© Health Research and Educational Trust
DOI: 10.1111/1475-6773.12508
RESEARCH BRIEF

Hospital Surgical Volumes and Mortality after Coronary Artery Bypass Grafting: Using International Comparisons to Determine a Safe Threshold

Nils Gutacker, Karen Bloor, Richard Cookson, Chris P. Gale, Alan Maynard, Domenico Pagano, José Pomar, and Enrique Bernal-Delgado as part of the ECHO collaboration

Objective. To estimate a safe minimum hospital volume for hospitals performing coronary artery bypass graft (CABG) surgery.

Data Source. Hospital data on all publicly funded CABG in five European countries, 2007–2009 (106,149 patients).

Design. Hierarchical logistic regression models to estimate the relationship between hospital volume and mortality, allowing for case mix. Segmented regression analysis to estimate a threshold.

Findings. The 30-day in-hospital mortality rate was 3.0 percent overall, 5.2 percent (95 percent CI: 4.0–6.4) in low-volume hospitals, and 2.1 percent (95 percent CI: 1.8–2.3) in high-volume hospitals. There is a significant curvilinear relationship between volume and mortality, flatter above 415 cases per hospital per year.

Conclusions. There is a clear relationship between hospital CABG volume and mortality in Europe, implying a “safe” threshold volume of 415 cases per year.

Key Words. Coronary artery bypass surgery, center-volume, mortality, international comparisons

The association between hospital volume and mortality after coronary artery bypass graft (CABG) surgery has been explored within countries since the 1970s, when a negative association was first described (Luft, Bunker, and Enthoven 1979). A statistically significant and clinically relevant relationship between hospital volume and mortality has subsequently been found for many different forms of complex surgery in both cardiac and noncardiac specialties. Relationships are generally attenuated but not eliminated after detailed adjustment for case mix (Sowden, Deeks, and Sheldon 1995; Halm, Lee, and Chassin 2002; Shahian 2004).

This evidence, mostly from U.S. studies, has generated debate about “safe” hospital volumes of surgery. The “Leapfrog Group,” a U.S. consortium of health care purchasers, recommended an annual minimum hospital volume of 450 CABG cases (Leapfrog Group 2008, Finks, Osborne, and Birkmeyer 2011). Others suggest this is too high (Shahian and Normand 2003) and that 125–150 procedures a year can be sufficient (Shahian 2004; ACCF/AHA 2011), reflecting recent evidence that mandatory public reporting of CABG mortality has reduced or even eliminated the volume–outcome relationship in the United States (Marcin et al. 2008). There is little evidence of this in other countries, many of which do not have mandatory public reporting of CABG mortality.

Some European countries—including England, the Netherlands, and Sweden—have responded to evidence of a volume–mortality relationship by centralizing CABG facilities (Banta and Bos 1991), but elsewhere hospital volumes remain low. This difference may help to explain observed cross-country differences in mortality after cardiac surgery within Europe (Bridgewater et al. 2010; Gutacker et al. 2015b). There remains uncertainty around a minimum “safe” hospital CABG volume to inform policy decisions in Europe and elsewhere about whether, and if so how far, to centralize CABG services.

We use comprehensive data on CABG in five countries to describe the relationship between hospital volume and short-term mortality, and to estimate a “safe” minimum hospital volume.

DATA AND METHODS

Study Population

The population was drawn from the European Collaboration for Healthcare Optimization (ECHO) project, including comprehensive record-level patient data on all patients treated in public hospitals from a number of European

Address correspondence to Karen Bloor, Ph.D., Department of Health Sciences, University of York, York YO10 5DD, UK; e-mail: karen.bloor@york.ac.uk. Nils Gutacker, Ph.D., and Richard Cookson, Ph.D., are with the Centre for Health Economics, University of York, York, UK. Chris P. Gale, Ph.D., is with the Division of Epidemiology and Biostatistics, University of Leeds, UK. Alan Maynard, B.Phil., Hon D.Sc., is with the Department of Health Sciences, University of York, York, UK. Domenico Pagano, M.D., is with the Department of Cardiothoracic Surgery, University Hospital Birmingham Queen Elizabeth, Edgbaston, UK. José Pomar, M.D., Ph.D., is with the Department of Cardiovascular Surgery, Hospital Clinic de Barcelona, Barcelona, Spain. Enrique Bernal-Delgado, M.D., Ph.D., is with the Institute for Health Sciences, IIS Aragón, Zaragoza, Spain.

countries (Bernal-Delgado et al. 2015). This study uses data from Denmark, England, Portugal, Slovenia, and Spain, 2007–2009. We followed the U.S. AHRQ indicator IQI#12 (Agency for Healthcare Research and Quality 2015), which includes all patients who have a CABG procedure. This is comparable with existing guidelines of “safe” volume (e.g., Leapfrog Group 2008) which apply to all procedures, not to isolated CABG. Concomitant procedures are included in the risk-adjustment model. As a sensitivity analysis, we included only patients with isolated CABG.

Patients were excluded if they were younger than 40 or had missing information for any of the variables used for case mix adjustment ($n = 21$). Hospital years were excluded if they included less than 50 patients (<1 percent of the sample).

Case Mix Adjustment

Expected deaths were predicted accounting for age group (40–55, 56–60, 61–65, 66–70, 71–75, 76–80, and >81), sex, age–sex interactions, year of hospitalization, and indicators for 31 Elixhauser comorbid conditions (Elixhauser et al. 1998; Quan et al. 2005; Gutacker, Bloor, and Cookson 2015a). Mean number of comorbidities coded at each hospital was included to account for possible differences in coding intensity. Models included those measures of severity of the underlying condition that are available in administrative data (Higgins et al. 1992; Pagano and Gale 2014): primary diagnosis of acute myocardial infarction (AMI), classified as ST-segment elevation (STEMI), non-STEMI, or unclear; replacement of a heart valve; implantation of a cardiac or circulatory assistance device; and whether the intervention was major structural surgery. We did not include emergency admission as an explanatory variable because of differences in clinical pathways for similar patients across countries, and because it is highly collinear with a primary diagnosis of AMI.

Clinical Outcomes

The clinical outcome was in-hospital 30-day all-cause mortality. Patients who were discharged or still in hospital 30 days after admission were classed as survivors.

Volume Thresholds

We used two thresholds for overall hospital case volume derived from literature: low (<125 cases per year) (ACCF/AHA 2011), medium (125–449 cases

per year), and high (≥ 450 cases per year) (Leapfrog Group 2008). Using pooled data from all five countries, we estimated statistically the threshold where the relationship between volume of cases and outcome changed.

Statistical Analysis

Expected deaths were predicted using hierarchical logit models accounting for case mix. Three approaches were used to identify a volume–outcome relationship. First, a smoothed (locally weighted) regression line was fitted through the points and confidence intervals were calculated. Second, thresholds for overall hospital case volume derived from literature were used to compare average adjusted mortality rates for different hospitals. Third, using pooled data, a threshold was determined where the relationship between volume and outcome appeared to change, using segmented regression analysis. All analyses were carried out using Stata version 12 (StataCorp, College Station, TX, USA).

Sensitivity Analysis

We conducted four sensitivity analyses. First, we restricted the population to patients with no other surgical procedure (isolated CABG). Next, we excluded patients who were transferred out of the hospital where the surgery took place to another hospital as this may underestimate mortality rates. This was most pronounced in Denmark, where around 48 percent were transferred for rehabilitation, compared with 0 percent to 6.5 percent in the other countries. Our analyses provide two bounds of likely mortality rates—including transfers out gives the lowest possible estimate, assuming all who are transferred out survive. As deaths are likely to occur in the first (specialist) hospital, excluding transfers out may overestimate mortality rates. Third, to mitigate between-country data differences (e.g., coding secondary diagnoses), we reestimated adjusting only for age, sex, and year, with and without transfers. Finally, we estimate a threshold using data from Spain and England only, which as the largest health care systems in our analysis constitute the majority of observations.

RESULTS

A total of 106,149 patients were included in the baseline analysis, with an overall mortality rate of 3.0 percent. The mean age and proportion male were

similar across the countries. The main difference in patient characteristics (Table 1) was the recorded number of comorbidities, notably lower in Denmark. Proportions of patients also varied by AMI type and in overall patients who were diagnosed with AMI, from 5.6 percent in England to 11.6 percent in Spain. There was substantial variation in the volume of cases across the five countries (Table 2).

Figure 1 illustrates CABG volume in each country and unadjusted mortality rates (see Figure S1, for individual countries). Hospital volume was lowest and unadjusted mortality rates highest in Spain. The case mix-adjusted relationship between volume and outcome is illustrated in Figure 2 (left panel), showing a clear downward curvilinear relationship. (See Appendix for effects of case mix covariates on outcome.) Volume explains almost half of the variation in adjusted mortality rates ($R^2 = 0.43$). Figure 2 (middle panel) illustrates the volume thresholds suggested by U.S. literature. The average adjusted mortality rate in lower volume hospitals was 5.2 percent (95 percent CI: 4.0–6.4), falling to 1.9 percent (1.7–2.2) in higher volume hospitals, or 2.1 percent (1.8–2.3) after weighting for hospital size (Table 3).

The center-volume threshold that best separated hospitals where volume affects mortality rates negatively from those where no volume effects are apparent was estimated at 415 procedures per hospital per year (Figure 2, right panel). Mortality rates declined by -1.1 percentage points (95 percent CI -1.7 to -0.4) per 100 additional operations below this threshold and were not affected by volume above the threshold (-0.05 percentage points per 100 operations; 95 percent CI -0.16 to 0.06).

Sensitivity Analyses

Sensitivity analyses did not alter the main finding of a relationship between center-volume of cases and mortality rates (see Figures S2–S6). The threshold center-volume inferred by the data under the different assumptions (excluding other procedures and transfers and simplifying risk adjustment) did differ, ranging between 291 and 519 procedures per year. Analysis based on Spanish and English data only (Figure S7) suggested a threshold of 512 procedures per year.

DISCUSSION

We found substantial differences in short-term mortality following CABG surgery in hospitals across five European countries. Patients treated in lower

Table 1: Patient Characteristics

	Denmark (n = 7,168)	England (n = 67,450)	Portugal (n = 7,639)	Slovenia (n = 2,345)	Spain (n = 21,547)	Total (n = 106,149)
Age: mean (SD), years	67.1 (9.3)	67.4 (9.6)	66.3 (9.7)	67.6 (9.2)	67.7 (9.6)	67.4 (9.6)
Male (%)	79.2	78.8	76.5	74.1	78.1	78.4
Number of comorbidities: mean (SD)	1.0 (1.2)	2.0 (1.4)	1.9 (1.4)	2.0 (1.4)	2.2 (1.4)	2.0 (1.4)
No comorbidities (%)	44.5	12.7	16.3	12.1	10.0	14.6
1 comorbidity (%)	27.0	27.9	28.1	29.9	24.0	27.5
2-3 comorbidities (%)	24.1	45.5	43.4	45.2	49.7	44.8
4+ comorbidities (%)	4.4	13.9	12.2	13.9	16.3	13.6
ST-elevation myocardial infarction (%)	0.8	1.8	2.9	3.5	4.6	2.4
Non-ST-elevation myocardial infarction (%)	3.4	0.5	6.0	5.5	6.3	2.4
Unspecified myocardial infarction (%)	1.9	2.4	0.1	0.4	0.7	1.8
Heart valve surgery (%)	29.5	7.5	4.0	83.0	5.9	10.1
Cardiac assistance device surgery* (%)	3.3	9.2	4.2	42.4	3.9	8.1
Repair/revision or major structural surgery (%)	19.9	18.6	20.8	30.1	27.1	20.8

Note. *Cardiac pacemaker and automatic implantable cardioverter defibrillator insertion during the same hospital stay.

Table 2: Descriptive Statistics

	Denmark	England	Portugal	Slovenia	Spain	Total
Number of hospital years*	18	87	18	9	129	261
Total volume (2007–2009)*	7,168	67,450	7,639	2,345	21,547	106,149
Mean (median) volume per hospital per year	398 (410)	775 (709)	424 (429)	260 (205)	167 (152)	407 (279)
Minimum–maximum volume per hospital per year	239–544	466–1,372	238–537	95–480	68–318	68–1,372
Mean (SD) length of stay, days†	14.3 (8.4)	11.6 (7.2)	11.6 (6.8)	15.5 (8.6)	17.0 (8.3)	13.0 (7.8)
Transfers out, %	47.9	6.5	0.0	4.9	2.6	8.0
Mean (SD) 30-day in-hospital mortality rate %, including transfers†	2.8 (16.6)	2.2 (14.5)	2.3 (15.0)	3.5 (18.4)	4.9 (21.5)	3.0 (16.5)
Mean (SD) mortality rate % excluding transfers (sensitivity analysis)†	5.1 (22.1)	2.3 (15.0)	2.3 (15.0)	3.7 (18.8)	5.0 (21.8)	3.0 (17.1)

Notes. *Hospital years with less than 50 patients were excluded.

†Mortality and length of stay are truncated at 30 days.

Figure 1: Unadjusted 30-day In-Hospital Mortality Rates and Hospital Annual Volume by Country

Figure 2: Adjusted 30-day In-Hospital Mortality Rate and Hospital Annual Volume, All Five Countries Pooled

Notes. LOWESS plot (left panel), average mortality by volume group (middle panel), and segmented regression line (right panel). Estimated threshold volume: 415 procedures per hospital per year.

volume hospitals had significantly higher 30-day inpatient mortality rates. Below 415 cases per hospital per year, mortality rates increased at a greater rate. Between-country variations in volume are clearly associated with

Table 3: Adjusted 30-day In-Hospital Mortality Rates in Low-, Medium-, and High-Volume Hospitals

<i>Volume (Cases per Hospital per Year)</i>	<i>No. of Hospitals</i>	<i>Adjusted Mortality Rates, Mean (95% CI), Unweighted</i>	<i>Adjusted Mortality Rates, Mean (95% CI), Weighted by Hospital Volume</i>
Low (<125)	15	5.2% (4.0–6.4)	5.1% (3.9–6.3)
Medium (125–449)	37	4.4% (3.6–5.1)	4.1% (3.3–4.8)
High (≥450)	35	1.9% (1.7–2.2)	1.9% (1.7–2.2)

international differences in mortality rates, of which hospital volume explains a large proportion after adjustment for case mix.

Our findings are consistent with earlier studies, primarily from the United States. More recent U.S. studies have, however, focused on the importance of public reporting of CABG surgery performance, which appears to have attenuated the volume–outcome effect. For example, Marcin et al. (2008), found a small but consistent volume–outcome relationship during a time when public reporting was voluntary, but that this disappeared once reporting was mandated.

A relationship between volume and outcome could be the result of hospital-level processes, individual surgeon experience (Birkmeyer et al. 2003), or both. Moreover, hospital volume of cases may be a marker for hospital quality (Peterson et al. 2004) or possibly a more direct determinant of mortality. Our study includes five different European health care systems, with different levels of concentration of cardiac surgery services, a key institutional feature influencing CABG outcomes. The mix of organizational systems increases the external validity of the results.

Our study confirms the presence of a strong center-volume–outcome relationship using comprehensive data on all publicly funded patients and hospitals across five countries. Low- and medium-volume hospitals have substantially and statistically significantly higher adjusted mortality than high-volume hospitals. The reduction in mortality risk of moving from “medium” to “high” volume appears greater than the reduction from moving from the “low” to “medium” category.

The data-driven estimate of the threshold volume, 415 cases per year, is similar to the 450 recommended by the U.S. Leapfrog group (2008), lower than the 600 implemented by the Netherlands in the 1990s (Banta and Bos 1991), but substantially higher than the 125–150 recommended in recent U.S. guidelines (ACCF/AHA 2011). The ACCF guidelines, however, reflect transparency about cardiac surgery performance, which is not publicly available in

many countries outside the United States (although it is available in the United Kingdom).

This analysis demonstrates the importance of international comparisons using administrative data and a pooled benchmark. This research, with a related study (Gutacker et al. 2015b), shows that restricting benchmarks to a region or even a country may provide false reassurance if there are systematic differences between countries. A threshold would not be adequately informed by any single country's data, and no one of these countries would have provided a sufficient sample to determine a volume–outcome relationship—Spanish hospitals are all (relatively) low volume, English hospitals are all relatively high volume, and the other three countries have only 3–6 medium-volume hospitals conducting CABG surgery.

Our findings raise important policy questions about the concentration of services, particularly in countries with low-volume hospitals, such as Spain. The Spanish health care system is decentralized in its decision making: hospitals are organized by autonomous communities and districts. Political opposition to centralization of services may contribute to explaining the relatively low hospital volume. In contrast, in England, networks of care, higher volume centers and transparent reporting of hospital, and surgeon mortality rates have driven quality improvements (Bridgewater et al. 2007).

There may be geographical, political, or practical difficulties that prevent substantial changes in service delivery in some communities in the short to medium term. In the absence of immediate policies to centralize cardiac surgical provision, it is important to consider how best to improve mortality rates in low-volume units. Our analysis does not permit direct exploration of this, but potential quality improvement processes include participation in registries and associated initiatives (Shahian et al. 2009; Bridgewater et al. 2010), public reporting initiatives, and improved transparency (Steinbrook 2006; Grant et al. 2013), and regional partnerships and quality improvement collaboratives (O'Connor et al. 1996; Finks, Osborne, and Birkmeyer 2011). Public reporting in the United States appears to have reduced or even eliminated the previous volume–outcome relationship, and this may be more achievable than centralization of services in a devolved health care system like Spain.

Previous international studies in this area have relied on clinical registry data (Bridgewater et al. 2010). In most countries, however, registry data are collected voluntarily and remain vulnerable to selection bias, if hospitals and surgeons with low mortality rates are more likely to participate (Bufalino et al. 2011). This is the first international study of the CABG volume–mortality relationship to use comprehensive international comparisons of patient-level

hospital administrative data. Our approach avoids selection bias, but it has a more limited set of covariates for case mix adjustment.

Other limitations also remain. First, not all countries could provide mortality data outside hospital for an overall 30-day mortality rate. We used in-hospital 30-day mortality because the length of hospital stay varied across countries, making inpatient mortality rates a less than ideal basis for comparison (Spiegelhalter 2013). If high-volume hospitals discharge patients earlier, then our estimated association between volume and outcome may be biased downwards.

Second, there may be cross-country differences in coding. CABG is well-defined and patient characteristics and secondary diagnoses are similar in four countries (Table 1), but apparent differences in comorbidity recording in Denmark may overestimate their adjusted mortality rates. There are also coding differences in concomitant procedures (e.g., apparently large numbers of heart valve replacements and cardiac assistance devices in Slovenia). Our sensitivity analyses, using only age and sex as risk adjustment measures to avoid any hospital- or country-level differences in coding, and including isolated CABG only, do not change the main findings of the analysis (see Appendix). A strong and significant association between volume and outcomes remains.

Finally, there may be hospital- or national-level differences in choice of treatments for similar conditions, in particular the choice between CABG surgery and percutaneous coronary interventions (PCIs) (Hlatky et al. 2009; Taggart 2009). Our dataset suggests that England (which dominates the high-volume segment) provides more CABG as a proportion of all revascularization procedures than the other countries: 30 CABG procedures to 70 PCIs in England over the period compared with around 20:80 in Portugal and Denmark and 15:85 in Slovenia and Spain. This raises the question of differential selection between CABG and PCI procedures, but in initial explorations of PCI data in the ECHO data warehouse, there was no negative correlation between hospital-level standardized mortality rates following CABG and PCI ($R = 0.045$).

Overall, our findings demonstrate a strong and statistically significant relationship between hospital volume of CABG surgery and in-hospital 30-day mortality, and a threshold of 415 cases per hospital per year above which mortality rates are stable and on average much lower. All hospitals in Spain were below this threshold, whereas all hospitals in England were above it. Higher volume, higher throughput systems of care have the potential to reduce mortality rates further, and there may be an

international case to regionalize services where the hospital volume of CABG surgery is low.

ACKNOWLEDGMENTS

Joint Acknowledgment/Disclosure Statement: The research has been supported from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement no. 242189. CPG is funded by the National Institute for Health Research (NIHR/CS/009/004) as a Clinician Scientist and Honorary Consultant Cardiologist. Sole responsibility lies with the authors, and the European Commission is not responsible for any use that may be made of the information contained therein. We are grateful to our collaborators in the ECHO project, including the partner organizations, researchers in the team, and our scientific advisory group, see <http://www.echo-health.eu/partners>. We would like to thank Natalia Martinez-Lizaga for her contribution to programming and data management.

Disclosures: None of the authors have any conflicts of interest with regard to this paper.

Disclaimers: None.

AUTHOR CONTRIBUTION

The statistical analysis was carried out by Nils Gutacker. Gutacker, Bloor, Cookson, and Bernal-Delgado conceived and designed the study, and all contributed substantially to data acquisition, analysis, and interpretation. Bloor wrote the first draft of the paper, with important contributions from all coauthors. Gale, Maynard, Pomar, and Pagano contributed substantially to interpreting the data and critical revisions of the paper for important intellectual content. Natalia Martinez-Lizaga provided programming and data management. All authors have approved the version to be submitted, and agree to be accountable for all aspects of the work.

REFERENCES

ACCF/AHA. 2011. "Guideline for Coronary Artery Bypass Graft Surgery: A Report of the American College of Cardiology Foundation/American Heart

- Association Task Force on Practice Guidelines 2011" [accessed on March 18, 2015]. Available at <http://www.guideline.gov/content.aspx?id=34979>
- Agency for Healthcare Research and Quality. 2015. "In-Patient Quality Indicators. IQI#12 Coronary Artery Bypass Graft (CABG) Mortality Rate" [accessed on March 18, 2015]. Available at <http://www.qualityindicators.ahrq.gov/Downloads/Modules/IQI/V42/TechSpecs/IQI%2012%20CABG%20Mortality.pdf>
- Banta, D., and M. Bos. 1991. "The Relation between Quantity and Quality with Coronary Artery Bypass Graft (CABG) Surgery." *Health Policy* 18: 1–10.
- Bernal-Delgado, E., T. Christiansen, K. Bloor, C. Mateus, A. M. Yazbeck, J. Munck, and J. Bremner. 2015. "ECHO: Health Care Performance Assessment in Several European Health Systems." *European Journal of Public Health* 25 (S1): 3–7.
- Birkmeyer, J. D., T. A. Stukel, A. E. Siewers, P. P. Goodney, D. E. Wennberg, and F. L. Lucas. 2003. "Surgeon Volume and Operative Mortality in the United States." *New England Journal of Medicine* 349: 2117–27.
- Bridgewater, B., A. D. Grayson, N. Brooks, G. Grotte, B. M. Fabri, J. Au, T. Hooper, M. Jones, and B. Keogh. 2007. "Has the Publication of Cardiac Surgery Outcome Data Been Associated with Changes in Practice in Northwest England: An Analysis of 25 730 Patients Undergoing CABG Surgery under 30 Surgeons Over Eight Years." *Heart* 93 (6): 744–8.
- Bridgewater, B., J. Gummert, P. K. H. Walton, and R. Kinsman and European Association for Cardio-Thoracic Surgery. 2010. *EACTS Adult Cardiac Surgical Database Report 2010*. Henley-on-Thames: Dendrite Clinical Systems Ltd.
- Bufalino, V. J., F. A. Masoudi, S. Stranne, K. Horton, N. M. Albert, C. Beam, R. O. Bonow, R. L. Davenport, M. Girgus, G. C. Fonarow, H. M. Krumholz, M. W. Legnini, W. R. Lewis, G. Nichol, E. D. Peterson, W. Rosamund, J. S. Rumsfeld, L. H. Schwamm, D. M. Shahian, J. A. Spertus, P. K. Woodard, and C. W. Yancy; on behalf of the American Heart Association Advocacy Coordinating Committee. 2011. "The American Heart Association's Recommendations for Expanding the Applications of Existing and Future Clinical Registries: A Policy Statement from the American Heart Association." *Circulation* 123 (19): 2167–79.
- Elixhauser, A., C. Steiner, D. R. Harris, and R. M. Coffey. 1998. "Comorbidity Measures for Use with Administrative Data." *Medical Care* 36 (1): 8–27.
- Finks, J. F., N. H. Osborne, and J. D. Birkmeyer. 2011. "Trends in Hospital Volume and Operative Mortality for High-Risk Surgery." *New England Journal of Medicine* 364: 2128–37.
- Grant, S. W., G. L. Hickey, R. Cosgriff, G. Cooper, J. Deanfield, J. Roxburgh, and B. Bridgewater. 2013. "Creating Transparency in UK Adult Cardiac Surgery Data." *Heart* 99 (15): 1067–8.
- Gutacker, N., K. Bloor, and R. Cookson. 2015a. "Comparing the Performance of the Charlson/Deyo and Elixhauser Comorbidity Measures across Five European Countries and Three Conditions." *European Journal of Public Health* 25 (S1): 15–20.
- Gutacker, N., K. Bloor, R. Cookson, S. Garcia-Armesto, and E. Bernal-Delgado. 2015b. "Comparing Hospital Performance within and across Countries: An

- Illustrative Study of Coronary Artery Bypass Graft Surgery in England and Spain." *European Journal of Public Health* 25 (S1): 28–34.
- Halm, E. A., C. Lee, and M. R. Chassin. 2002. "Is Volume Related to Outcome in Health Care? A Systematic Review and Methodologic Critique of the Literature." *Annals of Internal Medicine* 137: 511–20.
- Higgins, T. L., F. G. Estafanous, F. D. Loop, G. J. Beck, J. M. Blum, and L. Parandhi. 1992. "Stratification of Morbidity and Mortality Outcome by Preoperative Risk Factors in Coronary Artery Bypass Patients. A Clinical Severity Score." *Journal of the American Medical Association* 267: 2344–8.
- Hlatky, M. A., D. B. Boothroyd, D. M. Bravata, E. Boersma, J. Booth, M. M. Brooks, D. Carrié, T. C. Clayton, N. Danchin, M. Flather, C. W. Hamm, W. A. Hueb, J. Kähler, S. F. Kelsey, S. B. King, A. S. Kosinski, N. Lopes, K. M. McDonald, A. Rodriguez, P. Serruys, U. Sigwart, R. H. Stables, and D. K. Owens. 2009. "Coronary Artery Bypass Surgery Compared with Percutaneous Coronary Interventions for Multivessel Disease: A Collaborative Analysis of Individual Patient Data from Ten Randomised Trials." *Lancet* 373: 1190–7.
- Leapfrog Group. 2008. "Factsheet: Evidence-based Hospital Referral (04/09/08)" [accessed on March 18, 2015]. Available at http://www.leapfroggroup.org/media/file/Leapfrog-Evidence-Based_Hospital_Referral_Fact_Sheet.pdf
- Luft, H. S., J. P. Bunker, and A. C. Enthoven. 1979. "Should Operations Be Regionalized? The Empirical Relation between Surgical Volume and Mortality." *New England Journal of Medicine* 20 (301): 1364–9.
- Marcin, J. P., Z. Li, R. L. Kravits, J. J. Dai, D. M. Rocke, and P. S. Romano. 2008. "The CABG Volume-Outcome Relationship: Temporal Trends and Selection Effects in California, 1998-2004." *Health Services Research* 43 (1): 174–92.
- O'Connor, G. T., S. K. Plume, E. M. Olmstead, J. R. Morton, C. T. Maloney, W. C. Nugent, F. Hernandez, R. Clough, B. J. Leavitt, L. H. Coffin, C. A. S. Marrin, D. Wennberg, J. D. Birkmeyer, D. C. Charlesworth, D. J. Malenka, H. B. Quinton, J. F. Kasper, F. Hernandez, H. Quinton, D. Carey-Johnson, C. M. Downs, J. J. Hessel, R. M. Hoffman, E. R. Johnson, H. McKinnon, C. Mingo, C. Pedersen, W. Perkins, M. L. Rowe, K. Sargent, T. Silver, P. Ver Lee, C. Warren, S. Barber, P. Brown, R. G. Brandenburg, S. Colmanaro, W. D. Gundel, R. S. Jackson, D. Johnson, A. Laramée, W. C. Paganelli, D. Pappalardo, D. S. Raabe, C. Terrien, P. Vaitkus, M. Watkins, V. Beggs, W. Burke, E. Catherwood, L. J. Daeey, C. Darcey, G. Defoe, T. Dodds, M. Fillinger, B. Friedman, B. Hettleman, T. Kneeland, E. Maislen, N. Niles, N. J. O'Connor, J. Robb, W. Schults, W. J. Sullivan, J. Wahrenberger, B. Wolf, Y. Baribeau, A. Becker, C. C. Berry, K. Berry, W. A. Bradley, S. Cuddy, R. C. Dewey, F. Fedele, L. I. Fink, E. J. Funk, A. E. Garstka, D. Halstead, M. J. Hearne, J. B. Hunter, A. D. Kaplan, P. Lambert, P. M. Lawrence, J. Lockhart, K. McNeil, E. Palank, J. Porelle, D. Pulsifer, J. Robichaud, J. Schnitz, S. Shea, B. M. Westbrook, T. P. Wharton, K. W. Wheeler, D. White, R. B. Keller, D. C. Soule, M. Abbott, L. Adrian, W. D. Alpern, E. Anderson, R. A. Anderson, L. Banister, C. Berg, S. Blank, C. E. Bredenberg, M. Brennan, L. Brewster, D. Burkey, A. Cirillo, C. Clark, J. Cleaves, D. Courtney, J. Cutler, D. Donegal, P. Fallo, D. Hanley, J. Kane, S. Katz, M. A. Kellett,

- R. Kramer, C. T. Lambrew, S. Larned, C. A. Lutes, E. R. Nowicki, J. R. O'Meara, H. Osher, P. Peasley, C. Prouty, R. D. Quinn, D. Redfield, K. Reynolds, T. Ryan, J. Saunders, A. Schultz, S. Seekins, R. Stogsdill, P. W. Sweeny, K. Tolan, N. Tooker, J. F. Tryzelaar, M. Turcotte, K. Viger, C. Westlund, R. L. White, W. Whittet, and C. Zografos. 1996. "A Regional Intervention to Improve the Hospital Mortality Associated with Coronary Artery Bypass Graft Surgery." *Journal of the American Medical Association* 275 (11): 841–6.
- Pagano, D., and C. P. Gale. 2014. "The Death of Administrative Data for Benchmarking Cardiothoracic Mortality?" *Heart* 100 (9): 680–2.
- Peterson, E. D., L. P. Coombs, E. R. DeLong, C. K. Haan, and T. B. Ferguson. 2004. "Procedural Volume as a Marker of Quality for CABG Surgery." *Journal of the American Medical Association* 291: 195–201.
- Quan, H., V. Sundararajan, P. Halfon, A. Fong, B. Burnand, J.-C. Luthi, L. D. Saunders, C. A. Beck, T. E. Feasby, and W. A. Ghali. 2005. "Coding Algorithms for Defining Comorbidities in ICD-9-CM and ICD-10 Administrative Data." *Medical Care* 43 (11): 1130–9.
- Shahian, D. M. 2004. "Improving Cardiac Surgery Quality – Volume, Outcome, Process?" *Journal of the American Medical Association* 291 (2): 246–8.
- Shahian, D. M., and S.-L. T. Normand. 2003. "The Volume-Outcome Relationship: From Luft to Leapfrog." *Annals of Thoracic Surgery* 75: 1048–58.
- Shahian, D. M., S. M. O'Brien, G. Filardo, V. A. Ferraris, C. K. Haan, J. B. Rich, S.-L. T. Normand, E. R. DeLong, C. M. Shewan, R. S. Dokholyan, E. D. Peterson, F. H. Edwards, and R. P. Anderson. 2009. "The Society of Thoracic Surgeons 2008 Cardiac Surgery Risk Models: Part 1—Coronary Artery Bypass Grafting Surgery." *Annals of Thoracic Surgery* 88 (1): S2–22.
- Sowden, A. J., J. J. Deeks, and T. A. Sheldon. 1995. "Volume and Outcome in Coronary Artery Bypass Graft Surgery: True Association or Artefact?" *British Medical Journal* 311: 151.
- Spiegelhalter, D. 2013. "Are You 45% More Likely to Die in a UK Hospital Rather Than a US Hospital?" *British Medical Journal* 347: f5775.
- Steinbrook, R. 2006. "Public Report Cards - Cardiac Surgery and Beyond." *New England Journal of Medicine* 355 (18): 1847.
- Taggart, D. 2009. "PCI or CABG in Coronary Artery Disease?" *Lancet* 373: 1150–2.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article:

Appendix SA1: Author Matrix.

Figure S1: Unadjusted in-hospital 30-Day Mortality Rates and Hospital Annual Volume by Country.

Figure S2: Sensitivity Analysis—all CABG Patients; Full Case Mix Adjustment; Excluding Patients Transferred to Another Provider.

Figure S3: Sensitivity Analysis—Isolated CABG Patients; Full Case Mix Adjustment; Including Patients Transferred to Another Provider.

Figure S4: Sensitivity Analysis—Isolated CABG Patients; Full Case Mix Adjustment; Excluding Patients Transferred to Another Provider.

Figure S5: Sensitivity Analysis—all CABG Patients; Adjusted for Age, Sex, Age–Sex Interactions, and Year of Treatment; Including Patients Transferred to Another Provider.

Figure S6: Sensitivity Analysis—all CABG Patients; Adjusted for Age, Sex, Age–Sex Interactions, and Year of Treatment; Excluding Patients Transferred to Another Provider.

Figure S7: Sensitivity Analysis—Data from England and Spain Only, Segmented Regression Line.

Table S1: Odds Ratios (OR) and Associated 95% Confidence Intervals (CI).

Table S2: Sensitivity Analysis—Adjusted Mortality Rates in Low-, Medium-, and High-Volume Hospitals.