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Clinical Study

Repeat surgery after lumbar decompression for herniated disc: the quality implications of hospital and surgeon variation

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Abstract

BACKGROUND CONTEXT: Repeat lumbar spine surgery is generally an undesirable outcome. Variation in repeat surgery rates may be because of patient characteristics, disease severity, or hospital- and surgeon-related factors. However, little is known about population-level variation in reoperation rates.

PURPOSE: To examine hospital- and surgeon-level variation in reoperation rates after lumbar herniated disc surgery and to relate these to published benchmarks.

STUDY DESIGN/SETTING: Retrospective analysis of a discharge registry including all nonfederal hospitals in Washington State.

METHODS: We identified adults who underwent an initial inpatient lumbar decompression for herniated disc from 1997 to 2007. We then performed generalized linear mixed-effect logistic regressions, controlling for patient characteristics and comorbidity, to examine the variation in reoperation rates within 90 days, 1 year, and 4 years.

RESULTS: Our cohort included 29,529 patients with a mean age of 47.5 years, 61% privately insured, and 15% having any comorbidity. The age-, sex-, insurance-, and comorbidity-adjusted mean rate of reoperation among hospitals was 1.9% at 90 days (95% confidence interval [CI], 1.2–3.1), with a range from 1.1% to 3.4%; 6.4% at 1 year (95% CI, 3.9–10.6), with a range from 2.8% to 12.5%; and 13.8% at 4 years (95% CI, 8.8–19.8), with a range from 8.1% to 24.5%. The adjusted mean reoperation rates of surgeons were 1.9% at 90 days (95% CI, 1.4–2.4) with a range from 1.2% to 4.6%, 6.1% at 1 year (95% CI, 4.8–7.7) with a range from 4.3% to 10.5%, and 13.2% at 4 years (95% CI, 11.3–15.5) with a range from 10.0% to 19.3%. Multilevel random-effect models suggested that variation across surgeons was greater than that of hospitals and that this effect increased with long-term outcomes.

CONCLUSIONS: Even after adjusting for patient demographics and comorbidity, we observed a large variation in reoperation rates across hospitals and surgeons after lumbar discectomy, a relatively simple spinal procedure. These findings suggest uncertainty about indications for repeat

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surgery, variations in perioperative care, or variations in quality of care.

Keywords: Lumbar spine surgery; Herniated disc; Decompression; Repeat surgery; Quality; Back pain

Introduction

Unplanned repeat spinal surgery is generally an undesirable outcome for patients, surgeons, hospitals, and payers. Unexpected repeat surgery may be because of persistent or recurrent symptoms, progression of the underlying disease, medical comorbidity, or other patient-level factors. In addition, repeat surgery may be because of complications of the initial operation, such as infection or spinal fluid leak, and may be associated with hospital characteristics and surgeon experience. Variation in repeat spinal surgery rates, therefore, may serve as a potential marker of the quality of surgical care. However, little is known about hospital- and surgeon-level variation in reoperation rates.

We selected lumbar herniated disc surgery for evaluating population-level variation in rates of repeat spinal surgery. Systematic reviews have highlighted the generally favorable outcomes after lumbar discectomy [1]. It is a common and relatively straightforward procedure with low rates for complications, for which we might anticipate consistent rates of repeat surgery across hospitals and surgeons. Benchmark data for repeat surgery are available from the Spine Patient Outcomes Research Trial (SPORT), a study with rigorously selected patients recruited from 11 states, and 53 different orthopedic and neurological surgeons [2,3]. Reoperation rates similar to SPORT would suggest that routine clinical practice approaches the idealized practice conditions in SPORT. Repeat surgery rates significantly higher than SPORT may suggest differences in patients' conditions or expectations, difference in hospital factors related to surgery, or surgeons' technical expertise. In total, SPORT published data on the rate of repeat surgery after decompression surgery for herniated discs under ideal clinical trial conditions. We aimed to determine how well clinical practice approximates this standard.

Using a statewide inpatient discharge registry that allowed us to link successive episodes of care for the same patient across multiple years and institutions, we sought to examine variation in reoperation rates among hospitals and surgeons after lumbar decompressions for herniated disc, compare these rates to rates published for SPORT, and identify the percentage of hospitals or surgeons with reoperation rates substantially above the reoperation rate of SPORT benchmarks.

Methods

Data source

The Washington State Comprehensive Hospital Abstract Reporting System (CHARS) is a mandatory inpatient discharge registry of nonfederal hospitals maintained by the Washington State Department of Health [4]. Hospitals submitting data to CHARS receive quarterly quality reports that they then certify as being 95% accurate for reporting discharges.

Study period

We identified index cases from 1997 to 2007. The start of this period was selected because spine surgery practice changed in several important ways in 1997. This was the first calendar year following the Food and Drug Administration's approval of interbody fusion cages [5]; a time when substantial revisions were made to billing codes for spinal procedures; a time shortly after publication of the Agency for Health Care Policy and Research's guidelines for management of acute low back pain [6]; and a time marking the introduction of minimally invasive techniques for discectomy [7]. In addition, a starting time of 1997 allowed us to create a relatively homogeneous cohort of patients having a first-time operation by using previous years of data to exclude patients who had an earlier lumbar spine operation.

Study population

We included adults (aged 20 or older) who underwent an initial inpatient thoracolumbar, lumbar, or lumbosacral decompression procedure for herniated disc. We defined decompression procedures as those that included a discectomy, laminectomy, and/or laminotomy. Patients undergoing other types of spinal operations, including fusion procedures, were excluded. We focused on decompression for herniated discs because it is a clear diagnosis, with established clinical efficacy, represents a relatively simple procedure, and is common among younger patients with low comorbidity [8]. Patients who had secondary diagnoses for more severe degenerative pathology, such as scoliosis, spondylolisthesis, or stenosis, were excluded, as were patients with nondegenerative spinal conditions, such as fractures, spinal cord injuries, inflammatory spondylopathy, and osteoporosis. In addition, patients who had degenerative disc disease, axial back pain, or spondylosis in the absence of a herniated disc diagnosis were excluded.

Patients were identified using diagnosis and procedure codes from the *International Classification of Diseases, Ninth Revision, Clinical Modification* [9,10]. We excluded patients who were not admitted for decompression for herniated disc and those who, within the preceding 10 years, had any prior lumbar surgery. We also excluded patients with any procedure code implying a previous lumbar operation (such as "reopening of laminectomy site," "refusion," or "removal of an internal fixation device"). Finally, we excluded patients if they had inpatient diagnosis or procedure codes for trauma, vertebral fracture, or dislocation (include those undergoing vertebroplasty, kyphoplasty, or spinal fracture repair), neoplasm, human immunodeficiency virus or immune deficiency, intraspinal abscess, osteomyelitis, infection, pregnancy, and cervical or thoracic spine diagnosis or procedures in the previous year.

Inclusion of surgeons and hospitals

We were primarily interested in the variation among individual surgeons and hospitals in reoperation rates. We included all hospitals and attending surgeons who performed at least one inpatient lumbar decompression for herniated disc during the study period.

Measuring reoperations

The primary outcome was the first instance of any second lumbar spine operation (ie, "reoperation"). This included any subsequent inpatient lumbar spine procedure and not necessarily a repeat of the same procedure or one performed at the same vertebral level. Reoperations within 90 days, 1 year, and 4 years of discharge after the initial decompression were examined. Each reoperation was counted as a reoperation for the hospital or surgeon performing the initial surgery and not as an index case or reoperation for another hospital or surgeon.

Potentially confounding factors

Differences in reoperation rates among providers may be partly because of differences in patient characteristics. That is, some providers may operate on more difficult and complex patients relative to their peers. We, therefore, adjusted the reoperation rates for differences because of patient age, sex, comorbidity, and primary insurance. We used Quan's "enhanced" version of the Charlson index (categorized "none," "one," and "two or more") to adjust comorbidity, applying it to admissions at or in the year preceding each index visit [11]. Insurance was coded as "workers' compensation," "private (health maintenance organization/commercial)," or "public (Medicare/Medicaid)." Variables for race or ethnicity were not provided in CHARS during the study years.

Analysis

Bivariate associations between patient characteristics and reoperations were assessed using chi-square or Student *t* test. We examined reoperation rates among providers at 90 days, 1 year, and 4 years using logistic regression analysis. For each time point, we included only those patients who had at least the necessary follow-up time available. For example, patients who had an initial operation in 2006 were not eligible to be assessed for the 4-year reoperation outcomes because we received data only through 2007. As a result, the number of cases analyzed for each follow-up interval varied.

In addition to analyzing unadjusted reoperation rates, we conducted multivariate analyses to adjust potential confounding variables. For each follow-up interval, a generalized linear and latent logistic regression model with a random intercept for each hospital was used to estimate the probability of reoperation for each patient while adjusting for age, sex, comorbidity, and insurance. This approach adjusts the standard errors of the regression coefficients to account for residual "clustering" of patients with common characteristics within certain hospitals. For example, a given hospital may have an over-representation of certain demographic groups, types of insurance, or prognoses, resulting in a more homogeneous sample and more similar outcomes than among a general random sample of patients [12,13]. The multilevel models also account for a tendency of hospitals with a small volume of cases to have crude event rates that take extreme values because of sampling variability rather than an underlying systematic performance. Bayesian estimates of hospital-specific rates adjust, or "shrink" estimates for small-volume hospitals toward the overall mean rates.

To examine variation in surgeon reoperation rates, we then added a random-effect term to the previous model that represents the influence of each surgeon "nested" within each of the hospitals he/she was operated in. Because 25% of the surgeons attended more than one hospital and were therefore not perfectly "nested," we also examined an alternative "crossed" specification in which we included the hospital effects separate from the surgeon effects. Because the results for the two approaches were broadly similar, we report only the nested model because it is more intuitive to consider surgeons nested within hospitals. For all models, we assumed a normal distribution of the random-effect parameters. Model specification is presented in the Appendix.

To describe the risk of reoperation over time, we also performed a "time-to-event" survival analysis (with the event of interest being reoperation) [14]. We used the time to first reoperation as the outcome, measured as the number of days between discharge of the index procedure and admission for the first reoperation. Survival models examine differences in the risk of reoperation by examining all person-years of follow-up, and thus increase the sample size by including patients with fewer than 4 years of follow-up. For this approach, we included the same covariates that were used in the logistic models. Analysis was performed using Stata-MP, version 11(command GLLAMM, which uses an estimation procedure that is robust to uneven and small cluster sizes) with hypothesis testing performed using a two-sided alpha level of 0.05.

We adjusted the predicted probability of reoperation by applying the mean distributions for age, sex, comorbidity, and insurance to the estimates of the logistic regression models described previously. Predicted reoperation estimates were reported, along with the 95% empirical Bayes confidence intervals (CIs) [12] for reoperation within each hospital and surgeons within each hospital based on the predicted probability of reoperation.

SPORT benchmark

We compared the probability of reoperation in our cohort to the probabilities reported in the SPORT study. In SPORT, patients had positive physical findings, correlated images (magnetic resonance imaging), and 6 to 12 weeks' duration of symptoms. Furthermore, all patients underwent a formal shared decision-making process in which their values and preferences were elicited; an unusually high standard of informed consent. The rates of reoperation observed in SPORT were 2% at 90 days, 4% at 1 year, and 10% at 4 years [2,3,15]. For each of these time points, we calculated the number and percent of hospitals and surgeons in our study whose CIs for reoperation were entirely above these SPORT benchmarks.

Results

Study population

A total of 34,623 patients were identified as having an initial inpatient decompression for lumbar disc herniation between 1997 and 2007; however, 5,923 (17%) were excluded for reasons shown in Table 1. The predominant reason for exclusion was lumbar surgery in the previous 10 years. Excluded patients were older (51.9 vs. 48.2 years, $p<.001$), less likely to be privately insured (44.0% vs. 59.9%, $p<.001$), and more likely to have a comorbidity score greater than one (30.8% vs. 16.5%, $p<.001$) compared with those who were not excluded (not shown). The 4-year reoperation rate among excluded patients was also significantly higher than that of included patients (20.9% vs. 14.7%, $p<.001$).

After exclusions, 29,529 patients had an initial inpatient decompression during the study period, including 19,927 with 4 years of postoperative observation, 27,133 with 1 year of observation, and 28,916 with 90 days of observation. The index operations were performed by 1,096 surgeons with a median of 150 decompressions during the study period within 56 hospitals. The hospitals performed a median of 1,155 decompressions during the study period. The mean age of the cohort was 47.5 years; 61% were privately insured; and about 15% had a comorbidity index greater than zero (Table 2).

Reoperation rates

Female sex, comorbidity, and workers' compensation, or public insurance were associated with higher risk of reoperation within 4 years (Table 3). Older age was associated with higher short-term reoperation risk and lower long-term risk. The results of the survival model were similar to those obtained from the logistic regression models and are broadly consistent with rates reported from other studies, as annotated in Fig. 1.

Fig. 2 presents the age-, sex-, insurance-, and comorbidity-adjusted reoperation rates at 90 days, 1 year, and 4 years, for individual hospitals and surgeons within hospitals relative to the SPORT benchmarks. Among hospitals, we found that the adjusted mean rate of reoperation was 1.9% at 90 days (95% CI, 1.2–3.1; ranging from 1.1% to 3.4%), 6.4% at 1 year (95% CI, 3.9–10.6; ranging from 2.8% to 12.5%), and 13.8% at 4 years (95% CI, 8.8–19.8; ranging from 8.1% to 24.5%). Adjusting for hospital effects, the adjusted mean reoperation rates of surgeons were 1.9% at 90 days (95% CI, 1.4–2.4; ranging from 1.2% to 4.6%), 6.1% at 1 year (95% CI, 4.8–7.7%; ranging from 4.3% to 10.5%), and 13.2% at 4 years (95% CI, 11.3–15.5%; ranging from 10.0% to 19.3%). We further found that 10.7%, 44.6%, and 43.4% of the hospitals exceeded the SPORT benchmarks at 90 days, 1 year, and 4 years, respectively. Controlling for hospital effects, we found that 0.1%, 19.8%, and 15.8% of surgeons with a minimum of 10 cases exceeded the SPORT benchmark at 90 days, 1 year, and 4 years, respectively. Excluding patients who had any comorbidity did not substantially change our conclusions.

Examination of the multilevel models demonstrated that the variation among surgeons was greater than that of

Table 1
Reason for exclusions and the rates of lumbar spine reoperation among patients excluded from the study

Exclusion factors (not mutually exclusive)	Number excluded (n=5,091)	Number undergoing repeat lumbar spine operation through all available follow-up among excluded patients (percent within exclusion category)
Cancer in previous year	277	45 (16.2)
Trauma in previous year	427	90 (21.1)
Drug abuse in previous year	89	20 (22.5)
Neurological impairment in previous year	146	30 (20.5)
Human immunodeficiency virus or immune deficiency in previous year	15	3 (20.0)
Intraspinal abscess in previous year	3	0 (0)
Osteomyelitis in previous year	8	2 (25.0)
Pregnancy in previous year	196	37 (18.9)
Nondegenerative spinal diagnosis in previous year (vertebral fracture, spinal cord injury, congenital anomaly, inflammatory spondylopathy, osteoporosis)	171	1,178 (28.6)
Lumbar spine surgery in previous 10 y	4,123	55 (32.3)
Any of the above	5,091	1,349 (26.5)

Table 2
Characteristics of patients undergoing an initial and repeat (within 4 y) inpatient lumbar decompression surgery without fusion for disc herniation in Washington State between 1997 and 2007

Characteristics	Index surgery, column percentages reported	4-Year follow-up (n=19,927), row percentages reported unless otherside specified: No lumbar spine reoperation (n=16,994)	Any lumbar spine reoperation (n=2,933)	p Value for difference between groups
Number of patients	19,927	16,994 (85.3%)	2,933 (14.7%)	—
Age, mean (SD)	47.5 (14.2)	47.5 (14.3)	47.1 (13.6)	<.048
Sex, %				
Male	11,810 (59.3)	10,158 (86.0)	1,652 (14.0)	.001
Female	8,117 (40.7)	6,836 (84.2)	1,281 (15.8)	
Comorbidity, %				
None	16,998 (85.3)	14,569 (85.7)	2,429 (14.3)	<.000
1	2,375 (11.9)	1,975 (83.2)	400 (16.8)	
2+	554 (2.8)	450 (81.2)	104 (18.8)	
Number of all diagnosis codes at index, mean (SD)	6.5 (1.42)	6.51 (1.8)	6.62 (1.7)	.003
Number of all procedure codes at index, mean (SD)	4.38 (0.93)	4.38 (0.9)	4.40 (0.9)	.185
Insurance, %				
Private	12,161 (61.0)	10,566 (86.9)	1,595 (13.1)	<.001
Public	4,017 (20.2)	3,425 (85.3)	592 (14.7)	
Workers' compensation	3,748 (18.8)	3,002 (80.1)	746 (19.9)	
Length of stay, mean days (SD)	1.74 (1.4)	1.73 (1.4)	1.79 (1.4)	.033

SD, standard deviation.

hospitals at all follow-up time points. For example, the variance estimate of the surgeon-level random effects for 90-day reoperation was 0.173 compared with 0.116 for hospitals. The addition of surgeon-level random-effects parameters to a ''null'' model containing random effects for hospitals only reduced the variance estimate for hospitals by 21.6% at 90 days, 43.1% at 1 year, and 45.5% at 4 years.

Characteristics of reoperations

We found that 82% of the reoperations performed within 90 days were performed by the same surgeon who performed the initial surgery. This percentage declined to 75% at 1 year and 59% at 4 years. The most common diagnoses at the time of reoperation remained herniated disc (70.6%), followed by spondylosis (13.9%), stenosis (11.1%), listhesis (3.8%), and scoliosis or other diagnosis (<1%). The most common procedures at the time of reoperation were decompressions without fusion (73%) and fusion with or without decompression (25.7%).

Discussion

Even after adjusting patient characteristics, mean reoperation rates after decompression surgery for herniated disc varied substantially among hospitals and surgeons. Furthermore, the rates for many hospitals and surgeons exceeded the long-term SPORT reoperation benchmarks. Variations in reoperation rates may be the result of professional uncertainty about criteria or indications for repeat surgery, surgical complications, differences in postoperative care, potential problems with quality of care, differences in surgical training, practice philosophy, local practice patterns, and patient expectations. They may also reflect individual surgeons' thresholds for advancing failed patients into procedures that are perceived to be more ''definitive,'' such as spinal fusion. Wide variation in reoperation rates highlights the need for new research on outcomes in lumbar surgery and a growing consensus within surgeon organizations that reporting outcomes, as opposed to process measures alone, is important for improving safety [16].

Although many quality improvement efforts focus on reducing variations in care among hospitals, our study suggests that surgeon-level differences are also an important source of variation, particularly when examining long-term outcomes. Surgeon factors likely account for more variation than hospital factors, and the variability in reoperation rates increases with longer follow-up. An advantage of the empirical Bayesian approach is that it allows for a cluster-specific inference. On the other hand, because the estimates for relatively small-volume hospitals and surgeons are adjusted more toward the statewide mean and have less precision, their estimates tend to be more uninformative. Furthermore, the statistical uncertainty surrounding individual surgeon's repeat surgery rates is large and may

Table 3
Multivariate models to estimate reoperation after lumbar discectomy in Washington State between 1997 and 2007

Characteristics	90-d Reoperation risk based on logistic regression (95% CI)*	1-y Reoperation risk based on logistic regression (95% CI)*	4-y Reoperation risk based on logistic regression (95% CI)*	Any reoperation based on time-to-event analysis (95% CI)†
Number of eligible patients	28,914	27,132	19,926	29,492
Age group				
20–40	1.00 (ref.)	1.00 (ref.)	1.00 (ref.)	1.00 (ref.)
41–60	1.32 (1.09–1.60)	1.18 (1.05–1.31)	1.01 (0.92–1.10)	1.05 (0.99–1.13)
61–80	1.47 (1.14–1.91)	1.17 (1.00–1.38)	0.89 (0.77–1.03)	0.99 (0.90–1.10)
80+	2.25 (1.38–1.91)	1.28 (0.89–1.85)	0.77 (0.53–1.14)	0.80 (0.61–1.07)
Female	1.33 (1.14–1.56)	1.25 (1.13–1.37)	1.22 (1.13–1.33)	1.19 (1.12–1.26)
Any comorbidity				
None	1.00 (ref.)	1.00 (ref.)	1.00 (ref.)	1.00 (ref.)
One	1.22 (0.99–1.53)	1.43 (1.25–1.63)	1.26 (1.12–1.42)	1.28 (1.17–1.39)
Two or more	1.48 (1.03–2.11)	1.57 (1.24–1.99)	1.49 (1.19–1.87)	1.45 (1.24–1.70)
Insurance				
Private	1.00 (ref.)	1.00 (ref.)	1.00 (ref.)	1.00 (ref.)
Public	1.16 (0.92–1.44)	1.21 (1.05–1.40)	1.20 (1.05–1.36)	1.12 (1.02–1.23)
Workers' compensation	0.79 (0.62–1.00)	1.65 (1.46–1.87)	1.72 (1.56–1.91)	1.52 (1.41–1.64)
Variance estimate of random effects for hospitals, $\hat{\sigma}^2$	0.116	0.078	0.055	0.066†
Variance estimate of random effects of surgeon within hospital, $\hat{\nu}^2$	0.173	0.101	0.061	NA

CI, confidence interval; ref., reference; NA, not applicable.
* Odds ratio based on generalized linear and latent mixed models using Stata-MP command (GLLAMM).
† Hazard ratio based on survival models, hospital random-effects variance reported as theta (θ).

not be informative for identifying those who are above the overall state mean. As a result, we do not advocate using CHARS data to profile individual surgeons or for implementing sanctions. Nevertheless, data on reoperation rates for individual providers may be useful to stimulate practice improvements and inform patients about the risks of surgery [17–20]. This approach also may be important for more invasive types of spinal procedures where the reoperation may be more common. Future research should seek to identify patient characteristics, operative features, and provider factors that minimize variation in repeat surgery.

The SPORT, the largest ever randomized clinical trial for spine surgery, in which well-established surgeons and hospitals performed surgery on carefully selected patients, may

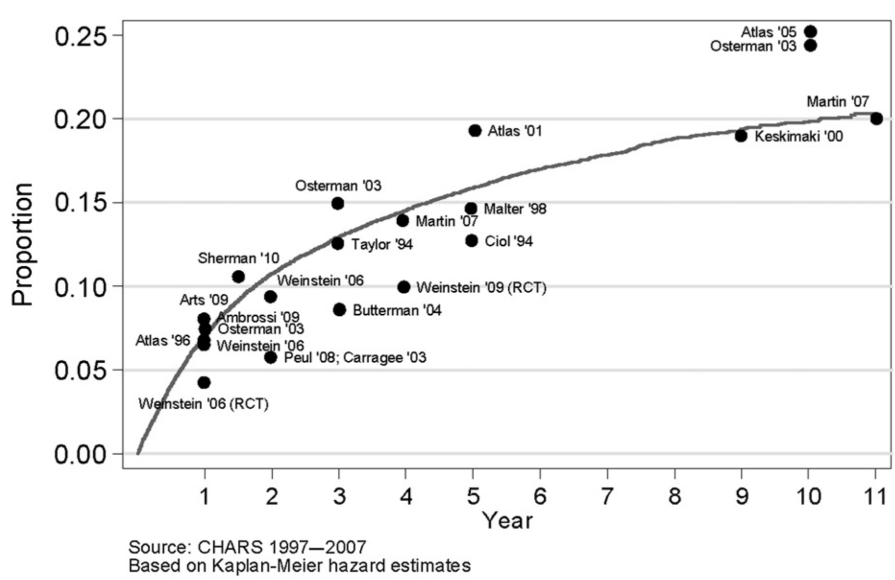

Fig. 1. Eleven-year cumulative incidence of reoperation after decompression surgery for herniated disc in Washington State (solid line). The figure is annotated with point estimates for reoperation rates from other studies on decompression surgery (clinical and administrative). CHARS, Comprehensive Hospital Abstract Reporting System; RCT, randomized control trial.

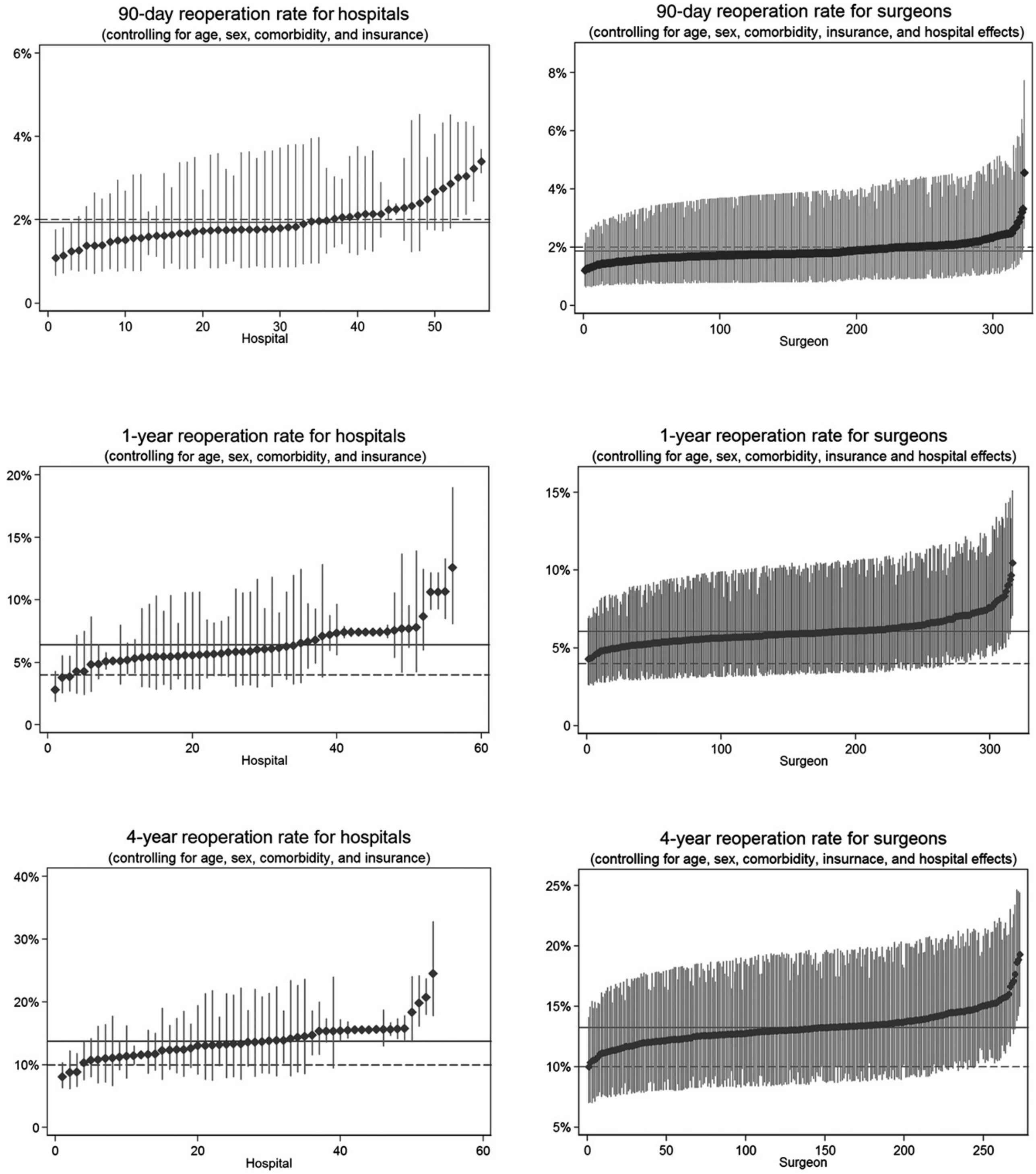

Fig. 2. The reoperation rates within 90 days, 1 year, and 4 years after inpatient lumbar decompression surgery for herniated disc. Each spike represents 95% Bayesian confidence interval for the probability of reoperation within hospitals (figures on left) and surgeons nested within hospitals (figures on right) in Washington State. For the purposes of presentation, we excluded those surgeons who have fewer than 10 cases (because of their uninformative low volumes, we could not identify any of them as being significantly above or below the Spine Patient Outcomes Research Trial [SPORT] benchmark). The solid horizontal line represents the overall reoperation rate, whereas dashed lines represent the reoperation benchmark from SPORT.

provide a standard for how ''safe'' back surgery can be under optimal conditions. We examined how back surgery in routine care compares to the SPORT benchmark for reoperations. The 1- and 4-year reoperation rates observed in Washington State exceeded those of the SPORT benchmarks. Differences between the fastidiously selected patients, select surgeons, and standardized techniques of a clinical research trial, and the more heterogeneous patients, surgeons, and techniques of clinical practice, may explain the observed differences. Variation in subject selection, surgical indications, technical skills, and follow-up protocols in clinical studies point to the importance of supplementing clinical trial data with population-based research when trying to generalize the benefits of a clinical intervention.

Previous studies have reported 1- to 10-year reoperation rates between 9.5% and 25%, depending on risk factors, follow-up duration, and insurance [21–36]. Contrary to concerns that administrative data may overestimate reoperation rates because of miscoding, we found that overall rates from administrative data and nonrandomized clinical trials are generally similar. Nonetheless, several limitations are noted. We cannot account for migration of patients into or out of Washington State and could not account for ambulatory discectomy. Ambulatory discectomies accounted for more than 24% of total discectomies in 2002 and are not included in CHARS [10]. Some reoperations may be unavoidable or planned consequences of the initial procedure and, therefore, not indicative of complications, or suggestive of quality problems. However, planned reoperations are more common in trauma or fusion surgery than for elective decompression. Long-term reoperations may also reflect the willingness of the surgeon performing the reoperation to operate and not necessarily the quality of the initial procedure. Undergoing a reoperation, however, implies persistent or recurring symptoms. We cannot differentiate severity of disease, level of pain, or specific procedures, such as minimally invasive techniques, on the basis of *International Classification of Diseases, Ninth Revision, Clinical Modification* codes. Finally, although we cannot exclude the possibility that unmeasured patient characteristics may result in some differences among providers, we have limited this possibility by restricting our study to a relatively homogenous cohort with a single surgical indication, low comorbidity, no previous lumbar surgery, and adjustment for demographic and insurance characteristics.

The National Quality Forum has identified safety as a national priority, ‘‘aiming for ‘zero’ harm wherever and whenever possible’’ and has further included spine surgery in its recommended areas of concentration for overuse measurement [37]. High rates of repeat surgery may point to unsuccessful initial surgery, potentially avoidable complications of surgery, new disc herniations, and progressive disease. High early repeat surgery rates, particularly among older patients, may be because of potentially preventable complications of surgery. High 4-year reoperation rates may suggest poorly indicated index surgery, residual or recurrent symptoms, or progressive disease. The decision to have an operation is an important irreversible choice, and patients seeking relief for low back pain may underestimate the associated risk-benefit trade-offs [38]. Quality measures based on empirical performance data may help patients make better choices about whether and where to have surgery. Data on reoperation rates may help patients to be better informed of the risks and to guide policies to make spinal surgery safer and its effects more durable.

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Appendix

Model specification and alternative specification

1. Specification of the nested model used to estimate mean hospital reoperation rates and their CIs

$$\log\left(\frac{\mu_{ik}^{\kappa_k}}{1-\mu_{ik}^{\kappa_k}}\right)=\alpha+\kappa_k+\beta X_{ik}\quad \kappa_k\sim \mathrm{Norm}\left(0,\sigma^2\right)$$

where μ represents the probability of reoperation for patient i, operated in hospital k. X represents a vector of covariates for age, sex, comorbidity, and insurance; α combined with K_k represents the intercept for each hospital. We further received predicted values and variances for the hospital random effects determined using the best linear unbiased predictor. Using these predicted random-effects variances, we then formed 95% confidence bands using

$$95\%\ \mathrm{CI}_\kappa=\left(\hat{\kappa}_k-1.96\sqrt{\hat{\sigma}_k^2},\quad \hat{\kappa}_k+1.96\sqrt{\hat{\sigma}_k^2}\right)$$

where σ_k represents the estimated posterior uncertainty in K_k.

2. Specification of the nested model used to estimate mean reoperation rates and CIs for surgeons within each of the hospitals he/she operates in.

$$\log\left(\frac{\mu_{ijk}^{\gamma_{k:j},\kappa_k}}{1-\mu_{ijk}^{\gamma_{k:j},\kappa_k}}\right)=\alpha+\gamma_{k:j}+\kappa_k+\beta X_{ijk}\quad \kappa_k\sim \mathrm{Norm}\left(0,\sigma^2\right)\quad \gamma_{k:j}\sim \mathrm{Norm}\left(0,\upsilon^2\right)$$

where μ represents the probability of reoperation for patient i, operated on by surgeon j, at hospital k. X represents a vector of covariates for age, sex, comorbidity, and insurance; α combined with κ_k and $\gamma k{:}j$ represents the intercept for each hospital and surgeon within hospitals, respectively. The coefficient estimates from these models are presented in Table 3. We further received predicted values and variance for each of the random effects determined using the best linear unbiased predictor. Using these predicted random-effects variances, we then formed 95% confidence bands for the combined random effects using

$$95\%\ \mathrm{CI}_{\kappa:j}=\left(\hat{\gamma}_{k:j}+\hat{\kappa}_k-1.96\sqrt{\hat{\upsilon}_{k:j}^2+\hat{\sigma}_k^2},\quad \hat{\gamma}_{k:j}+\hat{\kappa}_k+1.96\sqrt{\hat{\upsilon}_{k:j}^2+\hat{\sigma}_k^2}\right)$$

where σ_k represents the estimated posterior uncertainty in κ_k, and $v_{k:j}$ represents uncertainty in $\gamma_{k:j}$.

3. The above model specification may become somewhat problematic because some surgeons operate at more than one hospital and are thus not truly nested. An alternative specification, the ''crossed'' model, alters the nesting assumption by treating the hospital random effects separate from the surgeon random effects:

$$\log\left(\frac{\mu_{ijk}^{\gamma_j,\kappa_k}}{1-\mu_{ijk}^{\gamma_j,\kappa_k}}\right)=\alpha+\gamma_j+\kappa_k+\beta X_{ijk}\quad \kappa_k\sim \mathrm{Norm}\left(0,\sigma^2\right)\quad \gamma_j\sim \mathrm{Norm}\left(0,\upsilon^2\right)$$