# Do Hospitals Performing Frequent Neuraxial Anesthesia for Hip and Knee Replacements Have Better Outcomes?

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## ABSTRACT

**Background:** Neuraxial anesthesia is increasingly recommended for hip/knee replacements as some studies show improved outcomes on the individual level. With hospital-level studies lacking, we assessed the relationship between hospital-level neuraxial anesthesia utilization and outcomes.

**Methods:** National data on 808,237 total knee and 371,607 hip replacements were included (Premier Healthcare 2006 to 2014; 550 hospitals). Multivariable associations were measured between hospital-level neuraxial anesthesia volume (subgrouped into quartiles) and outcomes (respiratory/cardiac complications, blood transfusion/intensive care unit need, opioid utilization, and length/cost of hospitalization). Odds ratios (or percent change) and 95% CI are reported. Volume-outcome relationships were additionally assessed by plotting hospital-level neuraxial anesthesia volume against *predicted* hospital-specific outcomes; trend tests were applied with trendlines' $R^2$ statistics reported.

**Results:** Annual hospital-specific neuraxial anesthesia volume varied greatly: interquartile range, 3 to 78 for hips and 6 to 163 for knees. Increasing frequency of neuraxial anesthesia was not associated with reliable improvements in any of the study's clinical outcomes. However, significant reductions of up to –14.1% (95% CI, –20.9% to –6.6%) and –15.6% (95% CI, –22.8% to –7.7%) were seen for hospitalization cost in knee and hip replacements, respectively, both in the third quartile of neuraxial volume. This coincided with significant volume effects for hospitalization cost; test for trend $P < 0.001$ for both procedures, $R^2$ 0.13 and 0.41 for hip and knee replacements, respectively.

**Conclusions:** Increased hospital-level use of neuraxial anesthesia is associated with lower hospitalization cost for lower joint replacements. However, additional studies are needed to elucidate all drivers of differences found before considering hospital-level neuraxial anesthesia use as a potential marker of quality. (Anesthesiology 2018; 129:428-39)

WHILE volume-outcome relationships have been the subject of many studies across a number of specialties,[1–3] this topic remains largely unstudied in the field of anesthesiology in general and in the perioperative care of joint replacement recipients in particular. In this context, a number of population-based studies and meta-analyses have advanced the concept that the use of regional anesthesia, specifically neuraxial anesthesia, in joint replacements may be associated with improved perioperative outcomes on a patient level.[4–10] While still debated, government health-care agencies have started to recommend the use of neuraxial anesthesia in joint replacement recipients whenever possible.[11] Although critics point to the lack of adequately

### What We Already Know about This Topic

- Neuraxial anesthesia is being used more frequently for elective hip and knee replacements
- It is unclear whether increasing rates of hospital-level use of neuraxial anesthesia are associated with beneficial medical or economic outcomes

### What This Article Tells Us That Is New

- National administrative data demonstrate that increasing frequency of neuraxial anesthesia use is not associated with improved clinical outcomes
- However, hospitals using neuraxial anesthesia frequently did observe a decrease in inpatient costs compared to hospitals that did not use neuraxial anesthesia at all

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powered randomized trials and the risk of confounding burdening large observational studies, the fact remains that in addition to an increasing body of literature suggesting superiority, virtually no evidence of inferiority of neuraxial *versus* general anesthesia exists in this patient group.[12]

To date, however, the question whether neuraxial anesthesia can influence economic and medical outcomes positively has only been evaluated on an individual patient level. Thus, no conclusions can be drawn on how outcomes are affected by the utilization of neuraxial anesthesia in general and at various volumes on the hospital level.

In this study, we therefore attempted to elucidate if the use of neuraxial anesthesia in hip and knee replacement patients on a hospital level is associated with differential outcomes compared to no use (study aim I) and at different volumes (study aim II). If such a relationship exists, implications may be far-reaching for the over 1 million annual joint replacements performed in thousands of hospitals throughout the United States. Further, researchers, policymakers and administrators may apply this information in the consideration of anesthesia type as a modifiable risk factor for complications and as a marker of practice quality.

We hypothesized that when using nationwide data, we would find (1) differences in medical and economic outcomes between hospitals that utilize neuraxial anesthesia for joint replacement surgery *versus* those that do not, and (2) that a volume-outcome relationship exists.

## Materials and Methods

### *Data Source, Study Design, and Study Sample*

Approval was obtained by the Institutional Review Boards of the Hospital for Special Surgery (New York, New York, No. 2012-050-CR2) and the Icahn School of Medicine at Mt. Sinai (New York, New York, No. 14-00647). We used data from the nationwide all-payer Premier Healthcare[13] database (Premier Inc., Charlotte, North Carolina) containing detailed billing data on hospitalizations. The study sample included patient records with an *International Classification of Diseases, Ninth Revision* procedure code for primary hip (81.51) or knee (81.54) replacement from 2006 to 2014 and a diagnosis of osteoarthritis (*International Classification of Diseases, Ninth Revision* diagnosis code 715). Patients were excluded if they underwent a nonelective procedure (n = 67,782), had unknown sex (n = 14), had unknown discharge status (n = 601), had an outpatient procedure (n = 4,090), were treated at a hospital performing fewer than 30 primary lower joint replacements overall (n = 321), did not have billing for perioperative utilization of opioids (n = 54,910; this was applied as opioid utilization is one of the main outcomes of interest), and/or an *International Classification of Diseases, Ninth Revision* procedure code for a revision (81.53 hip/81.55 knee) procedure during the same hospitalization (n = 151).

### *Study Variables*

All study variables including main effects of interest and outcomes were specified *a priori* in an analysis plan. The main effect of interest was the hospital-level absolute volume of neuraxial anesthesia for patients undergoing lower joint replacements; this was dichotomized (one variable: yes/no neuraxial anesthesia use) as well as subgrouped into quartiles of absolute volume of neuraxial anesthesia by hospital (one variable with five categories, one for each quartile and a "no neuraxial use" category), combining patients who received neuraxial anesthesia and neuraxial/general anesthesia. We recognize that this step may lead to an underestimation of potential hospital-level effects as on the individual level, effect estimates from the comparison between neuraxial and general anesthesia are stronger than those from the comparison between neuraxial/general and general anesthesia. However, separating hospital specific volume of neuraxial and neuraxial/general anesthesia would mean that the same hospitals could potentially belong to two different volume groups based on quartiles of volume: *e.g.*, a hospital performing very few cases under neuraxial anesthesia may be in the lowest quartile for neuraxial anesthesia volume but in the third quartile for neuraxial/general volume. We therefore opted for the current strategy as we preferred a conservative over an overestimation of effects.

The main outcomes of interest were respiratory complications, cardiac complications, need for blood transfusion, admission to an intensive care unit, opioid utilization, cost of hospitalization, and length of hospital stay. Opioid utilization was assessed by converting billed opioids into oral morphine equivalents, calculated using the Lexicomp (Wolters Kluwer Clinical Drug Information, Inc., USA) "opioid agonist conversion" and the GlobalRPH (David McAuley, Pharm.D., USA) "opioid analgesic converter."[14,15] Cost data in the Premier database are submitted by hospitals that participate in Premier (determined by each hospital using their own cost accounting systems). A smaller number of hospitals submit charges that are then converted into costs using Medicare Cost to Charge Ratios.[16] The specific complications were selected based on strengths of association as well as prevalence of outcomes found in our previously published individual-level models.[6] Looking at both measures matters, because a strong association combined with a low prevalent outcome can be as important on the population level as a weak association with a highly prevalent outcome.

Patient-related variables included age, sex, race (white, black, Hispanic, other), year of procedure, and insurance type (commercial, Medicaid, Medicare, uninsured, other). Hospital-level variables were hospital location (urban, rural), hospital size (fewer than 300, 300 to 499, 500 or more beds), hospital teaching status, and the annual number of total hip/knee replacements performed per hospital. Anesthesia/analgesia-related variables captured the use of general anesthesia, peripheral nerve block, patient-controlled analgesia, and nonopioid analgesics (intravenous acetaminophen, gabapentin/pregabalin, nonsteroidal antiinflammatory drugs, cyclooxygenase-2 inhibitors, and ketamine). Overall comorbidity burden was assessed using the adaptation by Quan *et al.* of the

Deyo-Charlson Comorbidity Index.[17] Next to this index we included separate variables for sleep apnea, obesity, substance use/abuse (including smoking), chronic pain conditions, and psychiatric comorbidity variables as they may influence perioperative outcome and particularly opioid utilization.

### Statistical Analysis

Patients who underwent a total hip or knee replacement were analyzed separately. Univariable associations between hospital-level neuraxial anesthesia volume and study variables were analyzed using the chi-square test and Kruskal-Wallis test for categorical and continuous variables, respectively. To mainly address study aim I (and indirectly study aim II), multilevel, multivariable regression models were fitted to measure associations between hospital-level neuraxial anesthesia volume (compared to hospitals that do not use neuraxial anesthesia) and outcomes. Multilevel models account for correlation of patients within hospitals (*i.e.*, patients are "nested" within each hospital), and fit one regression line for each hospital, based on all patients within a given hospital.[18] This adjustment is necessary as patients within hospitals may be correlated as they may experience similar care. All included hospitals had a sufficient number of patients (n > 30) according to the recommended sample size for multilevel models to reduce bias.[19]

Covariates in the multilevel models were determined by clinical importance and/or univariable significance at the $P <$ 0.15 level. Analyses were first performed using a dichotomous measure of hospital-level use of neuraxial anesthesia, after which analyses were performed using quartiles of hospital-level volume of neuraxial anesthesia to assess a volume-outcome relationship. In a sequential modeling process, we fitted models using just hospital-level neuraxial anesthesia volume (model I), subsequently adding patient-level factors (model II) and finally adding hospital-level variables (model III). This approach allows for a better understanding of the role of both patient-level and hospital-level factors in any potential volume-outcome effect. Moreover, as adjusting for hospital factors may also adjust away effects of processes of care (such as use of neuraxial anesthesia), sequential modeling may further facilitate interpretation when comparing model II to model III.

In addition, to directly address study aim II, linear trend in odds ratios for hospital-level neuraxial anesthesia volume quartiles was tested by using the CONTRAST statement implemented in SAS (SAS Institute, USA),[20] *i.e.*, to test whether higher volumes of hospital-level use of neuraxial anesthesia are associated with differential outcomes. Moreover, we estimated the percent variance in outcomes explained by unspecified and specified (hospital-level neuraxial anesthesia volume) hospital-level effects by calculating the intraclass correlation coefficients.

We further directly addressed study aim II by applying a graph where hospital-level neuraxial anesthesia volume was plotted (x-axis) against *predicted* hospital-specific outcomes (y-axis) extracted from the multivariable models described above. This was only applied for the outcomes with the strongest effect estimates and most suggestive of a volume-outcome relationship. Moreover, hospitals that did not utilize neuraxial anesthesia were excluded from these graphs. The volume-outcome relationship was formally assessed with a trend test to evaluate whether higher neuraxial anesthesia volume was indeed associated with more beneficial outcomes. $R^2$ statistics are additionally reported as a measure of goodness of fit of each trendline.

Although all study variables (including main effects of interest and outcomes) were specified *a priori* based on our study group's previous study,[6] we report adjusted odds ratios and Bonferroni adjusted 95% CI, recognizing an increased likelihood of type II errors. For all models, we used the PROC GLIMMIX feature in SAS v9.4 statistical software; for opioid utilization, cost of hospitalization, and length of hospital stay, the gamma distribution with a log link function was applied as these variables are skewed.[21,22]

### Analyses Presented

Analyses presented in the manuscript reflect hospital-level neuraxial anesthesia volume as the main effect. However, as this is highly dependent on actual surgical volume, we initiated analyses using hospital-level *percent* neuraxial anesthesia (*i.e.*, the percentage of hip/knee replacements performed under neuraxial anesthesia) use as the main effect (presented in Supplemental Digital Content 1, http://links.lww.com/ALN/B733). Moreover, in our results, we present effect estimates for respiratory/cardiac complications combined, and blood transfusion/intensive care unit admission combined; analyses assessing these outcomes separately are presented in Supplemental Digital Content 2 (http://links.lww.com/ALN/B734).

## Results

We identified 550 hospitals performing 808,237 knee replacements and 371,607 hip replacements between 2006 and 2014 in the United States. Overall, 151 (27%) of hospitals did not use neuraxial anesthesia for these cases. Among hospitals utilizing neuraxial techniques, the range of annual neuraxial anesthesia volume per quartile for knee replacements was 1 to 6, 6 to 54, 54 to 163, and 163 to 708 for groups 1, 2, 3 and 4, respectively; for hip replacements, the annual volumes were 1 to 3, 3 to 20, 20 to 79, and 79 to 355, respectively.

### Demographics and Characteristics

Detailed patient and healthcare characteristics of patients undergoing surgery at the studied hospital universe can be found in table 1 and table 2 for knee and hip replacements, respectively (all comparisons in both tables $P < 0.0001$).

For knee replacements, hospital characteristics, more than patient- and procedure-related characteristics, determined differences in hospital-level use of neuraxial anesthesia: hospitals in the highest neuraxial anesthesia volume quartile were more commonly medium sized as measured by number of beds available and performed more knee replacements.

**Table 1.** Patient Demographics, Healthcare-related, Procedure-related, Anesthesia/Analgesia Variables, and Comorbidities by Hospital-level Use of Neuraxial Anesthesia in Quartiles for Knee Replacements; All Comparisons *P* < 0.0001*

| | No Neuraxial | | Quartile 1 | | Quartile 2 | | Quartile 3 | | Quartile 4 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | n = 170,551 | | n = 161,363 | | n = 156,819 | | n = 161,661 | | n = 157,843 | |
| | n | % | n | % | n | % | n | % | n | % |
| Patient demographics | | | | | | | | | | |
| Age† | 66 | 59–73 | 66 | 59–73 | 66 | 59–73 | 66 | 59–73 | 67 | 60–74 |
| Sex | | | | | | | | | | |
| Female | 109,181 | 64.0 | 101,320 | 62.8 | 99,379 | 63.4 | 101,284 | 62.7 | 97,974 | 62.1 |
| Male | 61,370 | 36.0 | 60,043 | 37.2 | 57,440 | 36.6 | 60,377 | 37.3 | 59,869 | 37.9 |
| Race | | | | | | | | | | |
| White | 120,494 | 70.7 | 135,155 | 83.8 | 112,105 | 71.5 | 128,268 | 79.3 | 117,493 | 74.4 |
| Black | 15,150 | 8.9 | 11,258 | 7.0 | 13,309 | 8.5 | 10,979 | 6.8 | 8,405 | 5.3 |
| Hispanic | 1,770 | 1.0 | 2,045 | 1.3 | 2,447 | 1.6 | 2,812 | 1.7 | 1,855 | 1.2 |
| Other | 33,137 | 19.4 | 12,905 | 8.0 | 28,958 | 18.5 | 19,602 | 12.1 | 30,090 | 19.1 |
| Healthcare-related | | | | | | | | | | |
| insurance type | | | | | | | | | | |
| Commercial | 62,655 | 36.7 | 61,739 | 38.3 | 55,057 | 35.1 | 58,378 | 36.1 | 57,079 | 36.2 |
| Medicaid | 6,652 | 3.9 | 3,352 | 2.1 | 4,867 | 3.1 | 3,979 | 2.5 | 2,087 | 1.3 |
| Medicare | 94,421 | 55.4 | 90,167 | 55.9 | 91,127 | 58.1 | 91,840 | 56.8 | 93,736 | 59.4 |
| Uninsured | 663 | 0.4 | 714 | 0.4 | 717 | 0.5 | 660 | 0.4 | 427 | 0.3 |
| Unknown | 6,160 | 3.6 | 5,391 | 3.3 | 5,051 | 3.2 | 6,804 | 4.2 | 4,514 | 2.9 |
| Hospital location | | | | | | | | | | |
| Rural | 15,523 | 9.1 | 14,724 | 9.1 | 13,479 | 8.6 | 31,471 | 19.5 | 15,569 | 9.9 |
| Urban | 155,028 | 90.9 | 146,639 | 90.9 | 143,340 | 91.4 | 130,190 | 80.5 | 142,274 | 90.1 |
| Hospital size | | | | | | | | | | |
| < 300 beds | 64,179 | 37.6 | 67,441 | 41.8 | 67,598 | 43.1 | 70,245 | 43.5 | 36,837 | 23.3 |
| 300–499 beds | 46,434 | 27.2 | 53,849 | 33.4 | 52,239 | 33.3 | 63,979 | 39.6 | 72,461 | 45.9 |
| ≥ 500 beds | 59,938 | 35.1 | 40,073 | 24.8 | 36,982 | 23.6 | 27,437 | 17.0 | 48,545 | 30.8 |
| Hospital teaching status | | | | | | | | | | |
| Nonteaching | 89,288 | 52.4 | 59,412 | 36.8 | 111,670 | 71.2 | 112,831 | 69.8 | 107,079 | 67.8 |
| Teaching | 81,263 | 47.6 | 101,951 | 63.2 | 45,149 | 28.8 | 48,830 | 30.2 | 50,764 | 32.2 |
| Annual procedure volume† | 268 | 181–595 | 417 | 216–754 | 253 | 164–444 | 338 | 234–497 | 632 | 435–798 |
| Procedure-related | | | | | | | | | | |
| Year of procedure | | | | | | | | | | |
| 2006 | 9,964 | 5.8 | 13,291 | 8.2 | 14,523 | 9.3 | 12,922 | 8.0 | 14,343 | 9.1 |
| 2007 | 11,416 | 6.7 | 13,615 | 8.4 | 15,099 | 9.6 | 14,736 | 9.1 | 15,708 | 10.0 |
| 2008 | 12,844 | 7.5 | 14,154 | 8.8 | 15,461 | 9.9 | 14,995 | 9.3 | 16,864 | 10.7 |
| 2009 | 15,303 | 9.0 | 17,213 | 10.7 | 16,485 | 10.5 | 17,161 | 10.6 | 17,676 | 11.2 |
| 2010 | 17,025 | 10.0 | 19,964 | 12.4 | 17,522 | 11.2 | 19,684 | 12.2 | 19,689 | 12.5 |
| 2011 | 23,198 | 13.6 | 20,456 | 12.7 | 18,301 | 11.7 | 20,632 | 12.8 | 17,845 | 11.3 |
| 2012 | 25,139 | 14.7 | 21,496 | 13.3 | 20,394 | 13.0 | 22,362 | 13.8 | 17,915 | 11.4 |
| 2013 | 28,278 | 16.6 | 21,423 | 13.3 | 20,771 | 13.2 | 20,923 | 12.9 | 19,979 | 12.7 |
| 2014 | 27,384 | 16.1 | 19,751 | 12.2 | 18,263 | 11.6 | 18,246 | 11.3 | 17,824 | 11.3 |
| Anesthesia/analgesia | | | | | | | | | | |
| General anesthesia | 106,830 | 62.6 | 127,088 | 78.8 | 113,938 | 72.7 | 120,286 | 74.4 | 96,358 | 61.0 |
| Peripheral nerve block | 15,806 | 9.3 | 30,574 | 18.9 | 22,194 | 14.2 | 13,948 | 8.6 | 24,529 | 15.5 |
| Intravenous acetaminophen | 19,892 | 11.7 | 19,569 | 12.1 | 15,545 | 9.9 | 15,163 | 9.4 | 16,179 | 10.3 |
| PCA | 31,631 | 18.5 | 38,593 | 23.9 | 35,606 | 22.7 | 33,618 | 20.8 | 43,995 | 27.9 |
| NSAIDs | 80,890 | 47.4 | 82,520 | 51.1 | 74,795 | 47.7 | 94,575 | 58.5 | 79,660 | 50.5 |
| Cyclooxygenase-2 inhibitors | 65,038 | 38.1 | 63,286 | 39.2 | 53,705 | 34.2 | 53,181 | 32.9 | 67,059 | 42.5 |
| Ketamine | 4,795 | 2.8 | 4,668 | 2.9 | 5,251 | 3.3 | 7,554 | 4.7 | 9,858 | 6.2 |
| Pregabalin/gabapentin | 37,742 | 22.1 | 36,126 | 22.4 | 29,870 | 19.0 | 33,406 | 20.7 | 30,077 | 19.1 |
| Comorbidities | | | | | | | | | | |
| Deyo-Charlson Comorbidity Index | | | | | | | | | | |
| 0 | 125,195 | 73.41 | 120,555 | 74.71 | 116,389 | 74.22 | 119,984 | 74.22 | 116,730 | 73.95 |
| 1 | 33,023 | 19.36 | 29,733 | 18.43 | 29,021 | 18.51 | 30,275 | 18.73 | 29,501 | 18.69 |
| 2 | 8,322 | 4.88 | 7,424 | 4.60 | 7,680 | 4.90 | 7,690 | 4.76 | 7,925 | 5.02 |
| 3+ | 4,011 | 2.35 | 3,651 | 2.26 | 3,729 | 2.38 | 3,712 | 2.30 | 3,687 | 2.34 |
| History of substance use/abuse | 13,975 | 8.2 | 12,189 | 7.6 | 13,354 | 8.5 | 14,005 | 8.7 | 12,399 | 7.9 |
| Pain conditions | 28,034 | 16.4 | 22,882 | 14.2 | 22,290 | 14.2 | 24,423 | 15.1 | 25,699 | 16.3 |
| Psychiatric comorbidities | 32,796 | 19.2 | 31,420 | 19.5 | 28,279 | 18.0 | 31,078 | 19.2 | 29,546 | 18.7 |
| Obesity | 42,454 | 24.9 | 37,580 | 23.3 | 34,474 | 22.0 | 39,037 | 24.1 | 33,661 | 21.3 |
| Sleep apnea | 19,716 | 11.6 | 19,222 | 11.9 | 17,280 | 11.0 | 20,172 | 12.5 | 19,813 | 12.6 |

*Chi-square test for categorical variables; Kruskal-Wallis test for continuous variables. †Continuous variable median and interquartile range reported, instead of N and %, respectively.

NSAID = nonsteroidal antiinflammatory drug; PCA = patient-controlled analgesia.

**Table 2.** Patient Demographics, Healthcare-related, Procedure-related, Anesthesia/Analgesia Variables, and Comorbidities by Hospital-level Use of Neuraxial Anesthesia in Quartiles for Hip Replacements; All Comparisons $P < 0.0001$*

| | No Neuraxial | | Quartile 1 | | Quartile 2 | | Quartile 3 | | Quartile 4 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | n = 112,368 | | n = 65,439 | | n = 65,640 | | n = 63,121 | | n = 65,039 | |
| | n | % | n | % | n | % | n | % | n | % |
| Patient demographics | | | | | | | | | | |
| Age† | 65 | 56–73 | 66 | 58–74 | 66 | 57–74 | 66 | 58–74 | 65.0 | 57–74 |
| Sex | | | | | | | | | | |
| Female | 62,058 | 55.2 | 36,792 | 56.2 | 37,052 | 56.4 | 35,611 | 56.4 | 36,607 | 56.3 |
| Male | 50,310 | 44.8 | 28,647 | 43.8 | 28,588 | 43.6 | 27,510 | 43.6 | 28,432 | 43.7 |
| Race | | | | | | | | | | |
| White | 86,150 | 76.7 | 54,724 | 83.6 | 47,448 | 72.3 | 52,363 | 83.0 | 50,013 | 76.9 |
| Black | 7,776 | 6.9 | 4,681 | 7.2 | 5,022 | 7.7 | 4,572 | 7.2 | 2,815 | 4.3 |
| Hispanic | 660 | 0.6 | 317 | 0.5 | 423 | 0.6 | 698 | 1.1 | 587 | 0.9 |
| Other | 17,782 | 15.8 | 5,717 | 8.7 | 12,747 | 19.4 | 5,488 | 8.7 | 11,624 | 17.9 |
| Healthcare-related | | | | | | | | | | |
| insurance type | | | | | | | | | | |
| Commercial | 50,822 | 45.2 | 24,922 | 38.1 | 25,268 | 38.5 | 23,450 | 37.2 | 28,384 | 43.6 |
| Medicaid | 3,798 | 3.4 | 2,045 | 3.1 | 2,228 | 3.4 | 1,704 | 2.7 | 1,143 | 1.8 |
| Medicare | 54,585 | 48.6 | 36,215 | 55.3 | 36,016 | 54.9 | 35,447 | 56.2 | 33,663 | 51.8 |
| Uninsured | 699 | 0.6 | 567 | 0.9 | 640 | 1.0 | 512 | 0.8 | 416 | 0.6 |
| Unknown | 2,464 | 2.2 | 1,690 | 2.6 | 1,488 | 2.3 | 2,008 | 3.2 | 1,433 | 2.2 |
| Hospital location | | | | | | | | | | |
| Rural | 7,109 | 6.3 | 5,681 | 8.7 | 7,550 | 11.5 | 9,537 | 15.1 | 5,693 | 8.8 |
| Urban | 105,259 | 93.7 | 59,758 | 91.3 | 58,090 | 88.5 | 53,584 | 84.9 | 59,346 | 91.2 |
| Hospital size | | | | | | | | | | |
| < 300 beds | 40,405 | 36.0 | 21,316 | 32.6 | 33,289 | 50.7 | 24,466 | 38.8 | 16,672 | 25.6 |
| 300–499 beds | 27,818 | 24.8 | 25,866 | 39.5 | 20,794 | 31.7 | 20,428 | 32.4 | 30,927 | 47.6 |
| ≥ 500 beds | 44,145 | 39.3 | 18,257 | 27.9 | 11,557 | 17.6 | 18,227 | 28.9 | 17,440 | 26.8 |
| Hospital teaching status | | | | | | | | | | |
| Nonteaching | 46,989 | 41.8 | 26,193 | 40.0 | 47,349 | 72.1 | 44,057 | 69.8 | 40,432 | 62.2 |
| Teaching | 65,379 | 58.2 | 39,246 | 60.0 | 18,291 | 27.9 | 19,064 | 30.2 | 24,607 | 37.8 |
| Annual procedure volume† | 194 | 103–470 | 164 | 86–447 | 129 | 67–329 | 141 | 103–218 | 321 | 252–403 |
| Procedure-related | | | | | | | | | | |
| Year of procedure | | | | | | | | | | |
| 2006 | 7,282 | 6.5 | 5,578 | 8.5 | 4,886 | 7.4 | 4,517 | 7.2 | 6,147 | 9.5 |
| 2007 | 7,761 | 6.9 | 5,811 | 8.9 | 5,210 | 7.9 | 5,015 | 7.9 | 6,398 | 9.8 |
| 2008 | 8,604 | 7.7 | 5,841 | 8.9 | 5,366 | 8.2 | 5,075 | 8.0 | 6,635 | 10.2 |
| 2009 | 11,426 | 10.2 | 6,694 | 10.2 | 6,237 | 9.5 | 6,197 | 9.8 | 7,310 | 11.2 |
| 2010 | 11,896 | 10.6 | 7,256 | 11.1 | 6,873 | 10.5 | 7,313 | 11.6 | 8,529 | 13.1 |
| 2011 | 15,259 | 13.6 | 7,589 | 11.6 | 7,387 | 11.3 | 7,836 | 12.4 | 7,759 | 11.9 |
| 2012 | 16,441 | 14.6 | 8,499 | 13.0 | 9,673 | 14.7 | 8,810 | 14.0 | 7,802 | 12.0 |
| 2013 | 17,180 | 15.3 | 8,979 | 13.7 | 10,134 | 15.4 | 9,777 | 15.5 | 7,409 | 11.4 |
| 2014 | 16,519 | 14.7 | 9,192 | 14.0 | 9,874 | 15.0 | 8,581 | 13.6 | 7,050 | 10.8 |
| Anesthesia/analgesia | | | | | | | | | | |
| General anesthesia | 69,844 | 62.2 | 56,177 | 85.8 | 51,830 | 79.0 | 47,128 | 74.7 | 41,010 | 63.1 |
| Peripheral nerve block | 8,907 | 7.9 | 5,393 | 8.2 | 1,244 | 1.9 | 4,860 | 7.7 | 6,768 | 10.4 |
| Intravenous acetaminophen | 10,818 | 9.6 | 9,427 | 14.4 | 7,585 | 11.6 | 7,899 | 12.5 | 5,694 | 8.8 |
| PCA | 20,379 | 18.1 | 13,768 | 21.0 | 15,689 | 23.9 | 13,061 | 20.7 | 15,098 | 23.2 |
| NSAIDs | 47,989 | 42.7 | 26,319 | 40.2 | 31,985 | 48.7 | 31,232 | 49.5 | 29,877 | 45.9 |
| Cyclooxygenase-2 inhibitors | 48,381 | 43.1 | 24,957 | 38.1 | 22,830 | 34.8 | 21,762 | 34.5 | 26,250 | 40.4 |
| Ketamine | 2,719 | 2.4 | 1,210 | 1.8 | 3,530 | 5.4 | 2,690 | 4.3 | 5,128 | 7.9 |
| Pregabalin/gabapentin | 24,157 | 21.5 | 13,480 | 20.6 | 11,856 | 18.1 | 10,302 | 16.3 | 16,609 | 25.5 |
| Comorbidities | | | | | | | | | | |
| Deyo-Charlson Comorbidity Index | | | | | | | | | | |
| 0 | 86,633 | 77.10 | 49,281 | 75.31 | 49,327 | 75.15 | 47,468 | 75.20 | 49,757 | 76.50 |
| 1 | 18,483 | 16.45 | 11,364 | 17.37 | 11,518 | 17.55 | 10,994 | 17.42 | 10,639 | 16.36 |
| 2 | 4,824 | 4.29 | 3,114 | 4.76 | 3,174 | 4.84 | 3,068 | 4.86 | 3,078 | 4.73 |
| 3+ | 2,428 | 2.16 | 1,680 | 2.57 | 1,621 | 2.47 | 1,591 | 2.52 | 1,565 | 2.41 |
| History of substance use/abuse | 11,176 | 9.9 | 7,892 | 12.1 | 8,561 | 13.0 | 8,018 | 12.7 | 7,063 | 10.9 |
| Pain conditions | 17,674 | 15.7 | 10,765 | 16.5 | 11,025 | 16.8 | 10,550 | 16.7 | 12,368 | 19.0 |
| Psychiatric comorbidities | 18,632 | 16.6 | 11,620 | 17.8 | 11,085 | 16.9 | 10,929 | 17.3 | 11,214 | 17.2 |
| Obesity | 17,810 | 15.9 | 11,352 | 17.3 | 10,503 | 16.0 | 10,614 | 16.8 | 11,118 | 17.1 |
| Sleep apnea | 9,212 | 8.2 | 5,568 | 8.5 | 5,934 | 9.0 | 5,650 | 9.0 | 6,056 | 9.3 |

*Chi-square test for categorical variables; Kruskal-Wallis test for continuous variables. †Continuous variable mean and SD reported, instead of N and %, respectively.

NSAID = nonsteroidal antiinflammatory drug; PCA = patient-controlled analgesia.

Moreover, the highest volume hospitals were less commonly teaching facilities compared to those using no neuraxial anesthesia, but were associated with higher frequencies of peripheral nerve block use. No major differences were seen in the average comorbidity burden of patients served between these hospital groups. Overall, similar patterns were observed in patients undergoing hip replacements (table 2).

### Outcomes

Table 3 and table 4 list studied outcomes by hospital-level neuraxial anesthesia volume quartile for knee and hip replacements, respectively (all comparisons in both tables $P < 0.0001$). Univariable differences among clinical outcomes existed but were generally modest. Importantly, the median cost of hospitalization was slightly higher among hospitals not utilizing neuraxial anesthesia compared to the group with the highest neuraxial anesthesia volume for knee replacements ($16,832 *vs.* $15,335; $P < 0.0001$); the main difference in hip replacements was between hospitals not using neuraxial anesthesia and those in the third volume quartile ($17,220 *vs.* $15,473; $P < 0.0001$).

Results from the multivariable multilevel regression analyses where hospital-level neuraxial anesthesia use is dichotomized (hospitals that use neuraxial anesthesia compared to those that do not) can be found in Supplemental Digital Content 3 (http://links.lww.com/ALN/B735; these specifically address study aim I). The main contrasts appeared to be for cardiac complications in knee replacements (odds ratio, 0.82; 95% CI, 0.71 to 0.95), blood transfusions in hip replacements (odds ratio, 0.74; 95% CI, 0.56 to 0.97), and

**Table 3.** Outcomes by Hospital-level Use of Neuraxial Anesthesia in Quartiles for Knee Replacements; All Comparisons $P < 0.0001$*

| | No Neuraxial | | Quartile 1 | | Quartile 2 | | Quartile 3 | | Quartile 4 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | n = 170,551 | | n = 161,363 | | n = 156,819 | | n = 161,661 | | n = 157,843 | |
| | n | % | n | % | n | % | n | % | n | % |
| Oral morphine equivalents† | 290 | 156–495 | 417 | 216–754 | 330 | 203–522 | 275 | 156–465 | 296 | 183–455 |
| Length of hospital stay† (days) | 3 | 2–4 | 3 | 3–4 | 3 | 3–4 | 3 | 3–3 | 3 | 3–3 |
| Cost of hospitalization† | $16,832 | $13,749–$21,105 | $15,956 | $13,410–$19,649 | $16,375 | $13,241–$20,766 | $15,028 | $12,531–$18,514 | $15,335 | $12,737–$18,422 |
| Respiratory complications | 3,108 | 1.8 | 3,395 | 2.1 | 3,640 | 2.3 | 3,421 | 2.1 | 3,577 | 2.3 |
| Cardiac complications | 1,427 | 0.8 | 1,062 | 0.7 | 1,145 | 0.7 | 1,012 | 0.6 | 1,137 | 0.7 |
| Cardiac/respiratory complications combined | 4,336 | 2.5 | 4,322 | 2.7 | 4,607 | 2.9 | 4,298 | 2.7 | 4,555 | 2.9 |
| Blood transfusion | 18,323 | 10.7 | 14,401 | 8.9 | 15,195 | 9.7 | 18,724 | 11.6 | 22,462 | 14.2 |
| Intensive care unit admission | 4,016 | 2.4 | 7,744 | 4.8 | 3,486 | 2.2 | 3,677 | 2.3 | 2,450 | 1.6 |
| Blood transfusion/intensive care unit admission combined | 21,597 | 12.7 | 21,626 | 13.4 | 18,121 | 11.6 | 21,789 | 13.5 | 24,475 | 15.5 |

*Continuous variable median and interquartile range reported, instead of N and %, respectively. †Chi-square test for categorical variables; Kruskal-Wallis test for continuous variables.

**Table 4.** Outcomes by Hospital-level Use of Neuraxial Anesthesia in Quartiles for Hip Replacements; All Comparisons $P < 0.0001$*

| | No Neuraxial | | Quartile 1 | | Quartile 2 | | Quartile 3 | | Quartile 4 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | n = 112,368 | | n = 65,439 | | n = 65,640 | | n = 63,121 | | n = 65,039 | |
| | n | % | n | % | n | % | n | % | n | % |
| Oral morphine equivalents† | 249 | 127–420 | 293 | 180–475 | 285 | 173–458 | 256 | 142–448 | 248 | 148–405 |
| Length of hospital stay† (days) | 3 | 2–3 | 3 | 3–3 | 3 | 2–4 | 3 | 2–3 | 3 | 2–3 |
| Cost of hospitalization† | $17,220 | $14,493–$21,157 | $15,972 | $13,271–$19,903 | $16,034 | $12,849–$20,012 | $15,473 | $12,941–$18,958 | $17,178 | $14,287–$20,335 |
| Respiratory complications | 1,562 | 1.4 | 1,300 | 2.0 | 1,139 | 1.7 | 958 | 1.5 | 1,065 | 1.6 |
| Cardiac complications | 882 | 0.8 | 489 | 0.7 | 506 | 0.8 | 449 | 0.7 | 428 | 0.7 |
| Cardiac/respiratory complications combined | 2,343 | 2.1 | 1,742 | 2.7 | 1,586 | 2.4 | 1,359 | 2.2 | 1,445 | 2.2 |
| Blood transfusion | 15,523 | 13.8 | 8,700 | 13.3 | 10,921 | 16.6 | 8,852 | 14.0 | 8,497 | 13.1 |
| Intensive care unit admission | 2,922 | 2.6 | 3,405 | 5.2 | 2,185 | 3.3 | 1,307 | 2.1 | 1,383 | 2.1 |
| Blood transfusion/intensive care unit admission combined | 17,668 | 15.7 | 11,769 | 18.0 | 12,502 | 19.0 | 9,799 | 15.5 | 9,554 | 14.7 |

*Chi-square test for categorical variables; Kruskal-Wallis test for continuous variables. †Continuous variable mean and SD reported, instead of N and %, respectively.

cost of hospitalization in both groups: hospitals that used neuraxial anesthesia had a –10.5% decreased cost of hospitalization for knee replacement patients; this was –10.8% for hip replacement patients ($P < 0.05$).

Table 5 contains results from the sequential modeling, while results from model III are also depicted in figure 1 using forest plots (these results address study aim I and indirectly study aim II). Here, hospital-level neuraxial anesthesia volume is subgrouped by quartiles and compared to hospitals that do not use neuraxial anesthesia to test for potential volume-outcome relationships. No large differences were found when comparing effect estimates from model II (only patient-level factors in model) to model III (patient-level factors and hospital-level variables in model).

While mostly not significant (with wider 95% CI) after multiplicity adjustment, hospital-level neuraxial anesthesia volume (compared to hospitals without neuraxial anesthesia use) demonstrated consistently lower odds for particularly blood transfusion/intensive care unit admission combined (knee replacement quartile 4: odds ratio, 0.85; 95% CI, 50–1.46/hip replacement quartile 4: odds ratio, 0.55; 95% CI, 0.32 to 0.97). Results from analyses using separated outcome variables shown in Supplemental Digital Content 2 (http://links.lww.com/ALN/B734) also demonstrate nonsignificant effect estimates generally favoring hospitals that use neuraxial anesthesia.

The most consistent effects were seen for cost of hospitalization with up to –14.06% (quartile 3) significantly decreased costs in knee replacements; this was –15.58% (quartile 3) in hip replacements (compared to hospitals not using neuraxial anesthesia). Full model coefficients are shown in Supplemental Digital Content 4 (http://links.lww.com/ALN/B736). In knee replacements, significant linear trends in hospital-level neuraxial anesthesia volume effects were seen for length of hospital stay ($P = 0.0279$), but not for cost of hospitalization ($P = 0.0602$); in hip replacements this was seen for opioid utilization ($P = 0.0462$) and cost of hospitalization ($P = 0.0104$).

Figure 2 directly addresses study aim II for the outcome with the strongest effect estimates and most suggestive of a volume-outcome relationship: cost of hospitalization. Plotting hospital-specific neuraxial anesthesia volume against *predicted* hospital-specific median costs demonstrates a significant trend of decreasing cost with increasing volume of neuraxial anesthesia. This trend was more pronounced for knee replacements.

Table 6 shows the percent explained variance by unspecified and specified (hospital-level neuraxial anesthesia volume) effects; these were highest for cost of hospitalization and blood transfusion/intensive care unit admission combined.

**Percent Neuraxial Use.** Results from the analysis where hospitals were subgrouped into quartiles of percent use of neuraxial anesthesia (as opposed to absolute volume) can be found in Supplemental Digital Content 1 (http://links.lww.com/ALN/B733). Similar to the analysis presented in the manuscript, we found consistently lower odds for particularly cardiac complications and blood transfusion need while the strongest significant effects were seen for cost of hospitalization.

## Discussion

In this study utilizing population-based data from 550 hospitals throughout the United States, we found that hospital-level volume of neuraxial techniques for lower joint replacements was associated with an up to 15.58% decreased cost of hospitalization. Moreover, trends in decreased costs were visible with increasing use of neuraxial anesthesia, particularly for knee replacements. While the effect estimates may seem modest on the individual level, given the high and increasing volume of lower joint replacements, this finding could have profound implications on the population level. In addition, while mostly not significant after multiplicity adjustment, hospital-level neuraxial anesthesia volume demonstrated consistent lower odds for separate outcomes of cardiac complications and blood transfusion need. After multiplicity adjustment, no consistent impact of hospital level neuraxial anesthesia on clinical outcomes was observed. Interestingly, hospitals that frequently use neuraxial techniques for lower joint replacements are often medium-sized and nonteaching hospitals.

Our findings may suggest that benefits described with the use of neuraxial anesthesia on the individual patient level may also be present for at least cost outcomes on the hospital level, and importantly, that volume-outcome relationships may exist. Volume-outcome relationships have been reported in various medical and surgical settings over the period of the last decades[1,2,23–25] including for joint replacement recipients.[25–28] In this context, a number of studies suggest improved outcomes to be associated with a higher volume of experience in specific procedures performed or conditions treated on a hospital level as well as a provider level. While the reasons for such relationships are still not fully understood, main hypotheses include the "practice makes perfect" effect[29] where hospitals have better outcomes as their caseload and experience allow them to improve their systems and techniques. In addition, according to the "selective referral" effect, hospitals with better outcomes have larger patient volumes because their excellence is known and thus draws more patients; this could indeed be true in the case of neuraxial anesthesia.[29] While several drivers of volume-outcome effects may be at play in the context of complex surgeries and neuraxial anesthesia use, the main difference between the two may be the importance of each driver. In volume effects in the context of complex surgeries, the "practice makes perfect" effect may dominate, while in the case of neuraxial anesthesia, other factors may prevail. It is possible that neuraxial anesthesia is used more in sicker

**Table 5.** Results from Sequential Models Comparing Hospital-level Use of Neuraxial Anesthesia (in Quartiles, Q1–Q4) to Hospitals that Do Not Use Neuraxial Anesthesia; ORs for Binary Outcome Variables, for Continuous Outcomes Exponentiated Coefficients from the Log Model Depicting % Change Compared to Reference

| | Knee Replacements | | | | | | | | | | Hip Replacements | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model I | | | Model II | | | Model III | | | | Model I | | | Model II | | | Model III | | |
| | OR | 95% CI | | OR | 95% CI | | OR | 95% CI | | | OR | 95% CI | | OR | 95% CI | | OR | 95% CI | |
| Oral morphine equivalents* | | | | | | | | | | Oral morphine equivalents* | | | | | | | | | |
| Q1 | 2.02 | −10.93 | 16.86 | 0.32 | −12.39 | 14.88 | −1.16 | −13.86 | 13.41 | Q1 | 10.14 | −5.76 | 28.71 | 4.81 | −10.04 | 22.10 | 3.90 | −10.85 | 21.08 |
| Q2 | 5.69 | −7.01 | 20.12 | 3.79 | −8.65 | 17.93 | 2.56 | −9.94 | 16.80 | Q2 | 16.21* | 0.08 | 34.93 | 6.59 | −7.93 | 23.39 | 5.83 | −8.63 | 22.57 |
| Q3 | −10.81 | −22.56 | 2.72 | −10.35 | −22.14 | 3.22 | −11.34 | −23.19 | 2.33 | Q3 | −2.85 | −16.67 | 13.26 | −3.41 | −16.90 | 12.28 | −4.00 | −17.49 | 11.71 |
| Q4 | −9.04 | −23.64 | 8.34 | −8.41 | −23.08 | 9.06 | −10.78 | −26.25 | 7.92 | Q4 | −9.25 | −25.82 | 11.02 | −12.11 | −27.91 | 7.14 | −9.87 | −26.45 | 10.46 |
| Length of hospital stay* | | | | | | | | | | Length of hospital stay* | | | | | | | | | |
| Q1 | 5.41 | −0.11 | 11.23 | 3.43 | −1.71 | 8.84 | 4.00 | −1.08 | 9.34 | Q1 | 5.07 | −1.83 | 12.45 | 0.58 | −5.47 | 7.02 | −0.44 | −6.19 | 5.67 |
| Q2 | 5.99† | 0.76 | 11.49 | 2.85 | −1.97 | 7.91 | 2.17 | −2.55 | 7.12 | Q2 | 5.11 | −1.52 | 12.18 | 1.44 | −4.42 | 7.65 | 0.71 | −4.88 | 6.63 |
| Q3 | −0.90 | −6.28 | 4.79 | −2.99 | −7.99 | 2.29 | −2.25 | −7.24 | 3.00 | Q3 | −1.49 | −7.87 | 5.33 | −3.62 | −9.34 | 2.46 | −4.30 | −9.79 | 1.51 |
| Q4 | −1.72 | −8.27 | 5.31 | −4.08 | −10.17 | 2.41 | −0.50 | −7.19 | 6.67 | Q4 | −3.47 | −11.64 | 5.45 | −7.43 | −14.62 | 0.35 | −4.09 | −11.41 | 3.82 |
| Cost of hospitalization* | | | | | | | | | | Cost of hospitalization* | | | | | | | | | |
| Q1 | −8.38† | −15.32 | −0.87 | −6.97 | −14.20 | 0.87 | −9.61† | −16.49 | −2.15 | Q1 | −7.24 | −15.15 | 1.42 | −9.47† | −17.21 | −1.00 | −9.58† | −17.33 | −1.11 |
| Q2 | −5.29 | −12.07 | 2.01 | −3.99 | −11.04 | 3.62 | −7.39† | −14.08 | −0.18 | Q2 | −8.45† | −15.95 | −0.28 | −10.34† | −17.70 | −2.31 | −10.65† | −18.01 | −2.63 |
| Q3 | −12.71† | −19.58 | −5.25 | −13.27† | −20.26 | −5.67 | −14.06† | −20.90 | −6.62 | Q3 | −13.83† | −21.10 | −5.91 | −14.89† | −22.07 | −7.03 | −15.58† | −22.76 | −7.74 |
| Q4 | −13.54† | −21.89 | −4.32 | −14.79† | −23.20 | −5.45 | −12.75† | −21.89 | −2.55 | Q4 | −7.39 | −17.58 | 4.06 | −9.63 | −19.60 | 1.58 | −8.87 | −19.18 | 2.77 |
| Cardiac/respiratory complications combined | | | | | | | | | | Cardiac/respiratory complications combined | | | | | | | | | |
| Q1 | 0.97 | 0.79 | 1.20 | 0.95 | 0.77 | 1.16 | 0.94 | 0.77 | 1.15 | Q1 | 1.07 | 0.83 | 1.38 | 1.02 | 0.79 | 1.31 | 0.98 | 0.76 | 1.25 |
| Q2 | 1.14 | 0.94 | 1.38 | 1.10 | 0.91 | 1.33 | 1.10 | 0.91 | 1.33 | Q2 | 1.08 | 0.85 | 1.38 | 1.03 | 0.81 | 1.31 | 1.00 | 0.79 | 1.27 |
| Q3 | 0.98 | 0.80 | 1.21 | 0.95 | 0.78 | 1.17 | 0.98 | 0.79 | 1.20 | Q3 | 0.90 | 0.70 | 1.16 | 0.87 | 0.68 | 1.12 | 0.87 | 0.68 | 1.11 |
| Q4 | 1.10 | 0.85 | 1.41 | 1.05 | 0.82 | 1.34 | 1.18 | 0.91 | 1.54 | Q4 | 0.90 | 0.66 | 1.23 | 0.85 | 0.62 | 1.15 | 0.94 | 0.69 | 1.28 |
| Blood Transfusion/Intensive Care Unit Admission Combined | | | | | | | | | | Blood Transfusion/Intensive Care Unit Admission Combined | | | | | | | | | |
| Q1 | 1.04 | 0.71 | 1.52 | 0.94 | 0.64 | 1.38 | 0.93 | 0.63 | 1.37 | Q1 | 0.95 | 0.63 | 1.43 | 0.79 | 0.52 | 1.20 | 0.76 | 0.50 | 1.16 |
| Q2 | 0.98 | 0.68 | 1.40 | 0.84 | 0.59 | 1.21 | 0.82 | 0.57 | 1.18 | Q2 | 1.06 | 0.72 | 1.57 | 0.91 | 0.61 | 1.37 | 0.88 | 0.59 | 1.31 |
| Q3 | 0.93 | 0.63 | 1.38 | 0.83 | 0.56 | 1.23 | 0.84 | 0.57 | 1.26 | Q3 | 0.78 | 0.52 | 1.17 | 0.69 | 0.46 | 1.05 | 0.68 | 0.45 | 1.03 |
| Q4 | 0.93 | 0.57 | 1.52 | 0.81 | 0.50 | 1.32 | 0.85 | 0.50 | 1.46 | Q4 | 0.60 | 0.35 | 1.03 | 0.50† | 0.29 | 0.86 | 0.55† | 0.32 | 0.97 |

Model I: unadjusted association between percent hospital-level use of neuraxial anesthesia (in quartiles) and outcomes. Model II: models adjusted for age, sex, race, insurance type, year of procedure, general anesthesia use, patient-controlled analgesia use, intravenous acetaminophen, nonsteroidal antiinflammatory drugs, cyclooxygenase-2 inhibitors, ketamine, pregabalin/gabapentin, peripheral nerve block use, Deyo-Charlson Comorbidity Index, history of substance use/abuse, pain conditions, psychiatric comorbidities, sleep apnea, and obesity. Model III: adjusted for all variables mentioned in model II and hospital-specific number of annual procedures, hospital teaching status, hospital location, and hospital bed size.

*Percent change. †$P < 0.05$.

OR = odds ratio.

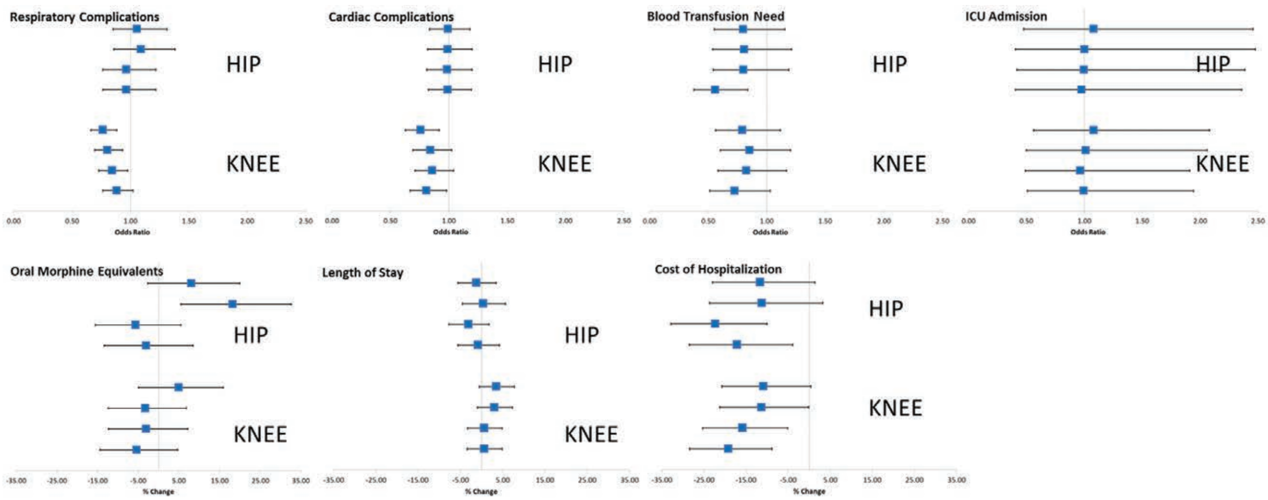


**Fig. 1.** Results from multivariable multilevel models comparing percent hospital-level use of neuraxial anesthesia (in quartiles) to hospitals that do not use neuraxial anesthesia; odds ratios for binary outcome variables, for continuous outcomes exponentiated coefficients from the log model depicting percent change compared to reference. Models adjusted for age, sex, race, year of procedure, insurance type, number of annual procedures, hospital teaching status, hospital location, hospital size, general anesthesia use, patient-controlled analgesia use, Deyo-Charlson Comorbidity Index, peripheral nerve block use, sleep apnea, obesity, history of substance use/abuse, pain conditions, and psychiatric comorbidities. Additional variables in model with the outcome of oral morphine equivalents: IV acetaminophen, nonsteroidal antiinflammatory drugs, cyclooxygenase-2 inhibitors, ketamine, and pregabalin/gabapentin. ICU = intensive care unit.

vor older patients where its benefit may be more profound. Alternatively, the simple translation of beneficial individual-level effects where a higher volume of a beneficial technique automatically results in better outcomes on the hospital level may represent a plausible explanation. Irrespective of the reasons, these are important policy questions that should be addressed in future research before recommendations on hospital-level neuraxial volume can be issued as a potential marker of quality. Indeed, the use of neuraxial anesthesia has been suggested in a number of population-based studies to improve outcomes on a patient level.[4–7,9] However, the influence of anesthesia-related hospital-level factors has not been studied extensively thus far.

We were able to show an association between hospitals that used neuraxial techniques for patients undergoing lower joint replacements and lower overall costs; moreover, our results also suggest a volume-outcome relationship. We additionally observed decreased odds for, particularly, cardiac complications and blood transfusion need when dichotomizing hospital-level neuraxial use. Directions of effects remained, although they were less strong after multiplicity adjustment in analyses with quartiles of hospital-level neuraxial volume. While exact reasons for these findings have to remain speculative and individual costs for specific items or associated with specific complications are not available in our dataset, a reduction in complications may contribute to this finding. Indeed, next to superior patient outcomes, high-volume care has also been associated with decreased costs of care.[30] In the context of neuraxial anesthesia, previous studies have suggested improved resource utilization profiles and overall cost benefits associated with its use.[6,9,31] Population-based studies have suggested overall reduced cost associated with neuraxial anesthesia on a patient level[6,31] as well as shorter operative and recovery room times.[8] A direct comparison between neuraxial and general anesthesia in orthopedic patients concluded that costs associated with the former approach may result in as much as 50% savings in the direct perioperative period when excluding personnel costs.[31] Next to the direct cost-sparing effects of neuraxial anesthesia, our findings also suggest that hospitals that perform neuraxial anesthesia more frequently may realize higher levels of cost-effectiveness through other pathways. Indeed, neuraxial anesthesia is commonly mentioned in so-called enhanced recovery pathways, which have been shown to result in superior outcomes.[32] Hospitals with higher volumes of neuraxial anesthesia may therefore be more likely to have adopted these pathways, which could also be one of the drivers of the effects found in the current study.

While generally nonsignificant (with wider 95% CI) after multiplicity adjustment, several of our analyses showed beneficial associations between hospital-level neuraxial anesthesia volume and particularly blood transfusion/intensive care unit utilization when compared to hospitals that do not use neuraxial anesthesia. Benefits of neuraxial anesthesia in terms of medical complications have been described widely on a patient level.[4–7] A reduction in sympathetic output and better hemodynamic management with the avoidance of blood pressure spikes may be likely mechanisms for outcomes related to blood loss, for example.[33] Potential confirmation of this association on a hospital level may lead to opportunities to improve outcomes driven by policy and administrative decisions, as they may reduce adverse events, which are associated with high cost and downstream complications.[34,35]

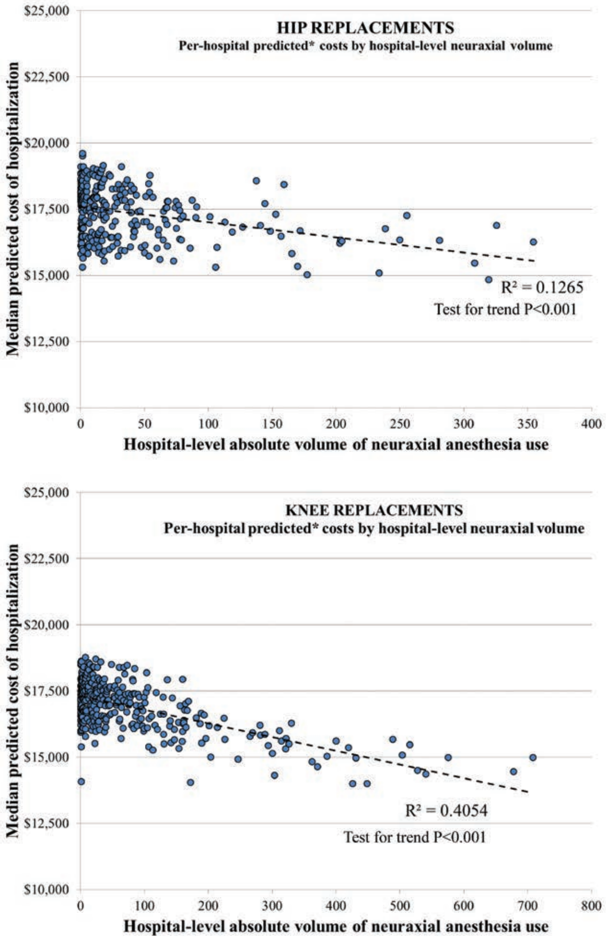


**Fig. 2.** Per-hospital predicted costs by hospital-level neuraxial volume for hip and knee replacement surgery. *Derived from Model III in table 5; adjusted for age, sex, race, insurance type, hospital annual procedure volume, hospital teaching status, hospital location, hospital bed size, year of procedure, general anesthesia use, patient-controlled analgesia use, intravenous acetaminophen, nonsteroidal antiinflammatory drugs, cyclooxygenase-2 Inhibitors, ketamine, pregabalin/gabapentin, peripheral nerve block use, Deyo-Charlson Comorbidity Index, history of substance use/abuse, pain conditions, psychiatric comorbidities, sleep apnea, and obesity.

We found that hospitals that frequently used neuraxial techniques for lower joint replacements were often medium-sized and nonteaching hospitals. This seemingly counterintuitive result has also been observed in other cohorts.[36] While reasons for this remain speculative, teaching hospitals may believe they are more obligated to provide trainees with experience in airway management and general anesthesia.

Our study is limited by a number of factors. First and foremost, the retrospective nature of our analysis and our data source do not allow for the determination of causal relationships. Confounding remains as clinical detail is missing. For example, while we were able to adjust for patient comorbidity burden, a full case-mix adjustment is not possible. Moreover, while we performed several analyses, we were unable to assess the robustness of our effect estimates using other approaches such as propensity score or instrumental variable analysis. The former would not be feasible as our main effect of interest is a hospital-level variable with five categories; the latter—suggested as an alternative in assessing volume-outcome relationships[29]—was also not feasible using our data since we did not have information on patients' distance to hospitals. Furthermore, our models did not include surgical volume as a covariate; therefore, this factor was only indirectly assessed through the sensitivity analysis using proportion of neuraxial use. Since this is among the first studies looking into volume-outcome relationships in the anesthesiology field, future studies should assess robustness using other data sources and alternative analyses.

Another limitation pertains to the issue of provider *versus* hospital volume: While volume of neuraxial anesthesia use can be determined on the hospital level, the role of individual provider volume has to remain unanswered as detailed information on this subject is missing. Additionally, while we found differences in the odds for various adverse outcomes between hospitals not utilizing neuraxial anesthesia and those performing this technique particularly for knee replacements, our results were primarily suggestive of a volume-related correlation for only cost of hospitalization. Moreover, it remains unclear at what volume level benefits could be realized. The fact that the hospital-level neuraxial volume started at 163 annual knee replacement procedures with neuraxial anesthesia in the highest quartile for knee replacements may suggest that a high rate of use is needed to recognize benefits in terms of patient outcomes statistically and likely clinically.

In summary, in this analysis of population-based data, we were able to demonstrate that a higher hospital-level



**Table 6.** Intraclass Correlation Coefficients; Percent Variance in Outcome Explained Unspecified Hospital-level Effects *versus* Specified (*i.e.*, Hospital-level Neuraxial Anesthesia Use) Effects

| | Unspecified | | Hospital-level Neuraxial Anesthesia | |
|---|---|---|---|---|
| | Knee | Hip | Knee | Hip |
| Oral morphine equivalents | 4.2% | 6.0% | 3.4% | 4.6% |
| Length of hospital stay | 11.6% | 11.3% | 10.8% | 10.0% |
| Cost of hospitalization | 23.4% | 32.2% | 20.4% | 27.3% |
| Cardiac/respiratory complications combined | 8.4% | 9.8% | 7.4% | 8.9% |
| Blood transfusion/intensive care unit admission combined | 27.2% | 27.1% | 26.3% | 23.8% |

volume of neuraxial techniques for lower joint replacements was associated with a trend in increased cost reductions. These may have been partly driven by a reduction in adverse patient outcomes. Our findings may point toward an important role of neuraxial anesthesia not only as a modifiable risk factor for outcomes on a patient level, but potentially to its suitability as a quality indicator among hospitals performing lower joint replacements. Further research and maturation of this field of research is needed to establish firm causal conclusions regarding a potential financial impact in the context of higher neuraxial anesthesia utilization.

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## Competing Interests

Dr. Memtsoudis is a one-time consultant for Sandoz Inc. (New Jersey) and the holder of U.S. Patent US-2017-0361063, Multicatheter Infusion System. He is the owner of SGM Consulting, LLC (New Jersey). None of the above relations influenced the conduct of the current study. The authors declare no competing interests.

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