complications due to the lack of in-hospital International Classification of Diseases, Ninth Revision and Current Procedural Terminology billing codes for less severe complications. It is thus likely that we missed minor self-limited complications, but such complications are also of questionable clinical importance. Unlike one investigation that reported minor clinically insignificant complications, such as "temporary arterial occlusion,"[24] we considered only clinically important vascular complications which included upper extremity ischemia, arterial thrombosis, pseudoaneurysm, and compartment syndrome. Our investigation could not compare the risk of complications between radial and brachial arterial lines, because radial arterial lines are only used at our institution when contraindications or difficulty with brachial arterial cannulation are present.

Although our secondary analysis adjusted for multiple confounding variables, the possibility of unmeasured covariates and residual confounders cannot be excluded. We were unable to determine the true incidence of infection because catheter tips were not always cultured; however, we conservatively included patients who experienced line-related sepsis, even though the central venous catheter was the more likely source of infection. Arterial line documentation was missing in approximately 20% of patients, mostly during the new implementation of our intraoperative electronic documentation record when documentation was in development. However, it seems unlikely that including these patients would substantively influence our conclusions.

In summary, brachial artery cannulation during cardiac surgery was associated rarely with complications. Most complications, unsurprisingly, were vascular. Because brachial artery pressure measurements better reflect aortic pressure

than radial arterial catheters and complications are rare, the brachial artery remains a reasonable site for direct arterial pressure measurement.

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Competing Interests

The authors declare no competing interests.

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Appendix 1. Variables Used to Identify Possible Complications Related to Brachial Arterial Catheterization from (1) ICD-9 Diagnoses and Procedures Codes, (2) CPT Procedure Codes from the Cleveland Clinic PHDS Registry, and (3) Postoperative Complications from the Institutional STS Database

Complications	Description	ICD-9 Diagnoses or Procedure Code or CPT Procedure Code
PHDS		
Vascular injury	Aneurysm of artery of upper extremity	442.0
	Chronic total occlusion of artery of the extremities	440.4
	Arterial embolism and thrombosis of upper extremity	444.21
	Air embolism as a complication of medical care not elsewhere classified	999.1
	Nontraumatic compartment syndrome of upper extremity	729.71
	Fasciotomy of hand	82.12
	Stricture of artery	39.31
	Surgical repair/exploration of brachial artery: decompression fasciotomy with brachial artery exploration	24495
	Fasciotomy (possible compartment syndrome) in the antecubital fossa: decompression fasciotomy forearm and/or wrist	25020–25025
	Thrombectomy of brachial artery	34101
Nerve injury	Carpal tunnel syndrome	354.0
	Injury to median nerve	955.1
	Other neuroplasty	04.79
	Median nerve damage (tingling numbness) in antecubital fossa: neuroplasty	64718
Loss of function	Other finger(s) amputation status	V49.62
	Below elbow amputation status	V49.65
	Digit amputation for upper extremity: amputation finger or thumb	26951, 26952
Infection	Other specified local infections of skin and subcutaneous tissue	686.8
Institutional STS database*		
Infection	Arm infection: infection with type “radial artery harvest site infection” or “arm”	—
	Bacteremia: Indicate whether a recognized pathogen is cultured from 1 or more blood cultures	—
	Sepsis: sepsis is defined as evidence of serious infection accompanied by a deleterious systemic response. In the time period of the first 48 postoperative or postprocedural hours, the diagnosis of sepsis requires the presence of an SIRS resulting from a proven infection (such as bacteremia, fungemia, or urinary tract infection). In the time period after the first 48 postoperative or postprocedural hours, sepsis may be diagnosed by the presence of an SIRS resulting from suspected or proven infection. During the first 48 h, an SIRS may result from the stress associated with surgery and/or cardiopulmonary bypass. Thus, the clinical criteria for sepsis during this time period should be more stringent. An SIRS is present when at least two of the following criteria are present: hypo- or hyperthermia (>38.5 or <36.0), tachycardia or bradycardia, tachypnea, leukocytosis or leukopenia, or thrombocytopenia.	
Neuroparalysis	Indicate whether the patient had a new postoperative permanent or transient paralysis, paraparesis, or paraplegia related to spinal cord ischemia and not related to a stroke.	—
Postoperative anticoagulation	Indicate whether the patient had bleeding, hemorrhage, and/or embolic events related to anticoagulant therapy postoperatively. This may include patients who experience disseminated intravascular coagulopathy or heparin-induced thrombocytopenia.	—
Acute limb ischemia	Indicate whether the patient had any complication producing limb ischemia. This may include upper or lower limb ischemia.	—
Noncardiac reoperations	Indicate whether the patient returned to the operating room for other noncardiac reasons. This includes procedures requiring a return to the operating room such as tracheostomy or general surgery procedures. This does not include procedures performed outside the operating room such as gastrointestinal laboratory for PEG tube, shunts for dialysis, etc.	—

*The description corresponds to STS Adult Cardiac Surgery Database Data Specifications, version 2.81.

CPT = Current Procedural Terminology; ICD-9 = International Classification of Diseases, Ninth Revision; PEG = polyethylene glycol; PHDS = Perioperative Health Documentation System; SIRS = systemic inflammatory response syndrome; STS = Society of Thoracic Surgeons.

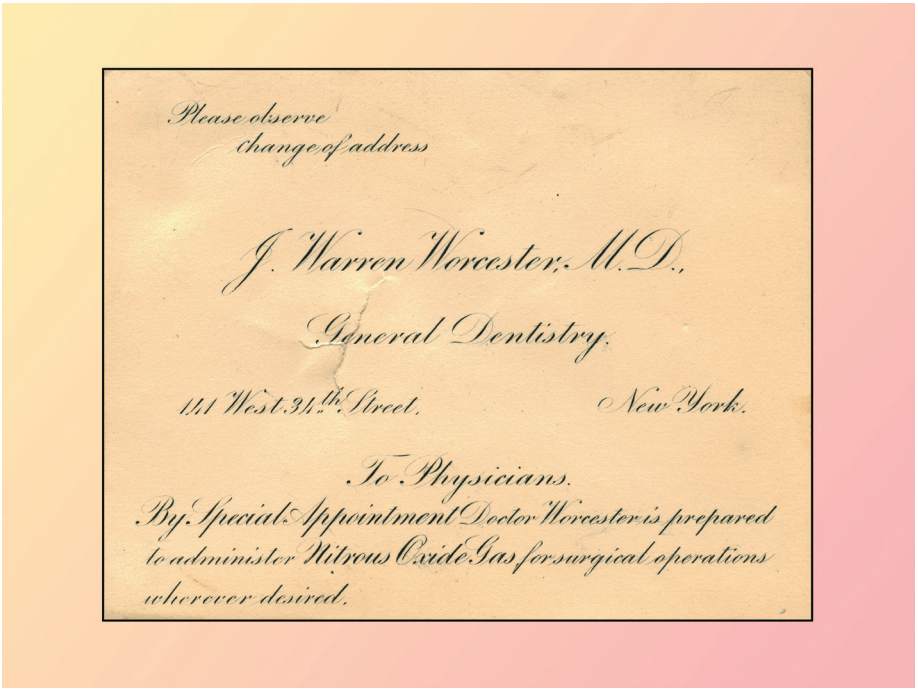
Appendix 2: Treatment for Brachial Arterial Complications

	Cases, No. (%) (n = 41)
Any treatment for brachial arterial complication*	37 (100)
Brachial artery injury or occlusion*	29 (78)
Surgical repair of brachial artery	8 (22)
Thrombectomy	18 (49)
Fasciotomy of forearm	1 (3)
Anticoagulation	17 (46)
Amputation	0 (0)
Compression	3 (8)
Thrombin injection	1 (3)
Rooke® mitt	3 (8)
Other	9 (2)
Infection	8 (12)
Antibiotic therapy	8 (12)
Median nerve injury	0 (0)

*A patient might have multiple treatments.

ANESTHESIOLOGY REFLECTIONS FROM THE WOOD LIBRARY-MUSEUM

Nitrous Oxide from a Peach of a Specialist: J. Warren Worcester, M.D.



After attending lectures at the New York College of Pharmacy and then the nearby College of Physicians and Surgeons, Joseph Warren Worcester (1860 to 1926) earned his M.D. in 1888 from another College of Physicians and Surgeons, the one in Baltimore, Maryland. He returned that same year to New York to marry and live with Ella Hallock, a lifelong Middletown resident. According to this now peach-framed trade card from the Wood Library-Museum's Ben Z. Swanson Collection, Doctor Worcester was "prepared / to administer Nitrous Oxide Gas for surgical operations / wherever desired." Branding himself a "Specialist in use of nitrous oxide gas for dental and general surgery," this physician and dental surgeon cited his professional "change of address" to Manhattan's "141 West 34th Street." Using that clue, a diligent historical researcher can comb city directories and newspapers and date this card to c. 1892. By that year, this versatile physician had successfully bred the fruit brand for which he would become nationally renowned, the "Dr. Worcester Peach." (Copyright © the American Society of Anesthesiologists' Wood Library-Museum of Anesthesiology.)

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