Journal of the American Heart Association

ORIGINAL RESEARCH

Institutional Red Blood Cell Transfusion Rates Are Correlated Following Endovascular and Surgical Cardiovascular Procedures: Evidence That Local Culture Influences Transfusion Decisions

Eirini Apostolidou, MD, MSc; Dhaval Kolte, MD, PhD; Kevin F. Kennedy, MS; Charles E. Beale, MD; J. Dawn Abbott, MD; Afshin Ehsan, MD; Hitinder S. Gurm, MD; Jeffrey L. Carson, MD; Shafiq Mamdani, MD; Herbert D. Aronow, MD, MPH

BACKGROUND: The relationship between local hospital culture and transfusion rates following endovascular and surgical cardiovascular procedures has not been well studied.

METHODS AND RESULTS: Patients undergoing coronary revascularization, aortic valve replacement, lower extremity peripheral vascular intervention, or carotid artery revascularization from up to 852 US hospitals in the Nationwide Readmissions Database were identified. Crude and risk-standardized red blood cell transfusion rates were determined for each procedure. Pearson correlation coefficients were calculated between respective procedural transfusion rates. Median odds ratios were estimated to reflect between-hospital variability in red blood cell transfusion rates following the same procedure for a given patient. There was wide variation in red blood cell transfusion rates across different procedures, from 2% following carotid endarterectomy to 29% following surgical aortic valve replacement. For surgical and endovascular modalities, transfusion rates at the same hospital were highly correlated for aortic valve replacement (r=0.67; P<0.001), moderately correlated for coronary revascularization (r=0.56; P<0.001) and peripheral vascular intervention (r=0.51; P<0.001), and weakly correlated for carotid artery revascularization (r=0.19, P<0.001). Median odds ratios were all >2, highest for coronary artery bypass graft surgery and surgical aortic valve replacement, indicating substantial site variation in transfusion rates.

CONCLUSIONS: After adjustment for patient-related factors, wide variation in red blood cell transfusion rates remained across surgical and endovascular procedures employed for the same cardiovascular condition. Transfusion rates following these procedures are highly correlated at individual hospitals and vary widely across hospitals. In aggregate, these findings suggest that local institutional culture significantly influences the decision to transfuse following invasive cardiovascular procedures and highlight the need for randomized data to inform such decisions.

Key Words: blood transfusion ■ endovascular procedures ■ surgical procedures ■ variability

Although red blood cell (RBC) transfusion may be lifesaving in the setting of profound anemia or ongoing bleeding, it has been associated with increased mortality and major adverse events in patients with acute coronary syndromes[1] and following percutaneous coronary intervention (PCI),[2,3] transcatheter aortic valve replacement (TAVR),[4–6] coronary artery bypass surgery (CABG), and cardiac valve surgery.[7–10] Potential underlying pathophysiologic mechanisms include impaired oxygen delivery, decreased

Correspondence to: Herbert D. Aronow, MD, MPH, 593 Eddy Street, APC 730, Providence, RI 02903. E-mail: herbert.aronow@lifespan.org

Supplementary Material for this article is available at https://www.ahajournals.org/doi/suppl/10.1161/JAHA.119.016232

For Sources of Funding and Disclosures, see page 8.

JAHA is available at: www.ahajournals.org/journal/jaha

CLINICAL PERSPECTIVE

What Is New?

- Red blood cell transfusion rates vary significantly across surgical and endovascular procedures employed for treatment of the same disease state.
- Postprocedure red blood cell transfusion rates are significantly correlated following surgical and endovascular cardiovascular procedures at any given hospital.

What Are the Clinical Implications?

- Local Institutional culture appears to strongly influence the decision for transfusion following invasive cardiovascular procedures.
- In the future, blood management programs may focus on improving institutional practice to optimize blood transfusion administration after cardiovascular procedures.

Nonstandard Abbreviations and Acronyms

CAS	carotid artery stenting
CEA	carotid endarterectomy
HCUP	Healthcare Cost and Utilization Project
MOR	median odds ratio
NRD	Nationwide Readmissions Database
PVI	peripheral vascular intervention
SAVR	surgical aortic valve replacement
TAVR	transcatheter aortic valve replacement

deformability of stored RBCs, prothrombotic effects of released procoagulant factors and transfusion-associated immunosuppression.[2]

In the absence of robust randomized data to guide transfusion practices following most cardiovascular procedures,[11–13] significant variability exists in RBC transfusion thresholds employed for various surgical and endovascular cardiovascular procedures.[14–19] Prior data from statewide PCI and CABG registries indicate that RBC transfusion rates are correlated at an institutional level, suggesting that a local transfusion culture may exist.[20] We sought to extend these observations to the larger US population and to include a broader array of endovascular and surgical cardiovascular procedures.

METHODS

Data Source

The Nationwide Readmissions Database (NRD) is a publicly available, all-payer database, developed by the Agency for Healthcare Research and Quality for the Healthcare Cost and Utilization Project (HCUP). The 2014 NRD contains data on 15 million discharges from 22 states representing ≈50% of the total US resident population and 50% of all US hospitalizations. The year 2014 was chosen as it is the final year during which *International Classification of Disease, Ninth Edition* (*ICD-9*) coding was used and where complete data are available. A single year was used because hospital identifications do not track across multiple years. The Agency for Healthcare Research and Quality uses numerous quality assurance procedures to ensure data quality for each data source participating in HCUP. The study was deemed exempt by the Lifespan–Rhode Island Hospital Institutional Review Board, as the NRD is a publicly available limited dataset.

Study Population

International Classification of Disease, Ninth Edition, Clinical Modification (*ICD-9-CM*) diagnosis and procedure codes (Tables S1 and S2) were used to identify all hospitalizations during which coronary revascularization, aortic valve replacement for any aortic valve pathology, lower extremity peripheral vascular intervention (PVI) or carotid revascularization was performed. Complementary endovascular and surgical procedure pairs were constructed as follows: (1) PCI—CABG; (2) TAVR—surgical aortic valve replacement (SAVR); (3) lower extremity endovascular—surgical PVI; and (4) carotid artery stenting (CAS)—carotid endarterectomy (CEA). Hospitals were included if at least 5 of each procedure in a complementary pair were performed. The minimum required volume for each procedure was set at this level to ensure adequate volume for statistical analysis. Patients <18 years of age, those who underwent hybrid (endovascular and surgical) peripheral revascularization procedures, or those who underwent >1 of the above procedures during the same hospitalization were excluded (Figure 1).

Patient and Hospital Characteristics

Patient demographics (age, sex, primary expected payer, median household income) and comorbid conditions (hypertension, dyslipidemia, diabetes mellitus, smoking, obesity, heart failure, coronary artery disease, carotid artery disease, peripheral artery disease, prior transient ischemic attack/stroke, chronic kidney disease, chronic lung disease, liver disease, anemia, coagulopathy, cancer, and total number of Elixhauser comorbidities[21]) were extracted, as were index hospitalization length of stay, discharge disposition, and hospital characteristics (bed size, location, and teaching status). *ICD-9-CM* codes used to

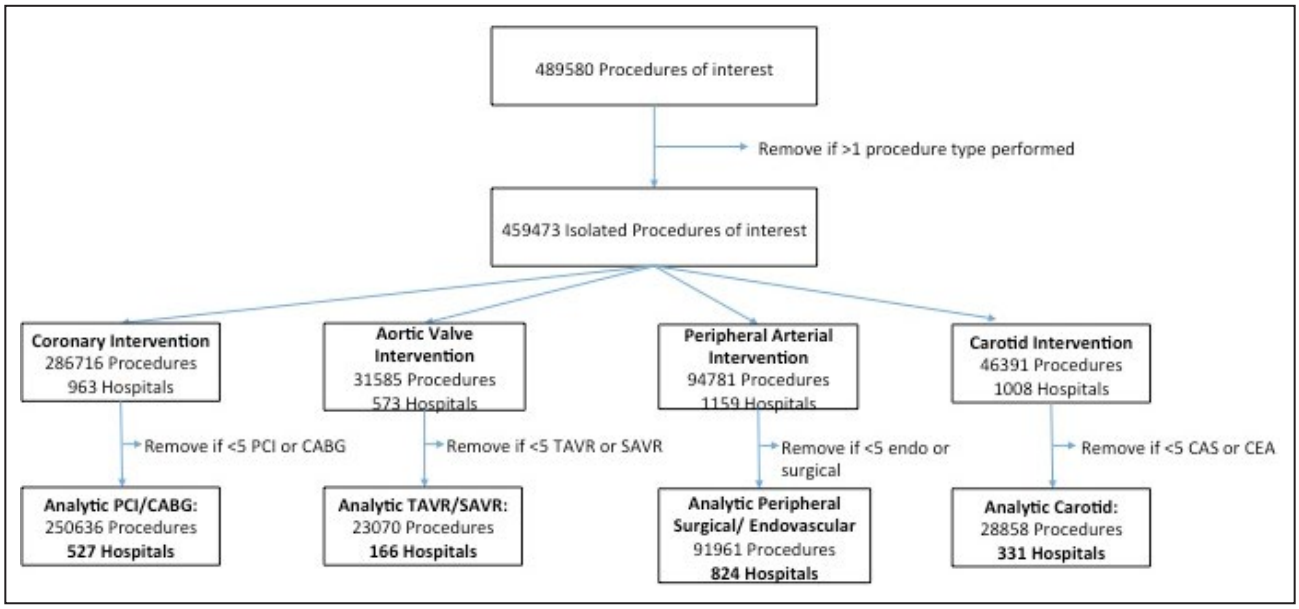

Figure 1. Study flowchart.
CABG indicates coronary artery bypass grafting; PCI, percutaneous coronary intervention; SAVR, surgical aortic valve replacement; and TAVR, transcatheter aortic valve replacement.

define comorbidities appear in Table S2. All comorbidity measures were assumed to be present before the hospital stay.

Outcomes

The primary outcome of interest was RBC transfusion during the index hospitalization.

Statistical Analysis

Unweighted data were used for all analyses. Continuous variables appear as mean± SD or median with interquartile range; and are compared with Student *t* or Wilcoxon rank sum tests, as appropriate. Categorical data appear as frequencies and percentages and are compared with chi-square or Fisher's exact tests, as appropriate.

Both crude and risk-standardized RBC transfusion rates were calculated for endovascular and surgical procedures at each hospital. Variables that were plausibly related to the outcome of interest were included in risk-standardized models and their source appears in Table S3. The statistical methodology used to calculate risk-standardized transfusion rates is identical to that employed by the Centers for Medicare and Medicaid Services for calculating risk-standardized readmission rates[22]; Specifically, we calculated risk-standardized hospital-specific transfusion rates using hierarchical generalized logistic regression models with site entered as a random effect. These rates were computed as the ratio of the predicted transfusions to expected transfusions multiplied by the registry unadjusted transfusion rate. The predicted number of transfusions was calculated using the hospital's own case mix and specific intercept, whereas the expected number of transfusions was estimated using the average hospital intercept of all sites in the registry. The publicly available SAS package (SAS Institute, Cary, NC) was used to construct a hierarchical logistic regression model using proc Glimmix with the fixed effects described above and a random hospital-specific intercept.[23] Discrimination for each procedural transfusion model was calculated using the C-statistic.

Pearson correlation coefficients were calculated between site-level crude and risk-standardized RBC transfusion rates for PCI and CABG, TAVR and SAVR, endovascular and surgical PVI, and CAS and CEA. Similarly, correlation coefficients were calculated between crude and risk-standardized RBC transfusion rates for any endovascular and any surgical procedure. To account for the possibility that some operators at the same hospital might perform both procedures within a given procedure pair, which could increase the correlation between observed RBC transfusion rates, a sensitivity analysis examining the correlation between transfusion rates for all studied procedures, was conducted. Separate sensitivity analyses were also performed, where: a) the minimum required volume was set to 20 procedures; b) patients who underwent the same procedure more than once during the study period were excluded; c) only postprocedure transfusions were included; and, d) where transfusion of any blood product was

included (*ICD-9* codes used for respective blood products appear in Table S4).

To quantify the amount of site variability in transfusion rates for each procedure, we calculated median odds ratios (MORs) for each procedure pair.[24] The MOR is interpreted as the odds that the same patient undergoing the same procedure would be transfused at one versus another randomly selected hospital; risk-adjusted transfusion rates were used for MOR calculations. To determine whether the observed variability, as reflected by the MOR, was influenced by patient- or hospital-level characteristics, statistical models were also generated where age and sex, HCUP comorbidity variables and major bleeding were sequentially added. All statistical analyses were performed with SAS 9.4 (SAS Institute). The level of statistical significance was set at a 2-sided $P<0.05$.

RESULTS

Hospitals and Patients

We identified 852 US hospitals that performed the endovascular and surgical procedures of interest (Table 1). Coronary revascularization, peripheral vascular revascularization, aortic valve replacement, and carotid artery revascularization were performed in 527, 824, 166, and 331 hospitals, respectively. Approximately half of the hospitals were large, and one third were medium size; most were urban teaching hospitals.

Patients' characteristics by transfusion status in the overall population and separately by cardiovascular procedure type are shown in Tables S5 and S6, respectively. Patients who were transfused had a longer length of stay compared with those who were not (12.4 versus 5.7 days; $P<0.001$) and a greater number of chronic conditions, including underlying anemia (37.4% versus 14.4%; $P<0.001$), chronic heart failure (6.8% versus 3.1%; $P<0.001$), coagulopathy (22.4% versus 7%; $P<0.001$) and renal failure (36% versus 18.9%; $P<0.001$).

Transfusion Rates

The overall crude RBC transfusion rates for endovascular and surgical procedures were 5.9% and 19.4%, respectively ($P<0.001$). There was wide variation in blood product transfusion rates across different procedures. The crude rates of RBC transfusion following TAVR (n=1521), SAVR (n=3983), PCI (n=5020), CABG (n=16 944), endovascular PVI (n=7564), surgical PVI (n=8160), CAS (n=227), and CEA (n=444) were 18.3%, 27%, 2.9%, 22%, 14.1%, 21.3%, 3.5%, and 2%, respectively. Median (IQR) risk-standardized transfusion rates for the same procedures were 20.5% (10.2%–30.7%), 34.2% (15.7%–46.7%), 3.4% (1.8%–4.8%), 29.1% (12.9%–40.5%), 15.4% (10.1%–20.7%), 23.2% (14.8%–31.6%), 2.5% (2.2%–5.4%), and 1.6% (1%–3.5%), respectively. Most transfusions occurred postprocedure (TAVR, 96%; SAVR, 94.7%; PCI, 82%; CABG, 95%; endovascular PVI, 83.9%; surgical PVI, 94%; CAS, 93.4%; and, CEA, 91.2%).

Cross-Procedure Transfusion Correlations

The correlation between risk-standardized transfusion rates was strongest for the SAVR-TAVR ($r=0.67$; $P<0.001$), intermediate for the CABG-PCI ($r=0.56$; $P<0.001$) and surgical-endovascular PVI ($r=0.51$; $P<0.001$) and weaker for the CEA-CAS procedure pairs ($r=0.19$; $P<0.001$) (Figure 2). The correlation for risk-standardized RBC transfusion rates for all endovascular and surgical procedures was 0.5 ($P<0.001$). Risk-standardized transfusion rates for unpaired procedures were also significantly correlated, suggesting that paired-procedure correlations could not have solely resulted from operators performing

Table 1. Hospital Characteristics

	Any (n=852 Hospitals)	Carotid (n=331 Hospitals)	Coronary (n=527 Hospitals)	Peripheral Vascular (n=824 Hospitals)	Aortic Valve (n=166 Hospitals)
Average number of surgery patients per hospital	236.1±280.2	70.8±51.1	177.9±142.0	59.1±59.7	134.6±106.3
Average number of endovascular patients per hospital	312.4±348.4	20.9±20.7	339.9±249.9	79.4±82.9	56.4±56.1
Hospital bed size, n(%)					
Small	145 (17)	25 (7.6)	57 (10.8)	139 (16.9)	9 (5.4)
Medium	186 (33.6)	90 (27.2)	146 (27.7)	271 (32.9)	31 (18.7)
Large	421 (49.4)	216 (65.3)	324 (61.5)	414 (50.2)	126 (75.9)
Hospital teaching status, n (%)					
Rural	333 (39.1)	91 (27.5)	179 (34)	314 (38.1)	21 (12.7)
Urban teaching	476 (55.9)	236 (71.3)	334 (63.4)	469 (56.9)	144 (86.7)
Urban non-teaching	43 (5.0)	4 (1.2)	14 (2.7)	41 (5.0)	1 (0.6)

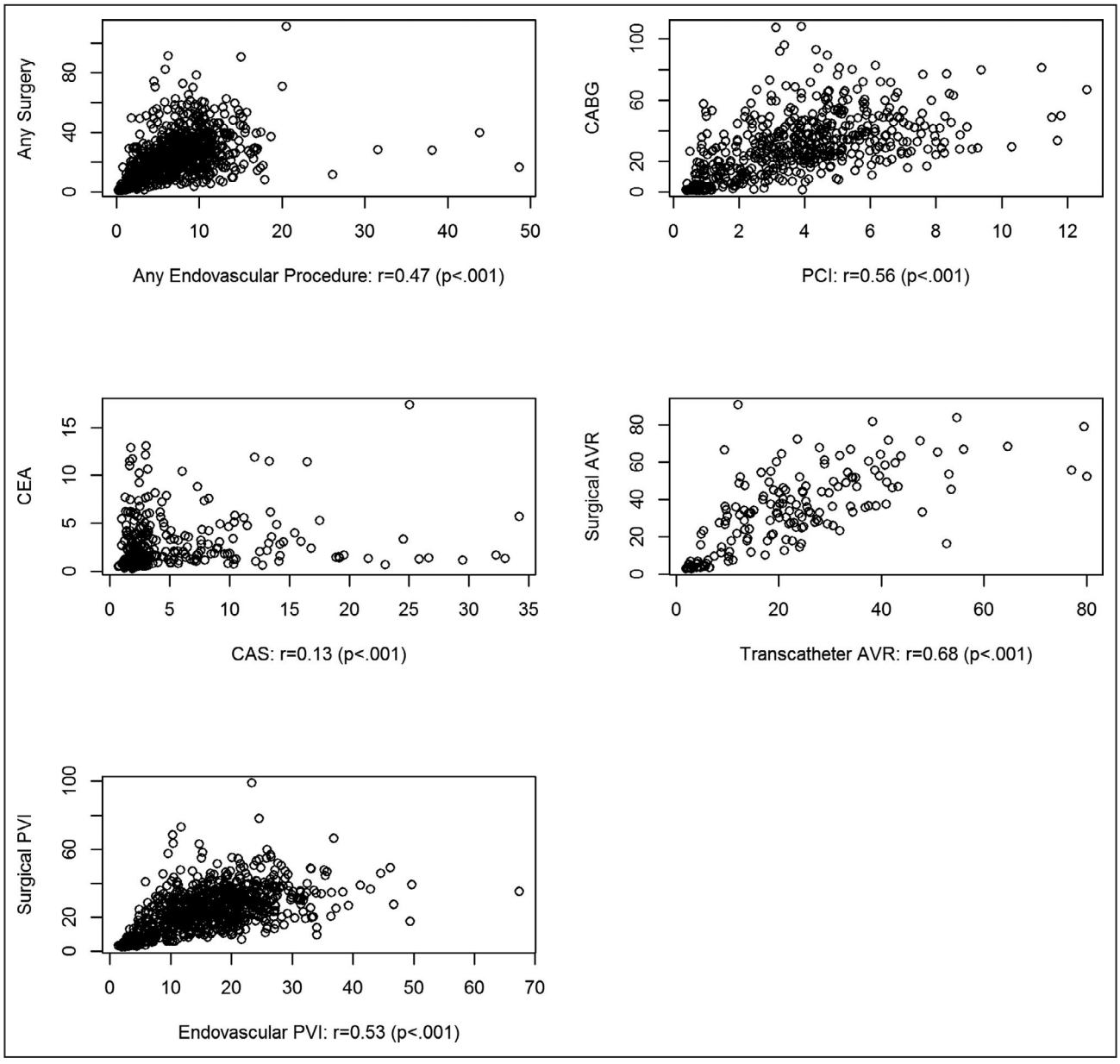

Figure 2. Risk-standardized RBC transfusion rates for pairs of surgical and endovascular procedures.
A, Risk-standardized transfusion rates for any surgical and any endovascular procedure. **B**, Risk-standardized transfusion rates for CABG vs PCI. **C**, Risk-standardized transfusion rates for carotid endarterectomy vs carotid stent. **D**, Risk-standardized transfusion rates for SAVR vs TAVR. **E**, Risk-standardized transfusion rates for surgical vs endovascular peripheral vascular intervention. CABG indicates coronary artery bypass grafting; CAS, carotid artery stent; CEA, carotid endarterectomy; PCI, percutaneous coronary intervention; PVI, peripheral vascular intervention; SAVR, surgical aortic valve replacement; and TAVR, transcatheter aortic valve replacement.

both procedures in a given pair (data not shown). In separate sensitivity analyses, where the minimum required procedural volume for a given procedure pair was set to 20 (Table S7), patients who underwent the same procedure more than once during 2014 (11.8% of the study population) were excluded (Table S8); only postprocedure transfusions were included (Table S9); and where all blood product transfusions were included in the primary outcome (Table S10), cross-procedure correlations were not materially changed.

Hospital-Level Variation in Transfusion

The distribution of risk-standardized transfusion rates at the hospital level, ranked from lowest to highest, is shown for each procedure in Figure 3. Median odds ratios (MORs) were calculated for RBC transfusion

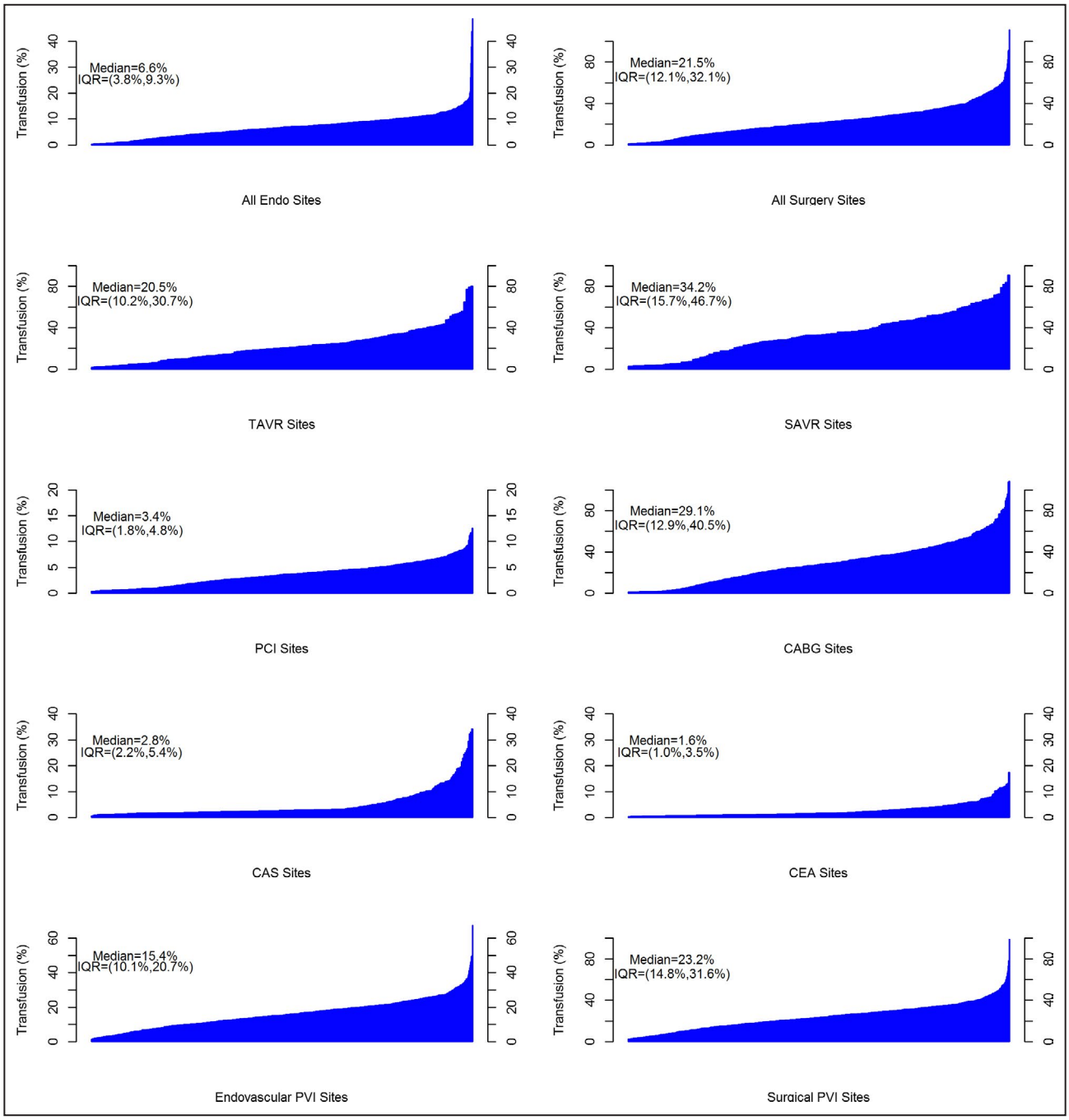

Figure 3. A distribution of risk standardized transfusion rates at the hospital level for all endovascular and surgical procedures, ranked from lowest to highest for each procedure.
CABG indicates coronary artery bypass grafting; CAS, carotid artery stent; CEA, carotid endarterectomy; PCI, percutaneous coronary intervention; PVI, peripheral vascular intervention; SAVR, surgical aortic valve replacement; and TAVR, transcatheter aortic valve replacement.

following each procedure and appear in Table 2. MORs were all >2, indicating substantial site variation in transfusion rates. MORs were highest for CABG and SAVR, each of which were >3.5, indicating that if the same patient underwent the same procedure at 2 different randomly selected hospitals, the odds of transfusion would be almost 4 times greater at one hospital than at the other. After adding age and sex, HCUP comorbidity variables, and major bleeding, MORs in the endovascular (unadjusted, 2.83 [2.65–3.00], 2.76 [2.60–2.94], 2.64 [2.49–2.80], and 2.97 [2.77–3.16], respectively) and surgical (unadjusted, 3.24 [3.03–3.46], 3.30 [3.09–3.52], 3.25 [3.04–3.47], and 3.54 [3.29–3.78], respectively) cohorts were not significantly altered.

Table 2. Risk-Adjusted MORs for RBC Transfusion Following Endovascular and Surgical Procedures

Procedure	MOR (95% CI)
TAVR	3.16 (2.63–3.72)
SAVR	3.68 (3.09– 4.30)
PCI	2.88 (2.65– 3.11)
CABG	4.44 (3.99– 4.90)
CAS	3.64 (2.99– 4.33)
CEA	3.20 (2.75– 3.67)
Endovascular PVI	2.51 (2.35– 2.67)
Surgical PVI	2.88 (2.68– 3.08)

CABG indicates coronary artery bypass grafting; CAS, carotid artery stent; CEA, carotid endarterectomy; MOR, median odds ratio; PCI, percutaneous coronary intervention; PVI, peripheral vascular intervention; RBC, red blood cell; SAVR, surgical aortic valve replacement; and TAVR, transcatheter aortic valve replacement.

DISCUSSION

In a large, nationally representative study of hospitalizations for coronary revascularization, aortic valve replacement, lower extremity PVI, or carotid revascularization procedures in the United States, we observed the following: (1) There was wide hospital-level variation in RBC transfusion rates across different cardiovascular procedures; (2) at any given hospital, postprocedure RBC transfusion rates were highly correlated for SAVR and TAVR, and moderately correlated for PCI and CABG, surgical and endovascular PVI, and for any surgical and any endovascular procedure; (3) for each procedure studied, there was substantial variation in the associated RBC transfusion rate across hospitals such that the same patient was >2 to 4 times more likely to receive a transfusion at one randomly selected hospital than at another. To our knowledge, this study is the first to relate RBC transfusion rates following a variety of surgical and endovascular cardiovascular procedures to the hospitals at which care was rendered.

Significant variability exists in RBC transfusion thresholds following different cardiovascular procedures, and the likelihood of transfusion may be influenced by patient- and provider-level factors.[14–17] At the patient level, preprocedure anemia, procedure-related hemodilution, blood loss following cardiopulmonary bypass, and vascular access site complications are common indications for transfusion.[1–4] That RBC transfusions are administered more commonly following surgical than endovascular cardiac procedures has been observed in prior studies and is not surprising.[25] This observation may be explained by the fact that endovascular procedures are associated with less blood loss, hemodilution, and volume shifts than surgical procedures.[15,25]

The relatively high transfusion rates observed for some procedures deserves comment. Transfusion rates have fallen over time for some procedures, such as TAVR, and may not be as high today as they were in 2014.[26] Also, global transfusion rates for a given procedure may not reflect the likelihood of transfusion for all patients undergoing these procedures. For example, one would expect the overall risk-standardized RBC transfusion rate for endovascular PVI to be higher in those with critical limb ischemia than in those with claudication.

In the present study, we demonstrated that RBC transfusion rates within assigned procedure pairs were highly correlated at individual hospitals. In fact, based on the associated r^2 values, approximately one third to one half of the variation in a hospital's RBC transfusion rate following CABG or SAVR can be explained by its rate in PCI or TAVR, respectively. Though still statistically significant, the correlations between a hospital's RBC transfusion rate for surgical and endovascular PVI and for CEA and CAS were weaker compared with those observed for other complementary procedures. The close cooperation of cardiac surgery and interventional cardiology through Heart Team participation[27,28] may contribute to some of this observed concordance; similarly, the rarity of multidisciplinary vascular teams may in part explain the weaker correlation between surgical PVI and endovascular PVI and between CEA and CAS, where physician operators may not be collaborating as closely.

Substantial variability in transfusion practices at the hospital level has been reported previously among patients undergoing CABG[17,18,29] and PCI.[15,16] A study from 33 Michigan centers found that local hospital practice patterns influenced the likelihood of transfusion; centers that transfused patients more often following CABG were also more likely to transfuse patients after PCI.[20] In our study, we observed similar wide variability in hospital-level transfusion practices for coronary revascularization procedures and extended these observations to all other surgical and endovascular procedures studied, including aortic valve replacement, lower extremity PVI, and carotid revascularization procedures.

For each procedure studied, on the basis of the observed MORs, we found that the same patient following the same procedure was ≈2 to 3 times more likely to receive a transfusion at one hospital than at another following PCI, CAS, CEA, surgical PVI, or endovascular PVI. For patients undergoing CABG or SAVR, the likelihood of receiving a transfusion was ≈4 times higher at one randomly selected hospital than at another. When age and sex, HCUP comorbidity variables, and major bleeding were added in a sequential fashion to MOR models, results were not materially different in the endovascular or surgical cohorts, suggesting that patient-level factors were not likely responsible for the observed hospital-level

difference in transfusion rates. Together, these observations suggest that institutional culture strongly influences the decision to transfuse following invasive cardiovascular procedures.

There are noteworthy limitations to our study. First, it is retrospective and observational in design, and despite adjustments for patient characteristics, the potential for unmeasured confounding and bias remains. We acknowledge that additional factors, not addressed in the current manuscript, may contribute to transfusion requirements after a cardiovascular procedure, including the technical approach (eg, radial versus femoral PCI or PVI; minimally invasive versus open surgery) and frequency of postprocedure hemoglobin measurements. Second, the NRD does not capture laboratory (eg, hemoglobin) data, procedural detail (eg, blood loss, number of transfusions administered) or medications (eg, antiplatelet or anticoagulant agents); we attempted to account for the absence of preprocedure hemoglobin, by adjusting for preprocedure anemia and comorbidities. Because the NRD is an administrative claims data set, some *ICD-9-CM* codes that were used to define diagnoses, procedures, and in-hospital outcomes may not be attributable to the index hospitalization but may instead be historical in nature. Notwithstanding this limitation, many prior studies employing the NRD have used a similar approach.[30,31] While variability was observed across hospitals, this analysis should not inform decisions about whether blood transfusion is beneficial or harmful following cardiovascular procedures; ongoing randomized studies such as MINT (Myocardial Ischemia and Transfusion; ClinicalTrials.gov identifier: NCT02981407) may help do so. Finally, some of the procedures studied may be performed in the outpatient setting (eg, PCI, endovascular PVI), especially in healthier patients; consequently, the denominator for these procedures may be larger than estimated in our study and the corresponding transfusion rates overestimated.

CONCLUSIONS

RBC transfusion rates vary significantly across surgical and endovascular procedures employed for treatment of the same disease state. Postprocedure RBC transfusion rates are significantly correlated following surgical and endovascular procedures at any given hospital and vary widely across hospitals for the same procedure. Our findings suggest that local institutional culture weighs heavily on the decision to transfuse patients following invasive cardiovascular procedures.

ARTICLE INFORMATION

Received May 4, 2020; accepted August 31, 2020.

Affiliations

From the Division of Cardiology, Alpert Medical School of Brown University, Providence, RI (E.A., J.D.A., S.M., H.D.A.); Division of Cardiology, Massachusetts General Hospital and Harvard Medical School, Boston, MA (D.K.); Statistical Consultant to the Cardiovascular Institute, Kansas City, MO (K.F.K.); St. Anne's Hospital, Fall River, MA (C.E.B.); Division of Cardiothoracic Surgery, Alpert Medical School of Brown University, Providence, RI (A.E.); Division of Cardiology, University of Michigan, Ann Arbor, MI (H.S.G.); and Division of Internal Medicine, Robert Wood Johnson University Hospital, New Brunswick, NJ (J.L.C.).

Sources of Funding

None.

Disclosures

None.

Supplementary Material

Tables S1–S10

REFERENCES

1. Chatterjee S, Wetterslev J, Sharma A, Lichstein E, Mukherjee D. Association of blood transfusion with increased mortality in myocardial infarction: a meta-analysis and diversity-adjusted study sequential analysis. *JAMA Intern Med*. 2013;173:132–139.
2. Doyle BJ, Rihal CS, Da G, Holmes DR Jr. Bleeding, blood transfusion, and increased mortality after percutaneous coronary intervention: implications for contemporary practice. *J Am Coll Cardiol*. 2009;53:2019–2027.
3. Chase AJ, Fretz EB, Warburton WP, Klinke WP, Carere RG, Pi D, Berry B, Hilton JD. Association of the arterial access site at angioplasty with transfusion and mortality: the M.O.R.T.A.L study (Mortality Benefit of Reduced Transfusion After Percutaneous Coronary Intervention Via the Arm or the Leg). *Heart*. 2008;94:1019–1025.
4. Tchetche D, Van der Boon RM, Dumonteil N, Chieffo A, Van Mieghem NM, Farah B, Buchanan GL, Saady R, Marcheix B, Serruys PW, et al. Adverse impact of bleeding and transfusion on the outcome post-transcatheter aortic valve implantation: insights from the Pooled-Rotterdam-Milano-Toulouse In Collaboration Plus (PRAGMATIC Plus) initiative. *Am Heart J*. 2012;164:402–409.
5. Seiffert M, Conradi L, Terstesse A, Koschyk D, Schirmer J, Schnabel RB, Wilde S, Ojeda FM, Reichenspumer H, Blankenberg S, et al. Blood transfusion is associated with impaired outcome after transcatheter aortic valve implantation. *Catheter Cardiovasc Interv*. 2015;85:460–467.
6. Nuis RJ, Sinning JM, Rodes-Cabau J, Gotzmann M, van Garsse L, Kefer J, Bosmans J, Yong G, Dager AE, Revilla-Orodea A, et al. Prevalence, factors associated with, and prognostic effects of preoperative anemia on short- and long-term mortality in patients undergoing transcatheter aortic valve implantation. *Circ Cardiovasc Interv*. 2013;6:625–634.
7. Murphy GJ, Reeves BC, Rogers CA, Rizvi SI, Culliford L, Angelini GD. Increased mortality, postoperative morbidity, and cost after red blood cell transfusion in patients having cardiac surgery. *Circulation*. 2007;116:2544–2552.
8. Surgenor SD, Kramer RS, Olmstead EM, Ross CS, Sellke FW, Likosky DS, Marrin CA, Helm RE Jr, Leavitt BJ, Morton JR, et al. The association of perioperative red blood cell transfusions and decreased long-term survival after cardiac surgery. *Anesth Analg*. 2009;108:1741–1746.
9. Paone G, Likosky DS, Brewer R, Theurer PF, Bell GF, Cogan CM, Prager RL. Transfusion of 1 and 2 units of red blood cells is associated with increased morbidity and mortality. *Ann Thorac Surg*. 2014;97:87–89.
10. Likosky DS, Surgenor SD, Dacey LJ, Defoe GR, Maislen EL, Clark JA, Aubuchon JP, Higgins JH, Beaulieu PA, O'Connor GT, et al. Rationalising the treatment of anaemia in cardiac surgery: short and mid-term results from a local quality improvement initiative. *Qual Saf Health Care*. 2010;19:392–398.
11. Mazer CD, Whitlock RP, Fergusson DA, Hall J, Belley-Cote E, Connolly K, Khanykin B, Gregory AJ, De Medicis E, McGuinness S, et al. Restrictive or liberal red-cell transfusion for cardiac surgery. *N Engl J Med*. 2017;377:2133–2144.

12. Koch CG, Sessler DI, Mascha EJ, Sabik JF, Li L, Duncan AI, Zimmerman NM, Blackstone EH. A randomized clinical trial of red blood cell transfusion triggers in cardiac surgery. *Ann Thorac Surg*. 2017;104:1243–1250.
13. Murphy GJ, Pike K, Rogers CA, Wordsworth S, Stokes EA, Angelini GD, Reeves BC. Liberal or restrictive transfusion after cardiac surgery. *N Engl J Med*. 2015;372:997–1008.
14. Salem-Schatz SR, Avorn J, Soumerai SB. Influence of knowledge and attitudes on the quality of physicians' transfusion practice. *Med Care*. 1993;31:868–878.
15. Sherwood MW, Wang Y, Curtis JP, Peterson ED, Rao SV. Patterns and outcomes of red blood cell transfusion in patients undergoing percutaneous coronary intervention. *JAMA*. 2014;311:836–843.
16. Rao SV, Chiswell K, Sun JL, Granger CB, Newby LK, Van de Werf F, White HD, Armstong PW, Califf RM, Harrington RA. International variation in the use of blood transfusion in patients with non-ST elevation acute coronary syndromes. *Am J Cardiol*. 2008;101:25–29.
17. Stover EP, Siegel LC, Body SC, Levin J, Parks R, Maddi R, D'Ambra MN, Mangano DT, Spiess BD. Institutional variability in red blood cell conservation practices for coronary artery bypass graft surgery. Institutions of the MultiCenter Study of Perioperative Ischemia Research Group. *J Cardiothorac Vasc Anesth*. 2000;14:171–176.
18. Jin R, Zelinka ES, McDonald J, Byrnes T, Grunkemeier GL, Brevig J. Effect of hospital culture on blood transfusion in cardiac procedures. *Ann Thorac Surg*. 2013;95:1269–1274.
19. Surgenor DM, Churchill WH, Wallace EL, Rizzo RJ, McGurk S, Goodnough LT, Kao KJ, Koerner TA, Olson JD, Woodson RD. The specific hospital significantly affects red cell and component transfusion practice in coronary artery bypass graft surgery: a study of five hospitals. *Transfusion*. 1998;38:122–134.
20. Likosky DS, Zhang M, Paone G, Collins J, DeLucia A, Schreiber T, Theurer P, Kazziha S, Leffler D, Wunderly DJ, et al. Impact of institutional culture on rates of transfusions during cardiovascular procedures: the Michigan experience. *Am Heart J*. 2016;174:1–6.
21. Moore BJ, White S, Washington R, Coenen N, Elixhauser A. Identifying increased risk of readmission and in-hospital mortality using hospital administrative data: the AHRQ elixhauser comorbidity index. *Med Care*. 2017;55:698–705.
22. Krumholz HM, Lin Z, Drye EE, Desai MM, Han LF, Rapp MT, Mattera JA, Normand SL. An administrative claims measure suitable for profiling hospital performance based on 30-day all-cause readmission rates among patients with acute myocardial infarction. *Circ Cardiovasc Qual Outcomes*. 2011;4:243–252.
23. Horwitz L, Partovian C, Lin Z, Grady JN, Herrin J, Conover M, Montaque J, Dillaway C, Bartczak K, Suter LG, et al. Development and use of an administrative claims measure for profiling hospital-wide performance on 30-day unplanned readmission. *Ann Intern Med*. 2014;161:S66–S75.
24. Larsen K, Merlo J. Appropriate assessment of neighborhood effects on individual health: integrating random and fixed effects in multilevel logistic regression. *Am J Epidemiol*. 2005;161:81–88.
25. Ferraris VA, Brown JR, Despotis GJ, Hammon JW, Reece TB, Saha SP, Song HK, Clough ER, Shore-Lesserson LJ, Goodnough LT, et al. Society of Thoracic Surgeons Blood Conservation Guideline Task Force, 2011 update to the Society of Thoracic Surgeons and the Society of Cardiovascular Anesthesiologists blood conservation clinical practice guidelines. *Ann Thorac Surg*. 2011;91:944–982.
26. Grover FL, Vemulapalli S, Carroll JD, Edwards FH, Mack MJ, Thourani VH, Brindis RG, Shahian DM, Ruiz CE, Jacobs JP, et al. 2016 annual report of the Society of Thoracic Surgeons/American College of Cardiology Transcatheter Valve Therapy Registry. *J Am Coll Cardiol*. 2017;69:1215–1230.
27. Levine GN, Bates ER, Blankenship JC, Bailey SR, Bittl JA, Cercek B, Chambers CE, Ellis SG, Guyton RA, Hollenberg SM, et al. 2011 ACCF/AHA/SCAI guideline for percutaneous coronary intervention: a report of the American College of Cardiology Foundation/American Heart Association Task Force on Practice Guidelines and the Society for Cardiovascular Angiography and Interventions. *Circulation*. 2011;124:e574–e651.
28. Serruys PW, Morice MC, Kappetein AP, Colombo A, Holmes DR, Mack MJ, Stahle E, Feldman TE, van de Brand M, Bass EJ, et al.; SYNTAX Investigators. Percutaneous coronary intervention versus coronary artery bypass grafting for severe coronary artery disease. *N Engl J Med*. 2009;360:961–972.
29. Bennett-Guerrero E, Zhao Y, O'Brien SM, Ferguson TB Jr, Peterson ED, Gammie JS, Song HK. Variation in use of blood transfusion in coronary artery bypass graft surgery. *JAMA*. 2010;304:1568–1575.
30. Khera S, Kolte D, Gupta T, Goldsweig A, Velagapudi P, Karla A, Tang GHL, Aronow WS, Fonarow GC, Bhatt DL, et al. Association between hospital volume and 30-day readmissions following transcatheter aortic valve replacement. *JAMA Cardiol*. 2017;2:732–741.
31. Kolte D, Kennedy KF, Shishehbor MH, Abbott JD, Khera S, Soukas P, Mamdani ST, Hyder ON, Drachman DE, Aronow HD. Thirty-day readmissions after endovascular or surgical therapy for critical limb ischemia: analysis of the 2013 to 2014 nationwide readmissions databases. *Circulation*. 2017;136:167–176.

SUPPLEMENTAL MATERIAL

Table S1: ICD-9 Codes for Cardiovascular Procedures

Cardiovascular Procedure	ICD-9 Code
TAVR	3505, 3506
SAVR	3521, 3522
PCI	3600, 3606, 3607, 3609, 0066
CABG	3610, 3611, 3612, 3613, 3614, 3615, 3616, 3619
CAS	0061, 0063, 0064
CEA	3812
Endovascular PVI	0055, 0060, 3950, 3990
Surgical PVI	3808, 3818, 3838, 3848, 3868, 3888, 3925, 3929

Abbreviations for Table S1: TAVR: Transcatheter Aortic Valve Replacement, SAVR: Surgical Aortic Valve Replacement, PCI: Percutaneous Coronary Intervention, CABG: Coronary Artery Bypass Grafting, CAS: Carotid Artery Stent, CEA: Carotid Endarterectomy, PVI: Peripheral Vascular Intervention

Table S2: ICD-9 Codes for Cardiovascular Diagnoses and Cardiovascular Complications

Cardiovascular Diagnosis	ICD-9 Code
Aortic Valve Disease	3950, 3951, 3952, 3959, 4241
Hypertension	40519, 40591, 40599
Old Myocardial Infarction	412
Coronary artery disease	41400-41407, 4142-4144, 4148, 4149
Atrial Fibrillation	42731
Chronic Heart Failure	4280, 4281, 42820, 42822, 42830, 42832, 42840, 42842
Transient Ischemic Attack	4358, 4359
Stroke (Intracranial Bleed)	430, 431, 4320, 4321, 4329
Stroke (Ischemia/ Thrombosis)	43301, 43311, 43321, 43331, 43381, 43391, 43401, 43411, 43491, 4350, 4351, 4353, 436, 4370, 4371, 4378, 43794380
Peripheral Arterial Disease	4400, 4401, 4404, 4408, 4409, 44020-44024, 44029-44032, 43300, 43310, 43320, 43330, 43380, 43390
Intracranial Hemorrhage Intraocular hemorrhage Hemopericardium Contusion of Extremity/ Abdomen Gastrointestinal Hemorrhage Hemorrhage Unspecified Hemarthrosis Hemoperitoneum Hematuria Epistaxis	430, 431, 432.x 362.43, 362.81, 363.61,363.62, 363.72, 364.41, 376.32, 377.42, 379.23 423.0 923.xx, 924.xx, 922.2, 922.31-33, 922.8, 922.9 456.0, 456.20, 530.7, 530.82, 531.00, 531.01, 531.20, 531.21, 531.40, 531.41, 531.60, 531.61, 532.00, 532.01, 532.20, 532.21, 532.40, 532.41, 532.60, 532.61, 533.00, 533.01, 533.20, 533.21, 533.40, 533.41, 533.60, 533.61, 534.00, 534.01, 534.20, 534.21, 534.40, 534.41, 534.60, 534.61, 569.3, 578.0, 578.1, 578.9 459.0 719.1 568.81 599.70, 599.71 784.7
Transfusion of red blood cell (RBC)	9904

Table S3: Variables included in the risk-adjusted models

Age	
Sex	
Primary Payer	
Heart Failure (HF)	HCUP Defined comorbidity
Chronic Pulmonary disease	HCUP Defined comorbidity
Liver disease	HCUP Defined comorbidity
Hypertension	HCUP Defined comorbidity
Diabetes Mellitus (uncomplicated)	HCUP Defined comorbidity
Diabetes Mellitus (with chronic complications)	HCUP Defined comorbidity
Peripheral Arterial Disease	HCUP Defined comorbidity
Valvular Disease	HCUP Defined comorbidity
Renal Failure	HCUP Defined comorbidity
Other neurologic disorders	HCUP Defined comorbidity
Paralysis	HCUP Defined comorbidity
Metastatic Cancer	HCUP Defined comorbidity
Lymphoma	HCUP Defined comorbidity
Fluid and electrolyte disturbances	HCUP Defined comorbidity
Hypothyroidism	HCUP Defined comorbidity
Obesity	HCUP Defined comorbidity
Pulmonary Circulation Disorders	HCUP Defined comorbidity
Alcohol use	HCUP Defined comorbidity
Drug abuse	HCUP Defined comorbidity
Immunodeficiency/ AIDS	HCUP Defined comorbidity
Deficiency anemias	HCUP Defined comorbidity
Chronic blood loss	HCUP Defined comorbidity
Coagulopathy	HCUP Defined comorbidity

Peptic ulcer disease	HCUP Defined comorbidity
Depression	HCUP Defined comorbidity
Psychoses	HCUP Defined comorbidity
Dypsnea	786.0
Stable Angina	413.9
Unstable Angina	411.1
CAD	414.00
CIHD	414.9
AMI	410.x
Acute HF	428.21, 428.31
Chronic HF	428.22, 428.32
Major Bleeding	'430','431','432.0','432.1','432.9','336','362.43','362.81','363.61','363.62','363.72','364.41','377.42', '379.23', '423.0','729.71','729.72','729.73' '456.0','456.20','530.7','530.82','531.00','531.01','531.20', '531.21','531.40','531.41','531.60','531.61', '532.00','532.01','532.20','532.21','532.40','532.41','532.60','532.61','533.00','533.01','533.20','533.21', '533.40','533.41','533.60','533.61','534.00','534.01','534.20','534.21','534.40','534.41','534.60','534.61', '569.3','578.0','578.1','578.9','568.81','599.70','599.71','784.7','784.8','459','998.11','998.12','285.1', '998.00','998.09','785.50','785.59','276.52'

Abbreviations for Table S3: AIDS: Acquired Immune Deficiency Syndrome, CAD: Coronary Artery Disease, CIHD: Chronic Ischemic Heart Disease, AMI: Acute Myocardial Infarction, HF: Heart Failure

Table S4: ICD-9 Codes for other blood products

Blood Product	**ICD-9 Code**
Whole Blood	9903
Platelets	9905
Coagulation factors	9906
Serum	9907
Blood Expander	9908
Other substance	9909

Table S5: Patients' Characteristics by Transfusion Status

	Total n = 394525	Transfusion n=43863	No transfusion n = 350662	p-value
Age in years at admission Mean ± SD Median (IQR)	 66.19 ± 12.48 67.00 (58.00, 75.00)	 68.71 ± 12.35 70.00 (61.00, 78.00)	 65.88 ± 12.46 66.00 (58.00, 75.00)	 <0.001
Disposition of patient (uniform) 1: Routine 2: Transfer to short term Hospital 5: Transfer to other: SNF 6: HHC 7: AMA 20: Died 99: Unknown	 259532 (65.8%) 2191 (0.6%) 47570 (12.1%) 73785 (18.7%) 1475 (0.4%) 9745 (2.5%) 85 (0.0%)	 13850 (31.6%) 516 (1.2%) 12515 (28.5%) 14428 (32.9%) 108 (0.2%) 2403 (5.5%) 26 (0.1%)	 245682 (70.1%) 1675 (0.5%) 35055 (10.0%) 59357 (16.9%) 1367 (0.4%) 7342 (2.1%) 59 (0.0%)	 <0.001
Primary expected payer (uniform) 1: Medicare 2: Medicaid 3: Private Insurance 4: Self Pay 5: No charge 6: Other	 235358 (59.7%) 34032 (8.6%) 98887 (25.1%) 13159 (3.3%) 2244 (0.6%) 10279 (2.6%)	 30561 (69.7%) 3786 (8.6%) 7666 (17.5%) 846 (1.9%) 125 (0.3%) 843 (1.9%)	 204797 (58.5%) 30246 (8.6%) 91221 (26.1%) 12313 (3.5%) 2119 (0.6%) 9436 (2.7%)	 <0.001
Female	135003 (34.2%)	19377 (44.2%)	115626 (33.0%)	<0.001

	Total n = 394525	Transfusion n=43863	No transfusion n = 350662	p-value
Length of stay (cleaned) Mean ± SD Median (IQR)	 6.48 ± 8.51 4.00 (2.00, 8.00)	 12.74 ± 11.91 9.00 (6.00, 15.00)	 5.69 ± 7.63 4.00 (2.00, 7.00)	 <0.001
Number of chronic conditions Mean ± SD Median (IQR)	 7.28 ± 3.11 7.00 (5.00, 9.00)	 8.90 ± 3.35 9.00 (6.00, 11.00)	 7.07 ± 3.02 7.00 (5.00, 9.00)	 <0.001
Acquired immune deficiency syndrome	588 (0.1%)	98 (0.2%)	490 (0.1%)	<0.001
Alcohol abuse	12336 (3.1%)	1588 (3.6%)	10748 (3.1%)	<0.001
Deficiency anemias	67058 (17.0%)	16398 (37.4%)	50660 (14.4%)	<0.001
Rheumatoid arthritis/collagen vascular diseases	9965 (2.5%)	1459 (3.3%)	8506 (2.4%)	<0.001
Chronic blood loss anemia	3242 (0.8%)	1400 (3.2%)	1842 (0.5%)	<0.001
Congestive heart failure	13738 (3.5%)	2987 (6.8%)	10751 (3.1%)	<0.001
Chronic pulmonary disease	81925 (20.8%)	11202 (25.5%)	70723 (20.2%)	<0.001
Coagulopathy	34377 (8.7%)	9822 (22.4%)	24555 (7.0%)	<0.001
Depression	30902 (7.8%)	3968 (9.0%)	26934 (7.7%)	<0.001
Diabetes, uncomplicated	118109 (29.9%)	12468 (28.4%)	105641 (30.1%)	<0.001
Diabetes with chronic complications	40011 (10.1%)	7434 (16.9%)	32577 (9.3%)	<0.001
Drug abuse	9043 (2.3%)	1078 (2.5%)	7965 (2.3%)	0.014
Hypertension (combine uncomplicated and compli cated)	303544 (76.9%)	34670 (79.0%)	268874 (76.7%)	<0.001

	Total n = 394525	Transfusion n=43863	No transfusion n = 350662	p-value
Hypothyroidism	41629 (10.6%)	5825 (13.3%)	35804 (10.2%)	<0.001
Liver disease	7766 (2.0%)	1446 (3.3%)	6320 (1.8%)	<0.001
Lymphoma	2200 (0.6%)	425 (1.0%)	1775 (0.5%)	<0.001
Fluid and electrolyte disorders	89918 (22.8%)	19482 (44.4%)	70436 (20.1%)	<0.001
Metastatic cancer	2301 (0.6%)	490 (1.1%)	1820 (0.5%)	<0.001
Other neurological disorders	17295 (4.4%)	2825 (6.4%)	14470 (4.1%)	<0.001
Obesity	68524 (17.4%)	7478 (17.0%)	61046 (17.4%)	0.060
Paralysis	6451 (1.6%)	1351 (3.1%)	5100 (1.5%)	<0.001
Peripheral vascular disorders	92381 (23.4%)	15183 (34.6%)	77198 (22.0%)	<0.001
Psychoses	9303 (2.4%)	1496 (3.4%)	7807 (2.2%)	<0.001
Pulmonary circulation disorders	3428 (0.9%)	835 (1.9%)	2593 (0.7%)	<0.001
Renal failure	81913 (20.8%)	15788 (36.0%)	66125 (18.9%)	<0.001
Solid tumor without metastasis	5603 (1.3%)	889 (2.0%)	4174 (1.2%)	<0.001
Peptic ulcer disease excluding bleeding	105 (0.0%)	21 (0.0%)	84 (0.0%)	0.003
Valvular disease	6020 (1.5%)	1177 (2.7%)	4843 (1.4%)	<0.001
Acute Heart Failure	11960 (3.0%)	1668 (3.8%)	10292 (2.9%)	<0.001
Unstable Angina	49301 (12.5%)	3826 (8.7%)	45475 (13.0%)	<0.001
Acute Myocardial Infarction	140049 (35.5%)	10375 (23.7%)	129674 (37.0%)	<0.001
Weight loss	13046 (3.3%)	3866 (8.8%)	9180 (2.6%)	<0..01

Table S6: Patient's characteristics by procedure type

	TAVR n = 8327	SAVR n = 14743	PCI n = 173762	CABG n = 76874	Endo PVI n = 53724	Surgical PVI n = 38237	CAS n = 6462	CEA n = 22396
Age in years at admission Mean ± SD Median (IQR)	81.22 ± 8.30 83.00 (77.00, 87.00)	65.80 ± 13.77 68.00 (58.00, 76.00)	65.07 ± 12.47 65.00 (56.00, 74.00)	65.55 ± 10.35 66.00 (59.00, 73.00)	65.79 ± 14.41 67.00 (57.00, 76.00)	66.75 ± 12.76 67.00 (59.00, 76.00)	68.85 ± 11.35 70.00 (62.00, 77.00)	71.02 ± 9.17 71.00 (65.00, 78.00)
Disposition of patient (uniform) 1: Routine 2: Transfer to short term Hospital 5: Transfer to other: SNF 6: HHC 7: AMA 20: Died 99: Unknown	 2968 (35.6%) 82 (1.0%) 1999 (24.0%) 3019 (36.3%) "<=10" (0.0%) 254 (3.1%) "<=10" (0.0%)	 5272 (35.8%) 154 (1.0%) 2641 (17.9%) 6268 (42.5%) 18 (0.1%) 379 (2.6%) "<=10" (0.0%)	 145941 (84.0%) 719 (0.4%) 8609 (5.0%) 13149 (7.6%) 862 (0.5%) 4401 (2.5%) 36 (0.0%)	 32130 (41.8%) 474 (0.6%) 12970 (16.9%) 29693 (38.6%) 63 (0.1%) 1500 (2.0%) 18 (0.0%)	 29442 (54.8%) 382 (0.7%) 11489 (21.4%) 10488 (19.5%) 375 (0.7%) 1497 (2.8%) 15 (0.0%)	 19375 (50.7%) 314 (0.8%) 8114 (21.2%) 8766 (22.9%) 119 (0.3%) 1519 (4.0%) "<=10" (0.0%)	 5069 (78.5%) 40 (0.6%) 680 (10.5%) 541 (8.4%) 12 (0.2%) 116 (1.8%) "<=10" (0.0%)	 19335 (86.3%) 26 (0.1%) 1068 (4.8%) 1861 (8.3%) 23 (0.1%) 79 (0.4%) "<=10" (0.0%)

	TAVR n = 8327	SAVR n = 14743	PCI n = 173762	CABG n = 76874	Endo PVI n = 53724	Surgical PVI n = 38237	CAS n = 6462	CEA n = 22396
Primary expected payer (uniform) 1: Medicare 2: Medicaid 3: Private Insurance 4: Self Pay 5: No charge 6: Other	 7606 (91.4%) 83 (1.0%) 483 (5.8%) 33 (0.4%) "<=10"(0.0%) 115 (1.4%)	 8654 (58.8%) 962 (6.5%) 4530 (30.8%) 240 (1.6%) 35 (0.2%) 308 (2.1%)	 93071 (53.6 %) 16357 (9.4 %) 49257 (28.4 %) 8258 (4.8%) 1322 (0.8%) 5266 (3.0%)	 42320 (55.2 %) 6153 (8.0%) 23374 (30.5 %) 2301 (3.0%) 439 (0.6%) 2122 (2.8%)	 37702 (70.2 %) 5544 (10.3 %) 8183 (15.2 %) 1029 (1.9%) 200 (0.4%) 1018 (1.9%)	 24695 (64.7 %) 3636 (9.5%) 7808 (20.5 %) 888 (2.3%) 171 (0.4%) 968 (2.5%)	 4468 (69.3 %) 439 (6.8%) 1249 (19.4 %) 139 (2.2%) 24 (0.4%) 131 (2.0%)	 16842 (75.3 %) 858 (3.8%) 4003 (17.9 %) 271 (1.2%) 52 (0.2%) 351 (1.6%)
Female	3773 (45.3%)	5629 (38.2%)	56215 (32.4 %)	19425 (25.3 %)	24549 (45.7 %)	13898 (36.3 %)	2414 (37.4 %)	9100 (40.6 %)
Length of stay (cleaned) Mean ± SD Median (IQR)	 7.71 ± 7.88 5.00 (3.00, 9.00)	 10.54 ± 10.63 7.00 (5.00, 12.0 0)	 3.94 ± 5.31 3.00 (2.00, 4.00)	 10.03 ± 7.86 8.00 (6.00, 12.00)	 8.53 ± 12.15 5.00 (2.00, 10.00)	 8.54 ± 11.07 5.00 (3.00, 10.00)	 4.87 ± 9.12 2.00 (1.00, 5.00)	 2.83 ± 4.83 1.00 (1.00, 3.00)
Number of chronic conditions Mean ± SD Median (IQR)	 9.60 ± 3.12 9.00 (7.00, 12.00)	 7.93 ± 3.12 8.00 (6.00, 10.0 0)	 6.91 ± 2.91 6.00 (5.00, 9.00)	 7.61 ± 2.94 7.00 (5.00, 9.00)	 8.02 ± 3.56 8.00 (5.00, 10.00)	 7.15 ± 3.25 7.00 (5.00, 9.00)	 6.62 ± 2.98 6.00 (5.00, 8.00)	 6.31 ± 2.80 6.00 (4.00, 8.00)
RBC Transfusion	1521 (18.3%)	3983 (27.0%)	5020 (2.9%)	16944 (22.0 %)	7564 (14.1 %)	8160 (21.3 %)	227 (3.5%)	444 (2.0%)

	TAVR n = 8327	SAVR n = 14743	PCI n = 173762	CABG n = 76874	Endo PVI n = 53724	Surgical PVI n = 38237	CAS n = 6462	CEA n = 22396
Acquired immune deficiency syndrome	“<=10” (0.0%)	“<=10” (0.0%)	235 (0.1%)	103 (0.1%)	163 (0.3%)	59 (0.2%)	“<=10” (0.1 %)	14 (0.1%)
Alcohol abuse	91 (1.1%)	490 (3.3%)	5120 (2.9%)	2807 (3.7%)	1580 (2.9%)	1595 (4.2%)	171 (2.6%)	482 (2.2%)
Deficiency anemias	1952 (23.4%)	2566 (17.4%)	21261 (12.2 %)	13669 (17.8 %)	18521 (34.5 %)	6735 (17.6 %)	665 (10.3%)	1689 (7.5%)
Rheumatoid arthritis/collagen vascular di seases	442 (5.3%)	463 (3.1%)	4058 (2.3%)	1675 (2.2%)	1694 (3.2%)	997 (2.6%)	117 (1.8%)	519 (2.3%)
Chronic blood loss anemia	115 (1.4%)	218 (1.5%)	695 (0.4%)	977 (1.3%)	675 (1.3%)	467 (1.2%)	24 (0.4%)	71 (0.3%)
Congestive heart failure	1891 (22.7%)	304 (2.1%)	2809 (1.6%)	882 (1.1%)	4614 (8.6%)	957 (2.5%)	665 (10.3%)	1616 (7.2%)
Chronic pulmonary disease	2787 (33.5%)	3029 (20.5%)	30855 (17.8 %)	16679 (21.7 %)	11396 (21.2 %)	10877 (28.4 %)	1362 (21.1 %)	4940 (22.1 %)
Coagulopathy	1882 (22.6%)	4954 (33.6%)	5728 (3.3%)	14598 (19.0 %)	3697 (6.9%)	2962 (7.7%)	158 (2.4%)	398 (1.8%)
Depression	610 (7.3%)	1282 (8.7%)	12566 (7.2 %)	5886 (7.7%)	4921 (9.2%)	3225 (8.4%)	546 (8.4%)	1866 (8.3%)
Diabetes, uncomplicated	2336 (28.1%)	3018 (20.5%)	55465 (31.9 %)	27457 (35.7 %)	12607 (23.5 %)	8668 (22.7 %)	1856 (28.7 %)	6702 (29.9 %)
Diabetes with chronic complications	604 (7.3%)	713 (4.8%)	11995 (6.9 %)	7965 (10.4 %)	13127 (24.4 %)	4398 (11.5 %)	296 (4.6%)	913 (4.1%)
Drug abuse	30 (0.4%)	443 (3.0%)	4435 (2.6%)	1653 (2.2%)	1283 (2.4%)	954 (2.5%)	94 (1.5%)	151 (0.7%)

	TAVR n = 8327	SAVR n = 14743	PCI n = 173762	CABG n = 76874	Endo PVI n = 53724	Surgical PVI n = 38237	CAS n = 6462	CEA n = 22396
Hypertension (combine uncomplicated and complicated)	6613 (79.4%)	10363 (70.3%)	131428 (75.6%)	62333 (81.1%)	40588 (75.5%)	28604 (74.8%)	5100 (78.9%)	18515 (82.7%)
Hypothyroidism	1611 (19.3%)	1902 (12.9%)	17492 (10.1%)	7788 (10.1%)	6202 (11.5%)	3306 (8.6%)	762 (11.8%)	2566 (11.5%)
Liver disease	259 (3.1%)	398 (2.7%)	2686 (1.5%)	1520 (2.0%)	1889 (3.5%)	736 (1.9%)	62 (1.0%)	216 (1.0%)
Lymphoma	128 (1.5%)	136 (0.9%)	851 (0.5%)	368 (0.5%)	421 (0.8%)	189 (0.5%)	31 (0.5%)	76 (0.3%)
Fluid and electrolyte disorders	2216 (26.6%)	6036 (40.9%)	27963 (16.1%)	25935 (33.7%)	16225 (30.2%)	9187 (24.0%)	751 (11.6%)	1605 (7.2%)
Metastatic cancer	42 (0.5%)	30 (0.2%)	789 (0.5%)	145 (0.2%)	876 (1.6%)	340 (0.9%)	24 (0.4%)	64 (0.3%)
Other neurological disorders	485 (5.8%)	768 (5.2%)	7305 (4.2%)	3084 (4.0%)	3678 (6.8%)	1821 (4.8%)	105 (1.6%)	49 (0.2%)
Obesity	1243 (14.9%)	3165 (21.5%)	30670 (17.7%)	19140 (24.9%)	6912 (12.9%)	4307 (11.3%)	639 (9.9%)	2448 (10.9%)
Paralysis	162 (1.9%)	237 (1.6%)	1897 (1.1%)	1193 (1.6%)	1600 (3.0%)	917 (2.4%)	306 (4.7%)	139 (0.6%)
Peripheral vascular disorders	2264 (27.2%)	3258 (22.1%)	20047 (11.5%)	11964 (15.6%)	27603 (51.4%)	20512 (53.6%)	1706 (26.4%)	5027 (22.4%)
Psychoses	149 (1.8%)	372 (2.5%)	3763 (2.2%)	1819 (2.4%)	1755 (3.3%)	1002 (2.6%)	117 (1.8%)	326 (1.5%)
Pulmonary circulation disorders	628 (7.5%)	128 (0.9%)	595 (0.3%)	221 (0.3%)	1073 (2.0%)	276 (0.7%)	132 (2.0%)	375 (1.7%)
Renal failure	2993 (35.9%)	2271 (15.4%)	28387 (16.3%)	13296 (17.3%)	24438 (45.5%)	7071 (18.5%)	798 (12.3%)	2659 (11.9%)
Solid tumor without metastasis	184 (2.2%)	179 (1.2%)	1994 (1.1%)	841 (1.1%)	963 (1.8%)	537 (1.4%)	116 (1.8%)	249 (1.1%)

	TAVR n = 8327	SAVR n = 14743	PCI n = 173762	CABG n = 76874	Endo PVI n = 53724	Surgical PVI n = 38237	CAS n = 6462	CEA n = 22396
Peptic ulcer disease excluding bleeding	"<=10" (0.0%)	"<=10" (0.1%)	34 (0.0%)	25 (0.0%)	24 (0.0%)	"<=10" (0.0 %)	"<=10" (0.0 %)	"<=10" (0.0 %)
Valvular disease	514 (6.2%)	309 (2.1%)	925 (0.5%)	383 (0.5%)	1361 (2.5%)	367 (1.0%)	507 (7.8%)	1654 (7.4%)
Acute Heart Failure	158 (1.9%)	567 (3.8%)	7169 (4.1%)	3349 (4.4%)	409 (0.8%)	238 (0.6%)	16 (0.2%)	54 (0.2%)
Unstable Angina	41 (0.5%)	89 (0.6%)	30850 (17.8%)	17961 (23.4%)	220 (0.4%)	82 (0.2%)	29 (0.4%)	29 (0.1%)
Acute Myocardial Infarction	152 (1.8%)	279 (1.9%)	112898 (65.0%)	24685 (32.1%)	1076 (2.0%)	747 (2.0%)	66 (1.0%)	146 (0.7%)
Weight loss	419 (5.0%)	786 (5.3%)	2742 (1.6%)	2483 (3.2%)	3871 (7.2%)	2471 (6.5%)	110 (1.7%)	164 (0.7%)

Abbreviations for Table S1: Transcatheter Aortic Valve Replacement, SAVR: Surgical Aortic Valve Replacement, PCI: Percutaneous Coronary Intervention, CABG: Coronary Artery Bypass Grafting, PVI: Peripheral Vascular Intervention, CAS: Carotid Artery Stent, CEA: Carotid Endarterectomy, RBC: Red Blood Cell

Table S7. Cross-procedure transfusion correlations when minimum required procedural volume set to > 20 procedures for each member of a complimentary procedure pair

	CABG	PCI	SAVR	TAVR	SURGICAL PVI	ENDO-VASCULAR PVI	CEA	CAS
CABG	-	0.57(N=516)	0.88 (n=132)	0.73 (N=132)	0.69(n=428)	0.69 (N=428)	0.42 (n=106)	0.43 (N=106)
PCI	0.57(N=516)	-	0.66(N=132)	0.48(n=132)	0.66 (N=428)	0.67 (n=428)	0.46 (N=106)	0.55 (n=106)
SAVR	0.88(n=132)	0.66 (N=132)	-	0.74 (N=132)	0.78(n=131)	0.74 (n=131)	0.52 (n=62)	0.49 (N=62)
TAVR	0.73 (N=132)	0.48 (n=132)	0.74 (N=132)	-	0.69(N=131)	0.55 (n=131)	0.52(N=62)	0.28(n=62)
SURGICAL PVI	0.69 (n=428)	0.66 (N=428)	0.78 (n=131	0.69(N=131)	-	0.65(N=564)	0.40 (n=108)	0.44 (N=108)
ENDOVASUCLAR PVI	0.69 (N=428)	0.67 (n=428)	0.74 (n=131)	0.55 (n=131)	0.65 (N=564)	-	0.56 (N=108)	0.52 (n=108)
CEA	0.42 (n=106)	0.46 (N=106)	0.52 (n=62)	0.52 (N=62)	0.40 (n=108)	0.56 (N=108)	-	0.27 (N=110)
CAS	0.43 (N=106)	0.55 (n=106)	0.49 (N=62)	0.28(n=62)	0.44 (N=180)	0.52 (n=108)	0.27 (N=110)	-

Table S8. Cross-procedure transfusion correlations after excluding patients who underwent more than 1 of the same procedure during 2014.

	CABG	PCI	SAVR	TAVR	SURGICAL PVI	ENDO-VASCULAR PVI	CEA	CAS
CABG	-	0.56 (N=527)	0.87 (n=166)	0.62 (N=166)	0.62 (n=512)	0.62 (N=512)	0.29 (n=289)	0.36 (N=289)
PCI	0.56 (N=527)	-	0.59 (N=166)	0.42 (n=166)	0.61 (N=512)	0.64 (n=512)	0.36 (N=289)	0.42 (n=289)
SAVR	0.87(n=166)	0.59 (N=166)	-	0.67 (N=166)	0.74 (n=166)	0.69 (n=166)	0.40 (n=137)	0.39 (N=137)
TAVR	0.62 (N=166)	0.42 (n=166)	0.67 (N=166)	-	0.56 (N=166)	0.49 (n=166)	0.36 (N=137)	0.20 (n=137)
SURGICAL PVI	0.62 (n=512)	0.61 (N=512)	0.74 (n=166)	0.56(N=166)	-	0.51(N=824)	0.44 (n=328)	0.42 (N=328)
ENDOVASUCLAR PVI	0.62 (N=512)	0.64 (n=512)	0.69 (n=166)	0.49 (n=166)	0.51 (N=824)	-	0.29 (N=328)	0.40 (n=328)
CEA	0.29 (n=289)	0.36 (N=289)	0.40 (n=137)	0.36 (N=137)	0.44 (n=328)	0.29 (N=328)	-	0.19 (N=331)
CAS	0.36 (N=289)	0.42 (n=289)	0.39 (N=137)	0.20 (n=137)	0.42 (N=328)	0.40 (n=328)	0.19 (N=331)	-

Table S9. Cross-procedure transfusion correlations including only those with post-procedure transfusion.

	CABG	PCI	SAVR	TAVR	SURGICAL PVI	ENDO-VASCULAR PVI	CEA	CAS
CABG	-	0.53(N=527)	0.88(n=166)	0.63 (N=166)	0.61 (n=512)	0.60 (N=512)	0.25 (n=289)	0.40 (N=289)
PCI	0.53 (N=527)	-	0.61(N=166)	0.42(n=166)	0.59 (N=512)	0.61 (n=512)	0.39(N=289)	0.33 (n=289)
SAVR	0.88(n=166)	0.641(N=166)	-	0.68 (N=166)	0.74 (n=166)	0.68 (n=166)	0.39(n=137)	0.34 (N=137)
TAVR	0.63 (N=166)	0.42 (n=166)	0.68 (N=166)	-	0.59(N=166)	0.49(n=166)	0.35 (N=137)	0.23 (n=137)
SURGICAL PVI	0.61 (n=512)	0.59 (N=512)	0.74(n=166)	0.59(N=166)	-	0.49(N=824)	0.43 (n=328)	0.37 (N=328)
ENDOVASUCLAR PVI	0.60 (N=512)	0.61(n=512)	0.68 (n=166)	0.49 (n=166)	0.49 (N=824)	-	0.28 (N=328)	0.32(n=328)
CEA	0.25 (n=289)	0.39(N=289)	0.39 (n=137)	0.35 (N=137)	0.43 (n=328)	0.28 (N=328)	-	0.09 (N=331)
CAS	0.40 (N=289)	0.33 (n=289)	0.34 (N=137)	0.23 (n=137)	0.37 (N=328)	0.32 (n=328)	0.09 (N=331)	-

Table S10. Cross-procedure transfusion correlations when all blood product transfusions were included.

	CABG	PCI	SAVR	TAVR	SURGICAL PVI	ENDO-VASCULAR PVI	CEA	CAS
CABG	-	0.58(N=527)	0.90 (n=166)	0.65 (N=166)	0.64 (n=512)	0.61 (N=512)	0.31 (n=289)	0.38 (N=289)
PCI	0.58 (N=527)	-	0.65 (N=166)	0.48 (n=166)	0.63 (N=512)	0.65 (n=512)	0.36 (N=289)	0.30 (n=289)
SAVR	0.90(n=166)	0.65(N=166)	-	0.71(N=166)	0.78 (n=166)	0.71 (n=166)	0.45 (n=137)	0.42 (N=137)
TAVR	0.65 (N=166)	0.48 (n=166)	0.71(N=166)	-	0.63 (N=166)	0.54 (n=166)	0.39 (N=137)	0.23 (n=137)
SURGICAL PVI	0.64 (n=512)	0.63 (N=512)	0.78(n=166)	0.63(N=166)	-	0.54(N=824)	0.45 (n=328)	0.37 (N=328)
ENDOVASUCLAR PVI	0.61 (N=512)	0.65 (n=512)	0.71 (n=166)	0.54 (n=166)	0.54(N=824)	-	0.30(N=328)	0.32 (n=328)
CEA	0.31 (n=289)	0.36 (N=289)	0.45 (n=137)	0.39 (N=137)	0.45 (n=328)	0.30 (N=328)	-	0.09 (N=331)
CAS	0.38 (N=289)	0.30 (n=289)	0.42(N=137)	0.23 (n=137)	0.37 (N=328)	0.32 (n=328)	0.09 (N=331)	-