

SPECIAL ARTICLE

## Surgeon Volume and Operative Mortality in the United States

John D. Birkmeyer, M.D., Therese A. Stukel, Ph.D., Andrea E. Siewers, M.P.H.,  
Philip P. Goodney, M.D., David E. Wennberg, M.D., M.P.H.,  
and F. Lee Lucas, Ph.D.

### ABSTRACT

#### BACKGROUND

Although the relation between hospital volume and surgical mortality is well established, for most procedures, the relative importance of the experience of the operating surgeon is uncertain.

#### METHODS

Using information from the national Medicare claims data base for 1998 through 1999, we examined mortality among all 474,108 patients who underwent one of eight cardiovascular procedures or cancer resections. Using nested regression models, we examined the relations between operative mortality and surgeon volume and hospital volume (each in terms of total procedures performed per year), with adjustment for characteristics of the patients and other characteristics of the providers.

#### RESULTS

Surgeon volume was inversely related to operative mortality for all eight procedures ( $P=0.003$  for lung resection,  $P<0.001$  for all other procedures). The adjusted odds ratio for operative death (for patients with a low-volume surgeon vs. those with a high-volume surgeon) varied widely according to the procedure — from 1.24 for lung resection to 3.61 for pancreatic resection. Surgeon volume accounted for a large proportion of the apparent effect of the hospital volume, to an extent that varied according to the procedure: it accounted for 100 percent of the effect for aortic-valve replacement, 57 percent for elective repair of an abdominal aortic aneurysm, 55 percent for pancreatic resection, 49 percent for coronary-artery bypass grafting, 46 percent for esophagectomy, 39 percent for cystectomy, and 24 percent for lung resection. For most procedures, the mortality rate was higher among patients of low-volume surgeons than among those of high-volume surgeons, regardless of the surgical volume of the hospital in which they practiced.

#### CONCLUSIONS

For many procedures, the observed associations between hospital volume and operative mortality are largely mediated by surgeon volume. Patients can often improve their chances of survival substantially, even at high-volume hospitals, by selecting surgeons who perform the operations frequently.

From the Department of Surgery, Dartmouth–Hitchcock Medical Center, Lebanon, N.H. (J.D.B., P.P.G.); the Veterans Affairs Outcomes Group, Veterans Affairs Medical Center, White River Junction, Vt. (J.D.B., P.P.G.); the Institute for Clinical Evaluative Sciences, Toronto (T.A.S.); and the Center for Outcomes Research and Evaluation, Maine Medical Center, Portland (A.E.S., D.E.W., F.L.L.). Address reprint requests to Dr. Birkmeyer at the Section of General Surgery, Dartmouth–Hitchcock Medical Center, Lebanon, NH 03756, or at [john.birkmeyer@hitchcock.org](mailto:john.birkmeyer@hitchcock.org).

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**F**OR MANY SURGICAL PROCEDURES, patients at hospitals where a high number of such procedures are performed (high-volume hospitals) have lower mortality rates than those at hospitals that are less experienced with the procedures.<sup>1-4</sup> In one recent study of the national population of Medicare recipients, we found strong relations between hospital volume and operative mortality associated with 14 high-risk cancer resections and cardiovascular procedures.<sup>5</sup> Despite the considerable body of research in this area, little is known about the mechanisms underlying the observed associations between volume and outcome. Because they tend to be much larger facilities, high-volume hospitals have a broader range of specialist and technology-based services, better-staffed intensive care units, and other resources that are not available at smaller centers. By virtue of these resources, high-volume hospitals may be better equipped to deliver the complex perioperative care required by patients who are undergoing high-risk surgery.

On the other hand, the outcome of a surgical procedure may depend as much on how well the operation itself is performed as on the resources available at the hospital. If so, another explanation for the observed relation between the hospital volume and the outcome may be that high-volume hospitals tend to have surgeons who are more experienced with specific procedures. Numerous studies have explored the associations between surgeon volume (the number of procedures performed by the surgeon) and mortality for some procedures.<sup>1,6-12</sup> However, relatively few of these analyses have simultaneously accounted for hospital volume and other potential confounding characteristics of the hospital that may be strongly correlated with surgeon volume. Moreover, few have been large enough to characterize the relative influence of these two measures of volume with sufficient precision.

To address these issues, we undertook a comprehensive evaluation of the operative risk associated with eight different cardiovascular procedures and cancer resections using data from the national population of Medicare recipients. We had two primary aims: to assess the association between surgeon volume and operative mortality for various procedures and to achieve a better understanding of the extent to which the observed effects of hospital volume can be explained by the experience of the operating surgeon.

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## METHODS

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### PATIENTS AND DATA BASES

We obtained 100 percent of the national analytic files from the Center for Medicare and Medicaid Services for 1998 and 1999. The Medicare Provider Analysis and Review (MEDPAR) and inpatient files, which contain hospital-discharge abstracts for the fee-for-service, acute care hospitalizations of all Medicare recipients, were used to create our main data sets for analysis; the Medicare denominator file was used to determine the vital status of the patients. The institutional review board of Dartmouth Medical School approved the study protocol.

As in our previous work,<sup>5,13,14</sup> we used the appropriate procedure codes from the *International Classification of Diseases, Ninth Revision (ICD-9)*, to identify all patients between 65 and 99 years of age who underwent 1 of 14 cardiovascular procedures or cancer resections. To simplify the presentation of our results, however, we present here the analyses for only four cardiovascular procedures and four cancer resections. These procedures, which were selected prospectively, included two that are frequently the focus of debate concerning the regionalization of health care services (coronary-artery bypass grafting and carotid endarterectomy). Six other procedures (aortic-valve replacement, elective repair of an abdominal aortic aneurysm, pancreatic resection, esophagectomy, lung resection, and cystectomy) for which we have previously found a relatively strong association between hospital volume and operative mortality were selected to represent diverse surgical subspecialties.

In examining the data related to the cancer resections, we excluded from the analysis of outcomes (but not from the tallies of volume) patients who did not have an accompanying diagnosis code for cancer. This restriction was intended to exclude small subgroups of patients who had a much higher level of risk at base line (e.g., patients who underwent pancreatic resection because of infection) and thus to minimize confounding. Similarly, patients who underwent repair of an abdominal aortic aneurysm were excluded if they had diagnosis or procedure codes suggesting the rupture of an aneurysm, the presence of a thoracoabdominal aneurysm, or both. We excluded from the analysis of the cohort that underwent coronary-artery bypass grafting patients who had a valve replaced simultaneously.

**IDENTIFICATION OF SURGEONS**

For all procedures, we identified the operating surgeon with the use of the unique provider identification number listed in the “primary operator” field of the inpatient file. Previous work has suggested the reliability of this approach in identifying operating surgeons.<sup>15</sup> Records containing invalid provider identification numbers (6 percent) were excluded from further analysis. For some procedures, the number of unique, valid identification numbers exceeded the number of surgeons in the relevant specialties in the United States. This problem was most apparent in the analysis of the two cardiac procedures, for which cardiologists were often identified in the primary-operator field. For this reason, we used information from the 1998 Medicare provider files to restrict our analysis to physicians who had designated themselves as surgeons. For coronary-artery bypass grafting and valve-replacement procedures, we included only self-designated cardiothoracic surgeons. Because the specialists who perform the other procedures are more diverse, we included any self-designated surgeon. These restrictions removed a large proportion of potentially eligible surgeons from our analysis (ranging from 6 percent for cystectomy to 72 percent for coronary-artery bypass grafting). However, because the physicians who were excluded tended to be associated with relatively few patients (most often only one each), the restrictions resulted in the exclusion of a relatively low proportion of patients from our analysis of outcomes (ranging from 4 percent for cystectomy to 13 percent for coronary-artery bypass grafting).

**STATISTICAL ANALYSIS**

Our primary analyses focused on the relations between surgeon volume and hospital volume (the main variables measuring exposure) and operative mortality, defined as death before hospital discharge or within 30 days after the index procedure. Because, for some procedures, a large proportion of operative deaths before discharge occurred more than 30 days after surgery, 30-day mortality alone would not adequately reflect the true operative mortality.

To characterize volume, we first determined the average number of procedures that each hospital and each surgeon performed on Medicare patients during each of the two years. To make our estimates of volume more easily interpretable, we then estimated the total (all-payer) volumes, using data from the 1997 Nationwide Inpatient Sample. As in

our previous research,<sup>5</sup> we determined the proportion of patients undergoing each procedure who were covered by Medicare — which ranged from 49 percent for esophagectomy to 75 percent for carotid endarterectomy — and divided each provider’s observed Medicare volume (the total number of each type of procedure performed on Medicare patients) by these procedure-specific proportions. Although volume was evaluated as a continuous (log-transformed) variable in the assessment of statistical significance, we also created categorical variables for volume by ranking providers in order of increasing estimated total volume and selecting cutoff points that most closely sorted patients into three evenly sized groups with low, medium, and high volume. In sensitivity analyses, we recategorized hospital volume as a binary variable according to the criteria established by the Leapfrog Group for four procedures: coronary-artery bypass grafting (450 or more procedures per year vs. fewer than 450), repair of abdominal aortic aneurysm (50 or more per year vs. fewer than 50), esophagectomy (13 or more per year vs. fewer than 13), and pancreatic resection (11 or more per year vs. fewer than 11).

We used multiple logistic-regression analyses to examine the relation between surgeon volume and operative mortality, with adjustment for characteristics of the patients.<sup>16</sup> We used the patient as the unit of analysis, with volume measured at the level of the surgeon and at the level of the hospital. All models were analyzed separately for each procedure. Separate models were used to investigate the relation between operative mortality and surgeon volume, with and without consideration of hospital volume, and the relation between operative mortality and hospital volume, with and without consideration of surgeon volume. To establish the general form of the relation, we first modeled the relations between operative mortality and the logarithms of surgeon volume and hospital volume considered separately. We then fitted the models to the three volume strata. We adjusted for the effect of clustering of patients within surgeons and clustering of surgeons within hospitals by using binary mixed-effects models incorporating the two levels of nesting.<sup>17</sup> Surgeons who operated in more than one hospital were assumed to be in different clusters and contributed a random effect for each hospital in which they worked. We used the statistical software package MLwiN (Centre for Multilevel Modeling) to perform all modeling.<sup>18</sup>

We adjusted the analyses for characteristics of both the patients and the hospitals. The characteristics of the patients for which we adjusted included age group (in five-year intervals), sex, race (black or nonblack), year of procedure (1998 or 1999), whether the procedure was performed electively or not, and the mean income from Social Security in the ZIP Code of the patient's residence. Coexisting conditions were identified by their appropriate ICD-9 codes, with the exclusion of conditions that were likely to reflect either the primary indication for surgery or postoperative complications.<sup>5</sup> We explored three alternative approaches to the incorporation of data on coexisting conditions into our models for risk adjustment, including the use of Charlson scores with published weights,<sup>19</sup> the use of Charlson scores with weights derived empirical-

ly for each procedure, and adjustment for all pertinent coexisting conditions as individual variables. Because all three approaches yielded virtually identical results, we report only those from the models derived according to the first approach. We used 1998 and 1999 files from the American Hospital Association to ascertain the characteristics of the hospitals specific to the year in which the event occurred. The characteristics of the hospitals for which we adjusted included the type of ownership (not-for-profit, for-profit, or government), location (urban or nonurban), and teaching status (as defined by Taylor et al.<sup>20</sup>).

We computed adjusted mortality rates on the basis of the average values of the characteristics of the patients and the hospitals by back-transforming predicted mortality from the logistic-regression

**Table 1. Characteristics of the Patients, According to Surgeon Volume.**

Characteristic	Low-Volume Surgeons	Medium-Volume Surgeons	High-Volume Surgeons
	<i>percentage of patients</i>		
<b>Cardiovascular procedures</b>			
<b>Carotid endarterectomy</b>			
Age >75 yr	49.4	50.1	50.4
Female sex	43.6	43.1	44.4
Black race	3.8	2.6	2.3
Charlson score $\geq 3$	10.7	10.2	9.9
Nonelective admission	32.2	27.4	26.3
<b>Coronary-artery bypass grafting</b>			
Age >75 yr	39.4	39.3	40.3
Female sex	35.0	35.4	34.9
Black race	4.6	3.7	2.9
Charlson score $\geq 3$	10.0	9.5	9.7
Nonelective admission	57.0	58.5	55.4
<b>Aortic-valve replacement</b>			
Age >75 yr	53.7	54.5	55.5
Female sex	43.8	43.4	44.3
Black race	4.7	2.8	2.0
Charlson score $\geq 3$	9.4	8.7	10.2
Nonelective admission	43.1	38.9	36.4
<b>Elective repair of an abdominal aortic aneurysm</b>			
Age >75 yr	46.3	45.4	47.0
Female sex	23.3	23.8	23.0
Black race	3.7	2.6	2.2
Charlson score $\geq 3$	9.3	9.9	10.2
Nonelective admission	26.5	23.9	22.5

models. To assess the relative contribution of surgeon volume to the observed associations between hospital volume and outcome, we used models that estimated the relation between the operative mortality and hospital volume, first excluding and then including a variable for surgeon volume. The relative attenuation of the odds ratio was computed as  $[\text{OR}_H - \text{OR}_{HS}] \div [\text{OR}_H - 1]$ , where  $\text{OR}_H$  is the odds ratio for operative death with a given hospital volume without consideration of surgeon volume and  $\text{OR}_{HS}$  is the odds ratio for operative death with a given hospital volume after adjustment for surgeon volume; both odds ratios were adjusted for patient characteristics and other characteristics of the hospital. A P value of less than 5 percent was considered to indicate statistical significance, and all tests were two-sided.

## RESULTS

A total of 474,108 Medicare patients underwent one of the eight cardiac procedures or cancer resections during 1998 or 1999. Overall, approximately 25 percent of the surgeons who were included in the study operated at more than one hospital. Patients were much more likely to undergo surgery performed by a low-volume surgeon if they went to a low-volume hospital (range, 51 percent for carotid endarterectomy to 70 percent for pancreatic resection) than if they went to a high-volume hospital (range, 6 percent for pancreatic resection to 21 percent for carotid endarterectomy). The numbers of Medicare patients treated by low-volume, medium-volume, and high-volume surgeons in different hospital-volume strata are given in Supplemen-

Table 1. (Continued.)

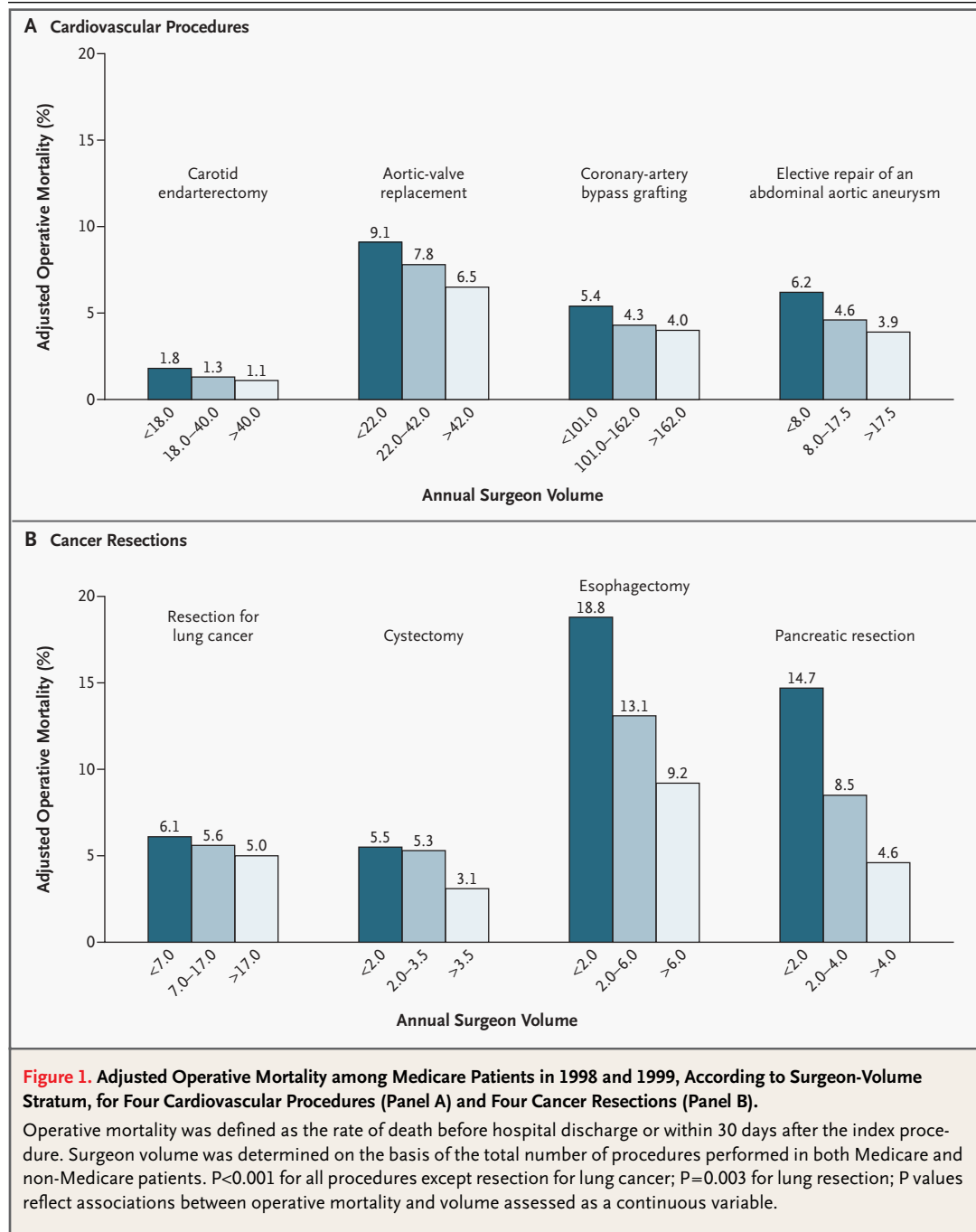
Characteristic	Low-Volume Surgeons	Medium-Volume Surgeons	High-Volume Surgeons
	<i>percentage of patients</i>		
<b>Cancer resections</b>			
Resection for lung cancer			
Age >75 yr	35.6	35.3	35.7
Female sex	42.6	43.2	43.5
Black race	5.9	4.5	4.1
Charlson score $\geq 3$	32.2	36.7	38.1
Nonelective admission	20.8	16.6	11.1
Cystectomy of the bladder			
Age >75 yr	44.3	47.0	43.8
Female sex	22.1	19.8	19.7
Black race	4.7	3.4	2.3
Charlson score $\geq 3$	34.2	34.1	41.4
Nonelective admission	20.4	19.4	15.6
Esophagectomy			
Age >75 yr	31.2	31.6	31.0
Female sex	24.4	25.1	21.5
Black race	8.7	6.8	4.3
Charlson score $\geq 3$	42.2	41.8	42.4
Nonelective admission	24.7	14.9	15.5
Pancreatic resection			
Age >75 yr	41.6	38.6	39.2
Female sex	49.1	51.9	48.8
Black race	8.0	7.2	4.2
Charlson score $\geq 3$	52.4	53.8	64.9
Nonelective admission	40.0	37.6	18.3

tary Appendix 1 (available with the full text of this article at [www.nejm.org](http://www.nejm.org)).

There were negligible differences in age and sex between the patients who received care from low-volume surgeons and those who received care from high-volume surgeons; for some procedures, the prevalence of coexisting conditions varied to a small

degree according to surgeon volume (Table 1). Patients receiving care from low-volume surgeons were more likely to be black and to be admitted to the hospital nonelectively. Overall, however, there were no clinically important differences in predicted mortality rates according to surgeon volume.

When surgeon volume was assessed as a con-



tinuous variable, it was inversely related to operative mortality for all eight procedures ( $P=0.003$  for lung resection,  $P<0.001$  for all other procedures). The strength of the inverse association between surgeon volume and outcome varied markedly according to the procedure in terms of both the absolute operative mortality rate (Fig. 1) and the adjusted odds ratio for operative death (Table 2). The adjusted odds ratios for operative death among patients of low-volume surgeons as compared with patients of high-volume surgeons ranged from 1.24 for lung resection to 3.61 for pancreatic resection. Adjusting for hospital volume attenuated the strength of the associations between surgeon volume and outcome, but the effect of surgeon volume remained statistically significant for seven of the eight procedures.

When hospital volume was assessed as a continuous variable, it was inversely related to operative mortality for seven of the eight procedures ( $P=0.20$  for carotid endarterectomy,  $P<0.001$  for all the other procedures). After adjustment for surgeon volume, however, higher hospital volume remained a significant predictor of decreased mortality for only four procedures (repair of an abdominal aor-

tic aneurysm, cystectomy, lung resection, and pancreatic resection). In fact, after adjustment for surgeon volume, high hospital volume was associated with increased mortality among patients undergoing carotid endarterectomy. For many procedures, surgeon volume accounted for a large proportion of the apparent differences in operative mortality between high-volume hospitals and low-volume hospitals. Among patients undergoing elective repair of an abdominal aortic aneurysm, for example, the adjusted odds ratio for death with surgery performed in a low-volume hospital as compared with that performed in a high-volume hospital decreased from 1.40 to 1.17 after adjustment for surgeon volume. Thus, surgeon volume accounted for 57 percent of the apparent difference in mortality between low-volume and high-volume hospitals ( $[(1.40-1.17) \div (1.40-1.00)]$ ). The proportion of the apparent effect of hospital volume that was actually attributable to surgeon volume varied according to the procedure: it was 100 percent for aortic-valve replacement, 54 percent for pancreatic resection, 49 percent for coronary-artery bypass grafting, 46 percent for esophagectomy, 39 percent for cystectomy, and 24 percent for lung resection.

**Table 2. Adjusted Odds Ratio for Operative Death, According to Surgeon Volume and Hospital Volume.\***

Procedure	Odds of Operative Death with Low Volume as Compared with High Volume					
	Surgeon Volume <i>adjusted odds ratio (95% CI)</i>	Surgeon Volume, Adjusted for Hospital Volume <i>(95% CI)</i>	Proportion of Effect of Surgeon Volume Attributable to Hospital Volume %	Hospital Volume <i>adjusted odds ratio (95% CI)</i>	Hospital Volume, Adjusted for Surgeon Volume <i>(95% CI)</i>	Proportion of Effect of Hospital Volume Attributable to Surgeon Volume %
<b>Cardiovascular procedures</b>						
Carotid endarterectomy	1.64 (1.47–1.84)	1.70 (1.51–1.91)	0	1.04 (0.92–1.17)	0.89 (0.79–1.01)	—†
Aortic-valve replacement	1.44 (1.29–1.59)	1.45 (1.30–1.63)	0	1.13 (1.00–1.28)	0.97 (0.86–1.10)	100
Coronary-artery bypass grafting	1.36 (1.28–1.45)	1.33 (1.25–1.42)	8	1.26 (1.15–1.37)	1.13 (1.03–1.24)	49
Elective repair of an abdominal aortic aneurysm	1.65 (1.46–1.86)	1.55 (1.36–1.77)	15	1.40 (1.23–1.59)	1.17 (1.02–1.35)	57
<b>Cancer resections</b>						
Resection for lung cancer	1.24 (1.08–1.44)	1.16 (0.99–1.36)	34	1.29 (1.11–1.51)	1.22 (1.04–1.44)	24
Cystectomy of the bladder	1.83 (1.37–2.45)	1.45 (1.03–2.04)	46	2.06 (1.50–2.83)	1.65 (1.14–2.39)	39
Esophagectomy	2.30 (1.54–3.42)	1.80 (1.13–2.87)	38	2.23 (1.47–3.39)	1.67 (1.02–2.73)	46
Pancreatic resection	3.61 (2.44–5.33)	2.31 (1.43–3.72)	50	3.95 (2.55–6.11)	2.34 (1.38–3.99)	54

\* Because of rounding, the values given for the proportion of the effect of surgeon volume attributable to hospital volume and the proportion of the effect of hospital volume attributable to surgeon volume may not match the values that can be calculated with the formula given in the text. CI denotes confidence interval.

† There was no statistically significant effect of hospital volume.

Figure 2 shows the relative effects of hospital volume and surgeon volume in terms of adjusted mortality rates. For carotid endarterectomy and aortic-valve replacement, the mortality rates decreased with increasing surgeon volume but did not change substantially with increasing hospital volume. Conversely, for lung resection, the adjusted mortality rates were strongly inversely related to hospital volume, but were less strongly related to surgeon volume. For the remaining five procedures, operative mortality decreased to relatively similar degrees with increasing hospital volume and increasing surgeon volume. Even within the high-volume-hospital stratum, the patients who received their care from low-volume surgeons had considerably higher mortality rates with several procedures than the patients who received care from high-volume surgeons.

We performed similar sensitivity analyses using the hospital-volume criteria that were established by the Leapfrog Group for four of the procedures (Table 3). High-volume hospitals (those with volumes at or above the Leapfrog cutoffs) had lower overall mortality rates than low-volume hospitals, largely because patients at high-volume hospitals were much more likely to be treated by high-volume surgeons than by low-volume surgeons. For coronary-artery bypass grafting, elective repair of an abdominal aortic aneurysm, and esophagectomy, the operative mortality among the patients treated by low-volume surgeons at high-volume hospitals was higher than the overall operative mortality at low-volume hospitals. For pancreatic resection, patients at high-volume hospitals had lower mortality rates than those at low-volume hospitals, regardless of the surgeon volume.

#### DISCUSSION

By virtue of the large size and generalizability of the national Medicare data base, we were able to examine with precision the associations between surgeon volume and operative mortality for a wide range of cardiovascular procedures and cancer resections. For all eight procedures we studied, the patients treated by high-volume surgeons had lower operative mortality rates than those treated by low-volume surgeons. Surgeon volume accounted for a relatively large proportion of the apparent effect of hospital volume, to a degree that varied according to the procedure. For some procedures, the association between hospital volume and out-

come disappeared almost entirely after surgeon volume had been taken into account.

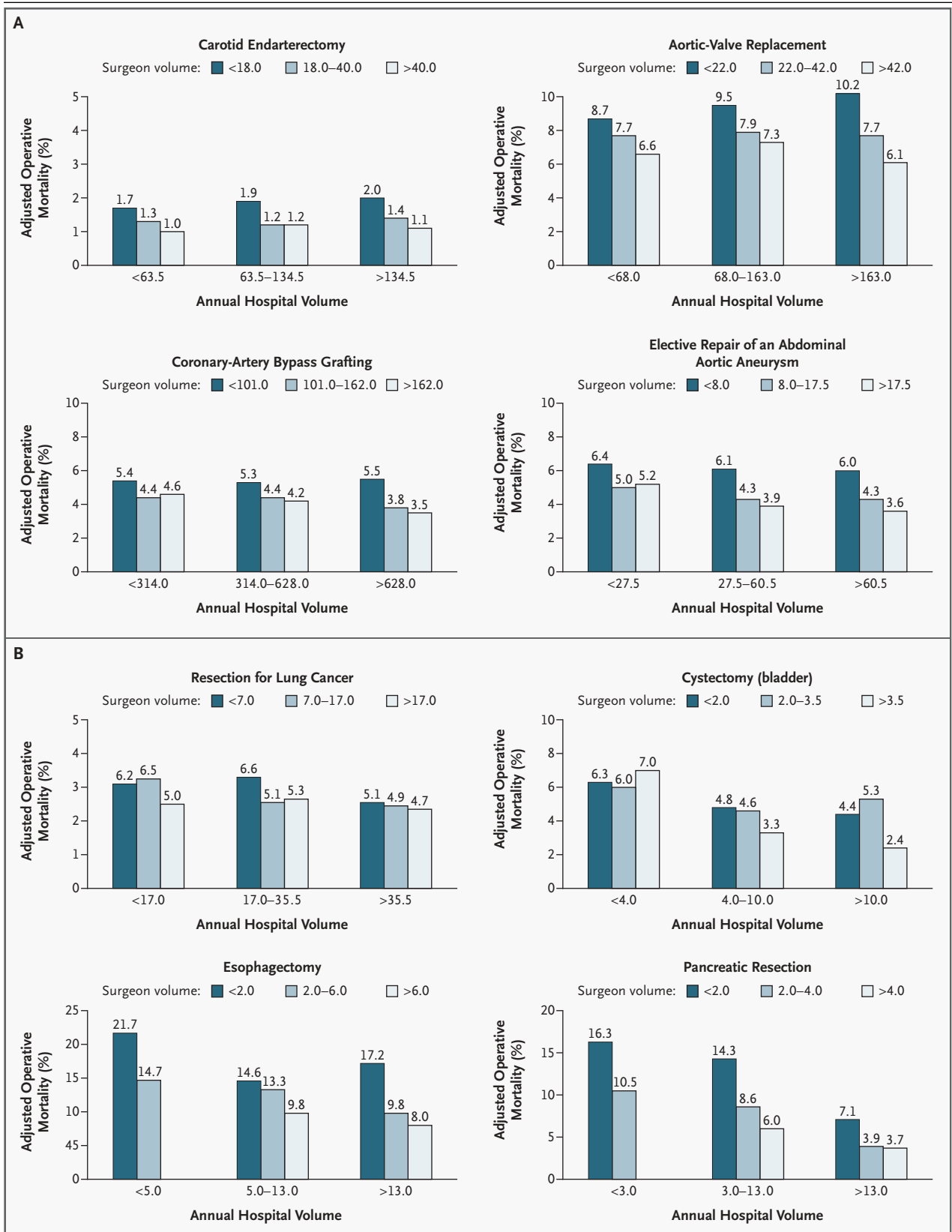
It is not surprising that the relative importance of surgeon volume and hospital volume varies according to the procedure. In the case of carotid endarterectomy, for example, technical skill and the use of specific intraoperative processes (e.g., intraarterial shunt insertion and patch angioplasty)<sup>21</sup>—processes used at the discretion of the operating surgeon—are important determinants of the risk of operative stroke or death. In contrast, other hospital-based services are relatively less important. Most patients undergoing carotid endarterectomy do not require intensive postoperative management, and the length of stay is typically just overnight. For these reasons, the preeminent role of surgeon volume in the outcome of this procedure has strong intuitive validity. In the case of lung resection, in contrast, patients rarely die because of direct technical complications of the procedure itself (e.g., bleeding or leakage from a bronchial stump); they die from cardiac events, pneumonia, and respiratory failure. Hospital-based services (e.g., intensive care, pain management, respiratory care, and nursing care) are very important, and the average length of stay is relatively long. Thus, it is not surprising that hospital volume was more important than surgeon volume in determining the outcome of this procedure. Of course, these two procedures represent the extremes. As suggested by our analysis, factors related to both surgeon volume and hospital volume seem to be important for most high-risk procedures.

Our study has several important limitations. First, because we used Medicare data, our study was restricted to patients 65 years of age or older. However, the elderly constitute the majority of patients undergoing the cardiovascular procedures and cancer resections that we examined in this study. Second, although our study was large, some of our subgroup analyses were based on relatively

**Figure 2 (facing page). Adjusted Operative Mortality among Medicare Patients in 1998 and 1999, According to Hospital-Volume Stratum and Surgeon-Volume Stratum for Four Cardiovascular Procedures (Panel A) and Four Cancer Resections (Panel B).**

Because of small samples (<20), mortality rates among patients treated by high-volume surgeons in low-volume hospitals are not shown for esophagectomy and pancreatic resection. Mortality rates were adjusted for characteristics of the patients.





**Table 3. Adjusted Operative Mortality Rates among Medicare Patients in 1998 and 1999, According to Total Hospital Volume, Relative to the Leapfrog Group Volume Criteria and Surgeon Volume.\***

Procedure	Cutoff no./yr	Hospital Volume <Cutoff			Hospital Volume ≥Cutoff		
		Low-Volume Surgeons	High-Volume Surgeons	Overall Hospital Mean	Low-Volume Surgeons	High-Volume Surgeons	Overall Hospital Mean
		percent					
Coronary-artery bypass grafting	450						
Proportion of patients		47.3	20.1		19.3	46.8	
Mortality		5.4	4.6	5.0	5.4	3.7	4.2
Elective repair of an abdominal aortic aneurysm	50						
Proportion of patients		45.3	18.1		17.8	52.5	
Mortality		6.4	4.3	5.4	5.8	3.6	4.3
Esophagectomy	13						
Proportion of patients		36.0	14.4		9.2	70.0	
Mortality		19.2	11.1	15.3	17.5	8.1	9.5
Pancreatic resection	11						
Proportion of patients		50.5	9.4		6.9	80.5	
Mortality		15.7	6.9	11.9	6.1	3.7	4.5

\* Operative mortality was defined as the rate of death before hospital discharge or within 30 days after the index procedure; total hospital volume included procedures in both Medicare and non-Medicare patients.

small numbers of patients. In particular, the number of patients who underwent procedures performed by low-volume surgeons at high-volume hospitals or by high-volume surgeons at low-volume hospitals was relatively low. Thus, estimates of mortality in these subgroups are relatively imprecise. Third, because of errors in the coding and assignment of unique provider identification numbers, we may have incorrectly identified the operating surgeon for some procedures. Such errors, if largely random, would tend to bias our results toward the null hypothesis (no effect of surgeon volume on outcome). However, to reduce any potential bias against low-volume surgeons, we excluded physicians who were not self-designated as surgeons.

Finally, many would question our ability to perform adequate risk adjustment with the use of administrative data.<sup>22,23</sup> Whether risk adjustment is important in studies of surgical volume and outcome is uncertain. Some have noted that analyses based on clinical studies are less likely to report statistically significant associations between volume and outcome than those (the majority) that are based on administrative data.<sup>4</sup> However, clinical studies also tend to be substantially smaller and often lack sufficient statistical power to detect clinically meaningful differences in operative mortality

rates. Moreover, there is little evidence from clinical studies that there are important, volume-related differences in case mix (i.e., that low-volume providers care for “sicker” patients). Although we cannot rule out confounding by unmeasured characteristics of the patients in our study, there is no reason to believe that such confounding would affect our analyses of hospital volume and surgeon volume disproportionately. Thus, we do not believe that limitations related to risk adjustment threaten our main conclusions about the relative importance of hospital volume and surgeon volume.

Our findings have direct implications for ongoing initiatives for volume-based referral. Leading the most visible of these initiatives, the Leapfrog Group, a coalition of more than 140 large public and private purchasers, has established “evidence-based hospital referral” standards for several surgical procedures.<sup>24</sup> Although the Leapfrog Group has recently incorporated data on outcomes and selected process measures into its 2003 standards for some procedures, criteria based on minimal hospital volume remain in place for coronary-artery bypass grafting, percutaneous coronary interventions, elective repair of an abdominal aortic aneurysm, esophagectomy, and pancreatic resection. Our analysis confirms that hospitals that exceed the volume criteria set by Leapfrog have lower mortality

ty rates, on average, than those that do not. However, our findings also suggest that high-volume hospitals have better outcomes in large part because patients at these hospitals are more likely to be treated by high-volume surgeons and that standards based on surgeon volume as well as hospital volume would be more useful in directing patients to the providers who are likely to achieve the best outcomes. Increasing surgeons' volumes would require that administrators and leaders in the field of surgery actively manage the way in which selected operations are distributed within their hospitals — that is, by restricting them to a smaller number of surgeons. Although such efforts would no doubt encounter resistance, they may be more practical and less controversial than policies focusing exclusively on redistributing patients among hospitals.

We should also look for opportunities to improve the quality of surgical care delivered by low-

volume surgeons. Determining whether this goal is realistic will require a better understanding of the mechanisms underlying the observed associations between volume and outcome. The key mechanism could simply be “practice” — clinical judgment and technical skill that are achieved only by surgeons who perform a specific procedure with sufficient frequency. Before jumping to this conclusion, however, we must better understand which specific processes of care are most important to the success of various operations and the extent to which they can be exported to other surgeons or hospitals.

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