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DEFORMITY

Utilization of Predictive Modeling to Determine Episode of Care Costs and to Accurately Identify Catastrophic Cost Nonwarranty Outlier Patients in Adult Spinal Deformity Surgery

A Step Toward Bundled Payments and Risk Sharing

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Study Design. Retrospective review of prospectively-collected, multicenter adult spinal deformity (ASD) database.

Objective. The aim of this study was to evaluate the rate of patients who accrue catastrophic cost (CC) with ASD surgery utilizing direct, actual costs, and determine the feasibility of predicting these outliers.

Summary of Background Data. Cost outliers or surgeries resulting in CC are a major concern for ASD surgery as some question the sustainability of these surgical treatments.

Methods. Generalized linear regression models were used to explain the determinants of direct costs. Regression tree and random forest models were used to predict which patients would have CC (>$100,000).

Results. A total of 210 ASD patients were included (mean age of 59.3 years, 83% women). The mean index episode of care direct cost was $70,766 (SD = $24,422). By 90 days and 2 years following surgery, mean direct costs increased to $74,073 and $77,765, respectively. Within 90 days of the index surgery, 11 (5.2%) patients underwent 13 revisions procedures, and by 2 years, 26 (12.4%) patients had undergone 36 revision procedures. The CC threshold at the index surgery and 90-day and 2-year follow-up time points was exceeded by 11.9%, 14.8%, and 19.1% of patients, respectively. Top predictors of cost included number of levels fused, surgeon, surgical approach, interbody fusion (IBF), and length of hospital stay (LOS). At 90 days and 2 years, a total of 80.6% and 64.0% of variance in direct cost, respectively, was explained in the generalized linear regression models. Predictors of CC were number of fused levels, surgical approach, surgeon, IBF, and LOS.

Conclusion. The present study demonstrates that direct cost in ASD surgery can be accurately predicted. Collectively, these findings may not only prove useful for bundled care initiatives, but also may provide insight into means to reduce and better predict cost of ASD surgery outside of bundled payment plans.

Key words: adult spinal deformity, bundled payment, catastrophic cost, cost, fusion, osteobiologic, Oswestry Disability Index, precitive model, spine, SRS-22r, surgery.

Level of Evidence: 3

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The current trajectory of health care cost in the United States is unsustainable,[1] with the cost projected to reach $3.8 trillion in 2019 and $6.0 trillion by 2027.[2] The direct cost of spine care is estimated at $80 to $100 billion annually and adult spinal deformity (ASD) surgery is a growing proportion of this expenditure.[1] This is because, at least in part, of a rapid increase in spine procedure volume, cost, and an aging population.[3]

There is wide variability surrounding the cost of ASD procedures.[4–11] Multiple initiatives have targeted areas that can drive consistency and improve value, as this could enable cost containment and sustainability for ASD surgery. In the United States, provisions in the Patient Protection and Affordable Care Act include creative payment models that transition away from fee-for-service reimbursement and provide incentives to help improve value.[12,13] The Center for Medicare and Medicaid Innovation is piloting episode-based bundled payments initiatives through its Bundled Payment for Care Improvement (BPCI) program. The BPCI provides a predetermined reimbursement that encompasses all services related to a target diagnosis or procedure over a predefined time frame. To be successful, the hospital must contain cost below the bundled payment threshold. This encourages coordination of care among hospitals, payers, and providers to eliminate unnecessary waste and promote accountability with an overall goal of improving cost effectiveness across the continuum of care.

Bundled care reimbursement models have been used in other areas of musculoskeletal care including joint arthroplasty[14] and are now being utilized in select centers for spinal fusions.[13,15,16] For ASD surgery, this model is arguably not plausible because of risk of these procedures resulting in catastrophic cost (CC). The objective of the present study was to evaluate the rates of CC outliers at three time points (index surgery and 90-day and 2-year follow-up) utilizing direct, actual cost of ASD index surgeries and subsequent required revision procedures. In addition, we sought to determine the feasibility of predicting these outliers and to identify variables that are primary drivers of CC. Better understanding the risk factors for CC not only provides valuable information for bundled care initiatives, but also may provide insight into means to reduce and better predict cost of ASD surgery outside of bundled payment plans.

METHODS

Patient Population

This is a retrospective analysis of surgically treated ASD patients prospectively enrolled into a multicenter database of 11 spine specialty surgical centers from 2008 to 2015. Of the 11 centers, four (located in different geographic areas of the United States) were able to share actual, direct hospital cost data. Inclusion criteria were: ASD, age $\geq$18 years, plan for surgical treatment, and eligibility for 2-year follow-up. ASD was defined by the presence of: scoliosis $>20^\circ$, sagittal vertical axis >5 cm, pelvic tilt $>25^\circ$, and/or thoracic kyphosis $>60^\circ$. Only patients with 2-year follow-up were analyzed. Patients were enrolled through an institutional review board approved protocol at each site.

Observable Patient Characteristics

Collected patient characteristics at baseline included age, sex, body mass index, comorbidities, and number of previous spine surgeries. Full-length free-standing spine radiographs were analyzed using validated software[17–19] for assessment of radiographic parameters.[20] Patient-reported outcomes measures (PROMs) included the Oswestry Disability Index (ODI), Scoliosis Research Society-22r, and the Optum SF-36v2 Health Survey.

Surgical Parameters

Collected surgical characteristics included: surgical approach, number of fused vertebral levels, pelvic fixation, use of interbody fusion (IBF), osteotomy use and type, operative time, estimated blood loss, and length of hospital stay (LOS). Use of biologics and bone graft products for arthrodesis was also collected.

Cost Data

Actual cost (not Medicare allowable rates) was collected from hospital administrative records containing the total hospital costs incurred for the index episode of care and any related reoperations performed up to the 90-day and 2-year postoperative time horizons. Cost was expressed in 2010 US dollars and discounted at 3.5%/year. Direct costs included overhead and operating room costs that were comprised mainly of instrumentation, biologics, graft extenders, and sealants. The index episode of care included direct costs associated with the index surgical procedure, whereas the 90-day and 2-year direct costs also included direct costs from any related revision procedures at the hospital at which the index procedure was performed. Reported direct costs do not include expenses incurred through other hospitals or facilities, including inpatient rehabilitation, outpatient physical therapy, and outpatient pharmacies. To help disentangle unobservable constant heterogeneity, a set of contextual factors, including weekday, year, hospital, and surgeon, were included as controls. The CC threshold was set at $100,000 based on sample size and the minimum that could provide reliable prediction owing to class imbalance.

Missing Values

Missing values in the dataset were imputed through a nonparametric missing value imputation using a random forest algorithm.[21]

Linear Regression Models

Multivariable linear regression models were fit to 90-day and 2-year cost time horizons. Forward variable selection was used, and maximization of adjusted-R^2 was set as the objective function upon P value significance.[22] No cross-validation was performed because of the limited available sample size; hence, we are not able to test whether the results are over-fitted. Goodness of fit was evaluated by means of adjusted-R^2 values.

Regression Trees and Forests

A conditionally unbiased regression tree (CTREE)[23] was fitted to 90-day and 2-year direct costs. The hierarchical structure of the algorithm allows for straightforward description of the data and the problem analyzed. Owing to the potential for instability with application of CTREE algorithm to small samples, a random forest algorithm (conditionally unbiased random forest [C-forest]) was also fitted to obtain more stable predictions. The nature of both models, binary recursive partitioning, incorporates automatic variable entry, as all variables at all potential cutoff points are evaluated hierarchically through a complexity parameter. Goodness of fit was evaluated by means of adjusted-R^2 values.

RESULTS

Patient Cohort, Operative Parameters, and Cost Data

A total of 210 patients met inclusion criteria. Tables 1–3 summarize baseline patient and operative data. Most patients were women (83%) with an average age of 59.3 years. Almost half (45%) of patients had previous spine surgery. Disease impact was substantial based on PROMs, including the ODI which had a mean score of 46, reflective of severe disability. Neurological symptoms and findings were common, including leg weakness (54%) and loss of balance (52%) (Table 2). The most common comorbidities included hypertension (45%), arthritis (41%), depression (32%), and osteoporosis (17%) (Table 2).

Seven surgeons at four sites contributed patients (Table 3). The mean number of levels fused was 12.3. Almost all cases included a posterior instrumented fusion (99%), and the majority included decompression (66%) and/or at least one osteotomy (64%). Grafting materials included allograft (53%), iliac crest autograft (26%), local bone autograft (58%), and recombinant human bone morphogenetic protein 2 (66.2%), with the latter used both on- and off-label.

The mean index episode of care cost was $70,766 (SD = $24,422, range: $28,748–$165,295). The CC threshold was exceeded by 25 (11.9%) patients. Within 90 days

TABLE 1. Baseline Continuous Patient and Operative Variables*

Variable	n	Missing	Mean	SD	SE
Demographics and outcomes measures					
Age, y	210	0	59.26	12.6	0.87
Body mass index	210	0	28.18	6.75	0.47
Height, cm	210	0	162.82	10.41	0.72
Weight, kg	210	0	74.88	20.24	1.4
Oswestry Disability Index	209	1	46.02	18.51	1.28
Short Form 36					
Physical component summary	204	6	31.07	8.94	0.63
Mental component summary	204	6	43.13	14.37	1.01
Physical functioning	206	4	28.86	10.97	0.76
Physical role functioning	206	4	29.95	10.67	0.74
Bodily pain	207	3	31.95	8.98	0.62
General health perceptions	204	6	45.37	10.77	0.75
Vitality	206	4	38.7	10.82	0.75
Social role functioning	207	3	34.93	13.34	0.93
Emotional role functioning	206	4	37.08	15.75	1.1
Mental health	206	4	42.44	13.21	0.92
Scoliosis Research Society-22r					
Total	209	1	2.7	0.68	0.05
Activity	209	1	2.73	0.85	0.06
Pain	209	1	2.4	0.85	0.06
Appearance	209	1	2.32	0.79	0.05
Mental	209	1	3.34	0.93	0.06
Satisfaction	207	3	2.68	1.09	0.08
Operative					
Year of surgery	210	0	2010.96	1.89	0.13
Length of hospital stay, days	209	1	7.56	4.68	0.32
Surgical time, min	186	24	386.68	126.47	9.27
Estimated blood loss, mL	203	7	1369.41	1312.91	92.15
Cell saver transfused, mL	193	17	454.15	444.05	31.96
Number of levels fused	209	1	12.31	3.71	0.26
Index direct cost (2010 USD)	210	0	70,765.66	24,421.61	1685.25
90-day direct cost (2010 USD)	210	0	74,072.98	26,150.19	1804.53
2-year direct cost (2010 USD)	210	0	77,764.6	32,753.27	2260.19

*SD indicates standard deviation; SE, standard error; USD, United States dollars.

TABLE 2. Baseline Categorical Patient Variables			
Variable	**Value Labels**	**Frequency**	**%**
Demographics			
Sex	Male	36	17.14
	Female	174	82.86
Race	Asian	5	2.4
	Black	9	4.33
	Hispanic	5	2.4
	White	187	89.9
	Other	2	0.96
Work status	Disabled	25	13.16
	Employed	71	37.37
	Retired	65	34.21
	Retired BP*	15	7.89
	Unemployed	14	7.37
Years with spine problems	<1	2	0.97
	1–2	8	3.88
	2–5	20	9.71
	5–10	40	19.42
	>10	136	66.02
Prior spine surgery	No	115	55.02
	Yes	94	44.98
Neurologic			
Bowel incontinence	No	162	86.63
	Yes	25	13.37
Bladder incontinence	No	139	75.14
	Yes	46	24.86
Leg numbness	No	87	46.28
	Yes	101	53.72
Leg weakness	No	86	45.74
	Yes	102	54.26
Loss of balance	No	89	47.59
	Yes	98	52.41
Comorbidities			
Anemia	No	172	91.98
	Yes	15	8.02
Arthritis	No	110	58.82
	Yes	77	41.18
Blood clots	No	181	96.79
	Yes	6	3.21
Cancer	No	168	89.84
	Yes	19	10.16
Depression	No	128	68.45
	Yes	59	31.55
Diabetes	No	174	93.05
	Yes	13	6.95
Drugs or alcohol	No	184	98.4
	Yes	3	1.6
Heart disease	No	173	92.51
	Yes	14	7.49
Hypertension	No	102	54.55
	Yes	85	45.45
Kidney disease	No	183	97.86
	Yes	4	2.14
Liver disease	No	186	99.47
	Yes	1	0.53

TABLE 2 (*Continued*)

Variable	Value Labels	Frequency	%
Lung disease	No	175	93.58
	Yes	12	6.42
Neurologic	No	178	95.19
	Yes	9	4.81
Osteoporosis	No	156	83.42
	Yes	31	16.58
Peripheral vascular disease	No	185	98.93
	Yes	2	1.07
Psychiatric comorbidities	No	175	93.58
	Yes	12	6.42
Stomach ulcer	No	149	79.68
	Yes	38	20.32
Charlson Comorbidity Index			
	0	47	25.13
	1	43	22.99
	2	45	24.06
	3	26	13.9
	4	17	9.09
	5	3	1.6
	6	4	2.14
	7	2	1.07
American Society of Anesthesiologists Grade			
	1	5	2.43
	2	105	50.97
	3	92	44.66
	4	4	1.94

*Retired because of back pain.

TABLE 3. Baseline Categorical Operative Variables*

Variable	Value Labels	Frequency	%
Site	A	60	28.57
	B	18	8.57
	C	43	20.48
	D	89	42.38
Surgeon	A	74	35.24
	B	18	8.57
	C	43	20.48
	D	15	7.14
	E	38	18.1
	F	3	1.43
	G	19	9.05
Weekday	Monday	37	17.62
	Tuesday	73	34.76
	Wednesday	47	22.38
	Thursday	30	14.29
	Friday	23	10.95
Anterior approach	No	141	67.14
	Yes	69	32.86
Staged procedure	No	178	84.76
	Yes	32	15.24

TABLE 3 (*Continued*)

Variable	Value Labels	Frequency	%
Posterior instrumented fusion	No	3	1.43
	Yes	207	98.57
Rod diameter	4.5	91	43.54
	5.5	45	21.53
Rod material	6.5	73	34.93
	Cobalt chromium	100	48.08
	Steel	78	37.5
	Titanium	30	14.42
Posterior upper-most instrumented vertebrae	T1	2	0.96
	T2	17	8.13
	T3	37	17.7
	T4	35	16.75
	T5	11	5.26
	T6	4	1.91
	T7	0	0
	T8	4	1.91
	T9	10	4.78
Posterior lower-most instrumented vertebrae	T10	57	27.27
	T11	14	6.7
	T12	10	4.78
	L1	4	1.91
	L2	3	1.44
	L3	1	0.48
	T12	3	1.44
	L1	3	1.44
	L2	2	0.96
	L3	5	2.39
	L4	14	6.7
	L5	5	2.39
	S1	7	3.35
	Ilium	170	81.34
Interbody fusion	No	107	50.95
	Yes	103	49.05
Decompression performed	No	71	33.81
	Yes	139	66.19
Osteotomy performed	No	76	36.19
	Yes	134	63.81
Use of allograft	No	99	47.14
	Yes	111	52.86
Use of iliac crest autograft	No	155	73.81
	Yes	55	26.19
Use of local bone autograft	No	88	41.9
	Yes	122	58.1
Use of rhBMP-2	No	71	33.81
	Yes	139	66.19
Postop stay in surgical ICU	No	67	33.67
	Yes	132	66.33

ICU indicates intensive care unit; L, lumbar; rhBMP-2, recombinant human bone morphogenetic protein-2; S, sacrum; T, thoracic.

following the index procedure, the cumulative mean direct costs, inclusive of the index surgery, had increased to $74,073 (SD = $26,150, range: $28,748–$172,660). At the 90-day time point, 31 (14.8%) patients had exceeded the CC threshold. Cumulatively, 13 revision procedures in 11 (5.2%) patients had been performed (Figure 1), with the most common indications of proximal junctional kyphosis (PJK), infection, and implant prominence/malposition.

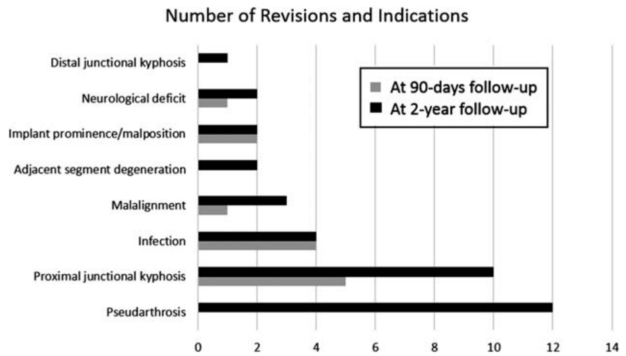

Figure 1. Cumulative number of revision procedures and indications at the 90-day and 2-year postoperative time points for 210 patients treated surgically for adult spinal deformity. At 90 days, nine patients had one revision, and two had two revisions. At 2 years, 19 patients had one revision, five had two revisions, one had three revisions, and one had four revisions. The total number of revisions at 90 days and 2 years was 13 and 36, respectively, and the total number of patients affected at 90 days and 2 years was 11 and 26, respectively.

By 2 years following the index procedure, the cumulative mean direct costs, inclusive of the index surgery, had increased to $77,765 (SD = $32,753, range: $28,748–$213,342). At the 2-year time point, 40 (19.1%) patients had exceeded the CC threshold. Cumulatively, 36 revision procedures in 26 (12.4%) patients had been performed (Figure 1), with the most common indications of pseudarthrosis (n = 12), PJK (n = 10), infection (n = 4), and malalignment (n = 3).

Histograms of 90-day and 2-year direct costs, inclusive of index episode of care costs, stratified by contributing site and surgeon are illustrated in Figure 2. Plots of 90-day and 2-year direct costs, stratified by number of levels fused and surgeon and by operative year and surgeon, are shown in Figures 3 and 4, respectively.

A total of 751 values of 21,299 data points (3.52%) were missing. These missing points were imputed with a normalized root mean squared error of 0.7%.

Linear Regression Models

Linear regression with forward stepwise selection obtained an in-sample R^2 of 87.8% and adjusted R^2 of 80.6% with 40 of 100 potential predictors for 90-day direct costs. For 2-year direct costs, linear regression obtained an in-sample R^2 of 73.8% and adjusted R^2 of 64% with 35 of 100 potential predictors. Tables 4 and 5 provide a summary of the variable selection process. Although no external validity can be placed in these results, the high degree of predictability achieved supports the usefulness of modeling of observable characteristics to infer future cost.

For 90-day direct costs, the three variables with the highest predictive ability were number of fused levels, approach, and surgeon (Table 4). These three factors alone achieved adjusted R^2 values of 53.6% and achieved respective adjusted R^2 increases of 23.4%, 18.1%, and 12.2%, respectively. Other relevant factors included LOS, previous posterior fusion, and age, which provide adjusted R^2 increases of 7.0%, 2.7%, and 2%, respectively. Other factors had statistically significant increases in predictive power but at lower levels (Table 4).

The three variables with the highest predictive ability for 2-year cost prediction based on linear regression models were number of fused levels, IBF, and surgeon (Table 5). These top three variables accounted for 34.8% of the 2-year cost variance. Other top variables that predicted 2-year cost included LOS, procedure staging, previous posterior fusion, surgical time, and years of spine problems (Table 5).

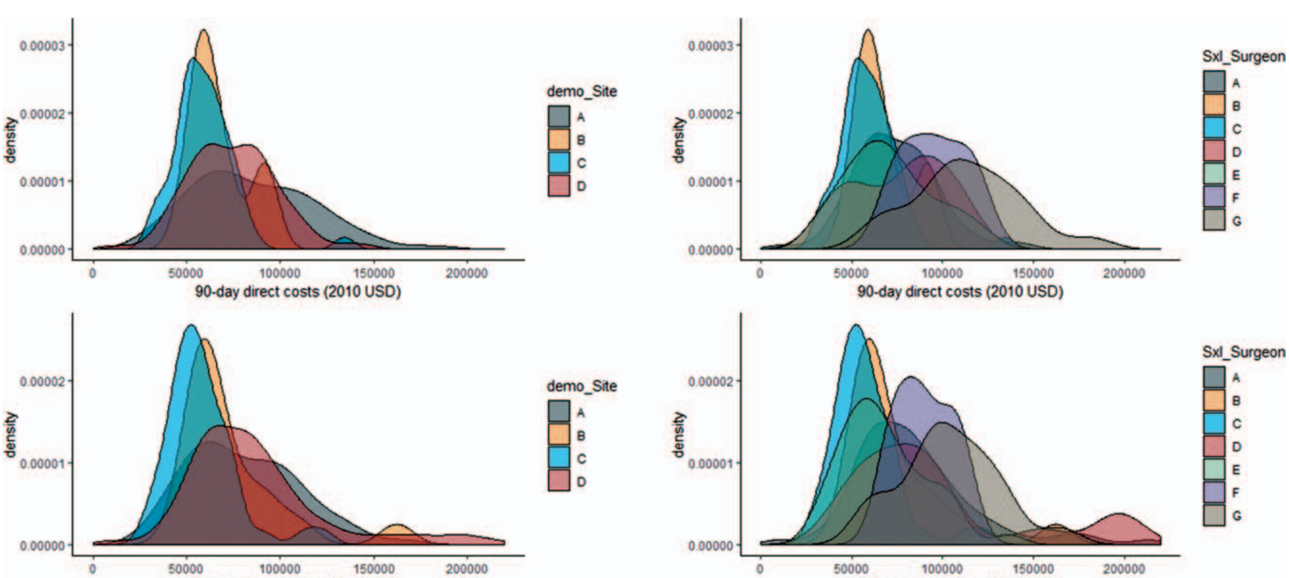

Figure 2. Direct costs of adult spinal deformity surgery (2010 US dollars) including index episode of care costs and cost of any related reoperations up to the 90-day and 2-year postoperative time points, stratified by site (left, upper and lower panels, for 90-day and 2-year time points, respectively) and by surgeon (right, upper and lower panels, for 90-day and 2-year time points, respectively).

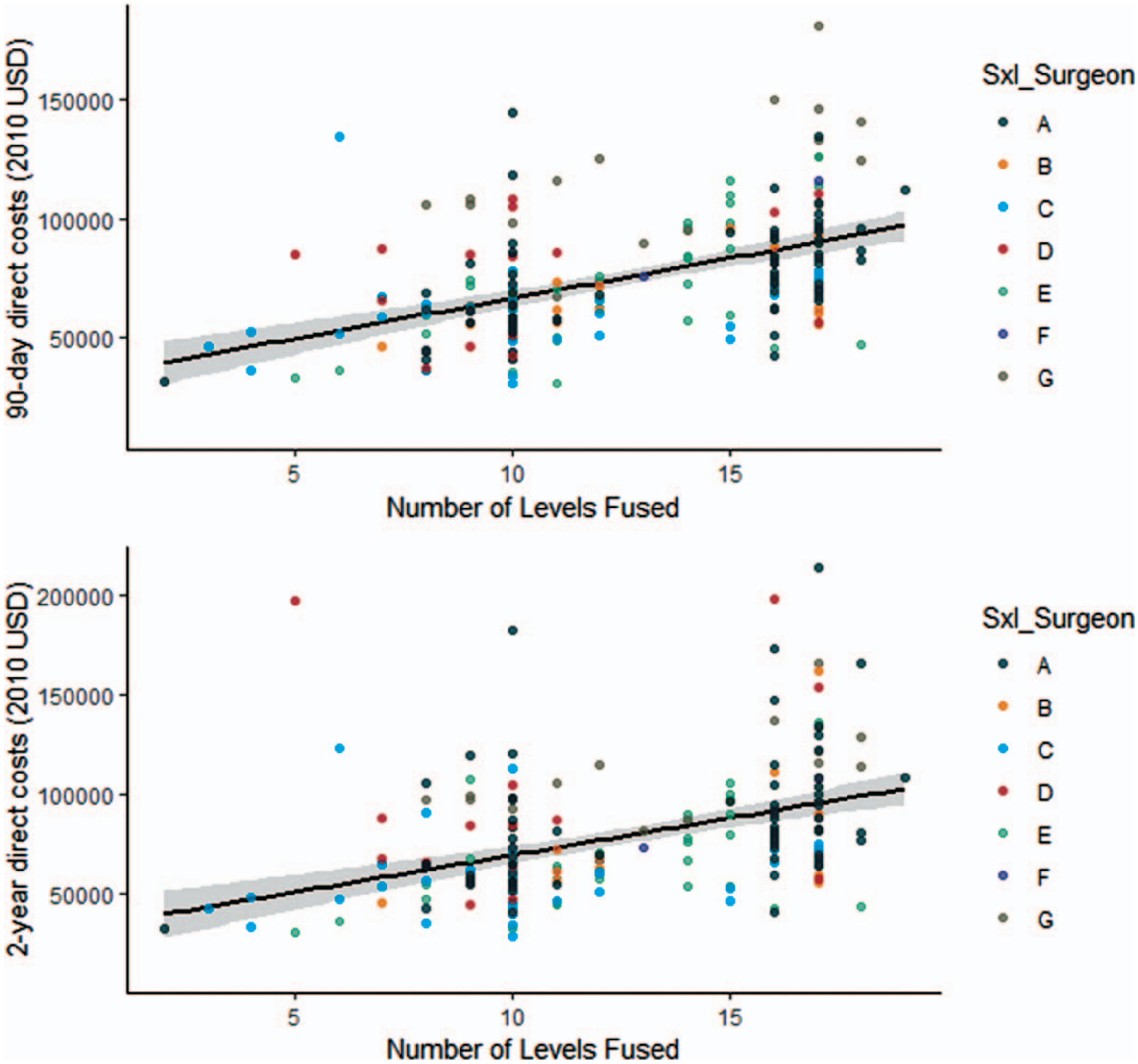

Figure 3. Direct costs of adult spinal deformity surgery (2010 US dollars) including index episode of care costs and cost of any related reoperations up to the 90-day (upper panel) and 2-year (lower panel) postoperative time points stratified by the number of vertebral levels fused. *x* Axis represents the number of vertebral levels fused in the surgery; *y* axis represents cost. Points represent the scatter of each observation and colors reflect different surgeons. Linear fit is presented by the black line fit with shadowed 95% confidence interval.

Regression Trees and Forests

Regression tree analysis using CTREEs resulted in adjusted R^2 values of 56% for 90-day and 35.6% for 2-year direct cost prediction and CC. Figures 5 and 6 present the structure of the simple predictive models for the two time horizons. Similar to the linear regression estimates, the number of vertebral levels fused (threshold of 12), surgical approach, IBF, and surgeon were the critical determinants of 90-day cost and CC (Figure 5). For 2-year estimates, the number of vertebral levels fused (threshold of 15) was the main determinant of cost and CC, whereas IBF, LOS, and number of vertebral levels fused (threshold of 10) were also in the model (Figure 6). However, it is important to recognize that the stability of these trees is limited when small sample sizes are used.

Random C-forest regression resulted in adjusted R^2 values of 57.4% for 90-day and 28.8% for 2-year direct cost prediction. Figures 7 and 8 provide the relative variable importance of predictors within the C-forest models. Although these estimates reflect lower predictive accuracy, the interpretation of variable importance is more stable than for the CTREE algorithm. Notably, for all three of the complex algorithms (linear regression, CTREEs, and random C-forest), top predictors were consistent and included number of vertebral levels fused, surgical approach, surgeon, IBF, and LOS.

DISCUSSION

There are many aspects of ASD with considerable variability, including occurrence of complications and outcomes.[24–32] ASD surgery costs can also vary substantially, owing at least in part to the high rates of complications.[11,33–38] The present study provides the rates of CC outliers for ASD surgery based on direct, actual cost, and identifies primary drivers of CC.

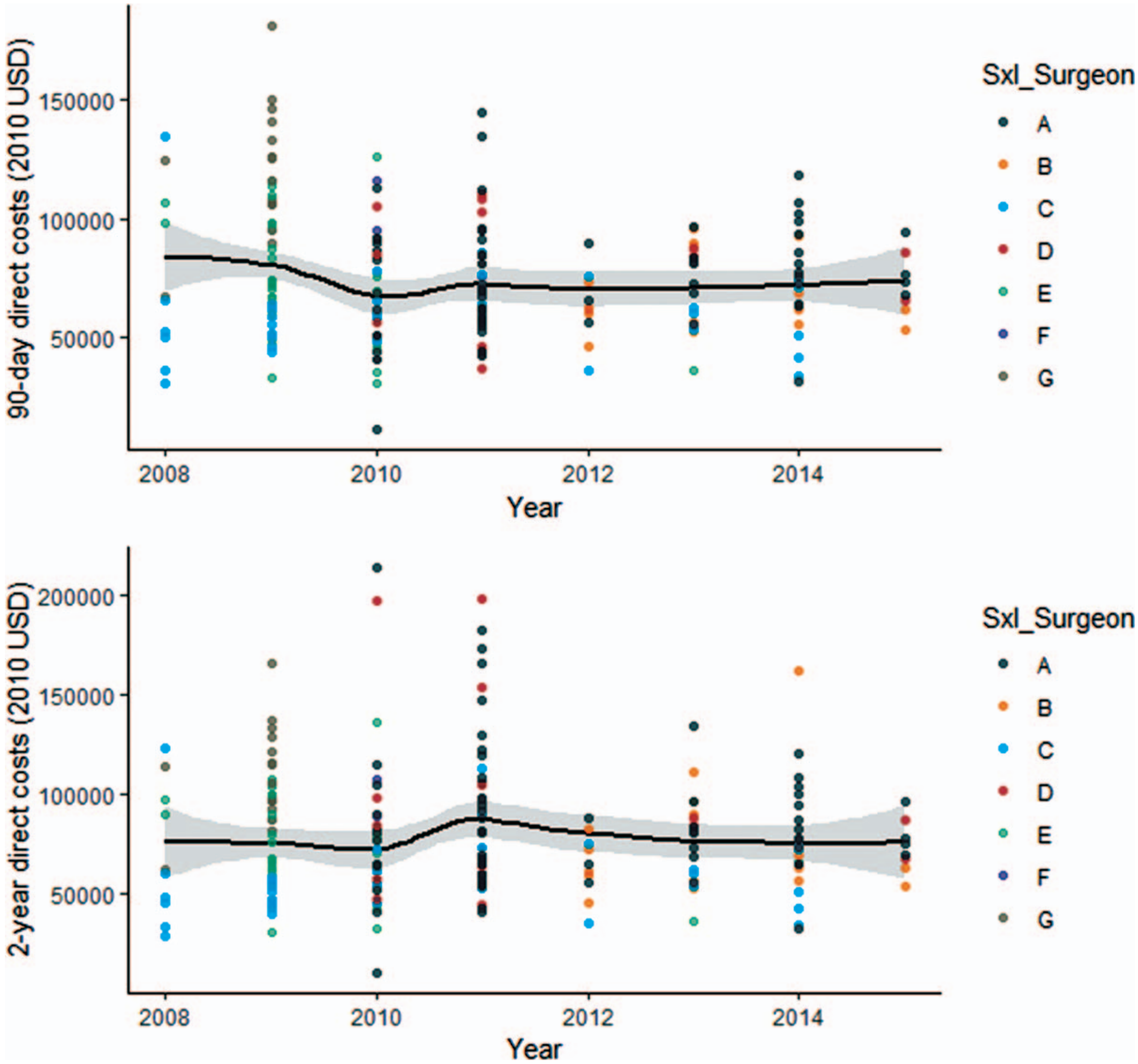

Figure 4. Direct costs of adult spinal deformity surgery (2010 US dollars) including index episode of care costs and cost of any related reoperations up to the 90-day (upper panel) and 2-year (lower panel) postoperative time points stratified by the year in which the index surgery was performed. *x* Axis represents the year in which the surgery took place; *y* axis represents 90-day cost. Points represent the scatter of each observation and colors reflect different surgeons. Polynomial fit is presented by the black line fit with shadowed 95% confidence interval.

Based on 210 ASD patients, the mean index episode of care direct cost was $70,766. By 90 days and 2 years following surgery, mean direct costs inclusive of the index procedure had increased to $74,073 and $77,765, respectively. Most commonly in cost analysis studies, Medicare allowable rates are utilized as a proxy for direct costs.[39] Although this is generalizable and provides a societal perspective, there are numerous flaws with this methodology especially in settings with known wide variation such as ASD surgery. In addition, Medicare reimbursement for spinal procedures has steadily and markedly decreased from 2000 to 2018,[40] without a commensurate decrease in cost. Our study is one of the few that provides cost analysis with actual cost data. Using direct cost offers potential advantages, as there are substantial variabilities in ASD surgical technique, instrumentation, biologics, and surgical cost incurred at the hospital level.[39,41–43]

Within 90 days of the index surgery, 11 (5.2%) patients underwent 13 revisions procedures, and by 2 years, 26 (12.4%) patients had undergone 36 revision procedures. The most common indications for revision were pseudarthrosis, PJK, wound infection, and malalignment. These revision rates and indications are comparable to previous reports. Crawford *et al*[35] reported that 7% of ASD patients required an unplanned reoperation within 90 days and 24% required reoperation at up to 44-month follow-up. Indications included rod fracture/pseudarthrosis, PJK, radiculopathy/screw removal, and wound-related issues. Smith *et al*[33] reported that 28.2% of ASD patients with 2-year follow-up required an unplanned reoperation, with the most common indications of rod breakage/pseudarthrosis, PJK, neurologic complications, and wound-related issues.

Three complex algorithms were applied to the data to identify factors associated with cost at 90 days and 2 years.

TABLE 4. Variable Selection for Linear Regression Model of 90-day Direct Costs for Adult Deformity Surgery*

Step	Variable Entered	R^2	Adj. R^2	R^2 ↑	AIC	RMSE
1	Number of fused levels	23.72%	23.35%	23.35%	4816.2	22893.8
2	Approach (ant vs post)	42.01%	41.45%	18.10%	4760.6	20009.5
3	Surgeon	55.40%	53.63%	12.18%	4717.5	17807.7
4	Length of hospital stay	61.97%	60.26%	6.63%	4686.0	16485.6
5	Prior posterior fusion	64.72%	62.95%	2.69%	4672.2	15918.0
6	Age	66.84%	64.99%	2.04%	4661.2	15471.8
7	Rod diameter	68.49%	66.40%	1.41%	4654.5	15157.1
8	History of blood clots	69.48%	67.29%	0.89%	4649.8	14956.9
9	SRS-22r Pain Score	70.66%	68.40%	1.11%	4643.5	14701.1
10	SRS-22r Appearance Score	72.04%	69.72%	1.32%	4635.4	14,390.5
11	Interbody fusion	72.88%	70.47%	0.75%	4631.0	14,209.5
12	SRS-22r Activity Score	73.71%	71.23%	0.76%	4626.5	14,026.2
13	Instrumented fusion	74.23%	71.65%	0.42%	4624.3	13,923.8
14	Years with spine problems	75.36%	72.32%	0.67%	4622.8	13,758.7
15	Use of allograft	75.78%	72.63%	0.31%	4621.3	13,680.0
16	Posterior approach	76.17%	72.94%	0.31%	4619.8	13,604.3
17	Estimated blood loss	76.58%	73.26%	0.32%	4618.2	13,523.2
18	SRS-22r Mental Health Score	76.93%	73.51%	0.25%	4617.0	13,459.3
19	History of anemia	77.26%	73.74%	0.23%	4616.0	13,400.1
20	Prior posterior fusion	77.64%	74.03%	0.29%	4614.5	13,325.3
21	UIV type: screw	78.61%	74.60%	0.57%	4613.2	13,179.5
22	Postop stay in surgical ICU	78.86%	74.76%	0.16%	4612.7	13,138.8
23	Psychiatry comorbidities	79.17%	74.99%	0.23%	4611.5	13,078.9
24	History of lung disease	79.45%	75.17%	0.18%	4610.8	13,030.4
25	UIV: level	81.77%	76.18%	1.01%	4611.6	12,761.5
26	History of heart disease	82.18%	76.57%	0.39%	4608.9	12,657.7
27	Decompression performed	82.56%	76.93%	0.36%	4606.3	12,561.6
28	No comorbidity	84.07%	77.81%	0.88%	4603.3	12,319.6
29	Osteotomy performed	84.39%	78.10%	0.29%	4601.0	12,236.4
30	History of hypertension	84.65%	78.32%	0.22%	4599.5	12,175.5
31	Use of rhBMP-2	84.89%	78.52%	0.20%	4598.2	12,120.3
32	No interbody fusion	85.12%	78.69%	0.17%	4597.0	12,070.3
33	History of cancer	85.36%	78.89%	0.20%	4595.6	12,014.5
34	Rod material	85.80%	79.25%	0.36%	4593.1	11,912.7
35	ASA Grade	86.32%	79.57%	0.32%	4591.3	11,818.9
36	SF-36 PCS	86.60%	79.85%	0.28%	4589.0	11,739.0
37	UIV Type: hook	86.93%	80.06%	0.21%	4587.7	11,677.4
38	Work status	87.54%	80.42%	0.36%	4585.6	11,570.3
39	History of stomach ulcer	87.69%	80.51%	0.09%	4585.1	11,545.0
40	Height	87.81%	80.55%	0.04%	4585.1	11,532.1

Adj. R^2, variable-adjusted coefficient of determination; AIC, Akaike Information criteria; ant, anterior; ASA, American Society of Anesthesiologists; ICU, intensive care unit; PCS, Physical Component Summary; post, posterior; R^2, coefficient of determination; R^2↑, increase in R^2 attributed to this variable; rhBMP-2, recombinant human bone morphogenetic protein-2; RMSE, root mean squared error; SRS, Scoliosis Research Society; Step, sequential iterative steps for variable inclusion in the linear regression model; UIV, upper-most instrumented vertebra.

At both time horizons, top predictors of cost on linear regression modeling included the number of fused vertebral levels, surgeon, revision status, and LOS. Other top predictors included surgical approach, use of IBF, age, operative time, and years of spine problems. Several of these predictive factors are likely directly linked to added cost. For example, increased number of fusion levels requires more implants and grafting material, longer hospital stays incur greater cost, and greater operative time incurs increased labor cost and resource use. As LOS is one of the primary factors associated with cost, development of enhanced recovery after spine surgery pathways may have significant impact on cost reduction for ASD surgery.[44–46] The reasons for the high degree of variance explained by the specific surgeon are not readily apparent, but suggest the potential for efficiency gains by standardization in patient and treatment selection.

TABLE 5. Variable Selection for Linear Regression Model of 2-year Direct Costs for Adult Deformity Surgery*

Step	Variable Entered	R^2	Adj. R^2	R^2 ↑	AIC	RMSE
1	Number of fused levels	18.28%	17.89%	17.89%	4925.2	29,679.1
2	Interbody fusion	28.26%	27.57%	9.68%	4899.8	27,874.6
3	Surgeon	37.26%	34.76%	7.19%	4883.7	26,454.9
4	Length of hospital stay	41.57%	38.94%	4.18%	4870.8	25,594.6
5	2-stage procedure	43.59%	40.75%	1.81%	4865.4	25,210.7
6	Prior posterior fusion	45.55%	42.52%	1.77%	4860.0	24,832.0
7	Surgical time	47.55%	44.35%	1.83%	4854.1	24,432.8
8	Years of spine problems	50.66%	46.57%	2.22%	4849.3	23,942.1
9	History of arthritis	51.78%	47.51%	0.94%	4846.4	23,730.6
10	SRS-22r Pain Score	52.76%	48.31%	0.80%	4844.1	23,548.6
11	SRS-22r Appearance Score	54.40%	49.84%	1.53%	4838.7	23,197.4
12	History of leg weakness	55.39%	50.67%	0.83%	4836.1	23,005.0
13	Postop stay in surgical ICU	56.61%	51.76%	1.09%	4832.3	22,749.3
14	History of blood clots	57.45%	52.45%	0.69%	4830.1	22,585.7
15	Rod diameter	58.80%	53.46%	1.01%	4827.4	22,344.4
16	UIV Type: screw	60.86%	54.80%	1.34%	4824.6	22,019.2
17	SF-36 Vitality Score	61.41%	55.20%	0.40%	4823.6	21,923.6
18	SRS-22r Total Score	62.16%	55.82%	0.62%	4821.5	21,770.0
19	LIV	64.67%	57.07%	1.25%	4821.1	21,459.7
20	Rod material	65.92%	58.10%	1.03%	4817.6	21,202.3
21	History of lung disease	66.55%	58.63%	0.53%	4815.6	21,065.6
22	SF-36 PCS	67.14%	59.12%	0.49%	4813.9	20,940.4
23	Oswestry Disability Index	67.74%	59.62%	0.50%	4812.0	20,812.6
24	History of PVD	68.38%	60.18%	0.56%	4809.8	20,667.5
25	SRS-22r Mental Health score	68.93%	60.65%	0.47%	4808.1	20,546.5
26	Estimated blood loss	69.36%	60.95%	0.30%	4807.2	20,466.7
27	History of depression	69.93%	61.45%	0.50%	4805.2	20,336.6
28	Work status	71.51%	62.55%	1.10%	4801.9	20,044.0
29	History of heart disease	72.01%	62.97%	0.42%	4800.2	19,931.3
30	History of bladder incontinence	72.44%	63.31%	0.34%	4799.0	19,840.4
31	History of cancer	72.90%	63.69%	0.38%	4797.4	19,735.6
32	History of loss of balance	73.17%	63.82%	0.13%	4797.3	19,701.0
33	SF-36 Social Role Functioning	73.38%	63.87%	0.05%	4797.7	19,688.5
34	Decompression performed	73.61%	63.95%	0.08%	4797.9	19,666.8
35	History of kidney disease	73.80%	63.98%	0.03%	4798.3	19,658.3

Adj. R^2, variable-adjusted coefficient of determination; AIC, Akaike Information criteria; ICU, intensive care unit; LIV, lower-most instrumented vertebra; PCS, Physical Component Summary; PVD, peripheral vascular disease; R^2, coefficient of determination; R^2↑, increase in R^2 attributed to this variable; RMSE, root mean squared error; SRS, Scoliosis Research Society; Step, sequential iterative steps for variable inclusion in the linear regression model; UIV, upper-most instrumented vertebra.

CTREE models were performed to predict which patients would exceed the CC threshold. At both 90-day and 2-year time points, the number of vertebral levels fused and use of IBF were predictive factors for exceeding CC. Other factors in the models included surgical approach, surgeon, and LOS. As the stability of CTREE models can be limited with small sample sizes, random C-forest modeling was used to confirm the stability of the CTREE models.

It is notable that for all three of the complex algorithm models, the top cost predictors were similar and included number of vertebral levels fused, surgical approach, surgeon, use of IBF, and LOS. Many of these predictors overlap with those in previous reports. Zygourakis *et al*[11] assessed more than 50,000 ASD fusions in the National Inpatient Sample database. They identified patient factors associated with cost, including age, race, insurance status, illness severity, LOS, and elective admission. Stephens *et al*[47] reported the following drivers of ASD surgery cost: patient comorbidities, deformity diagnosis, number of levels involved, length of surgery, LOS, 90-day readmission, and inpatient rehabilitation.

Strengths of the present study include the prospective multicenter design and utilization of direct cost data. Limitations include the relatively small number of patients. Direct costs in the present study do not include those incurred at other hospitals or facilities. However, it is likely

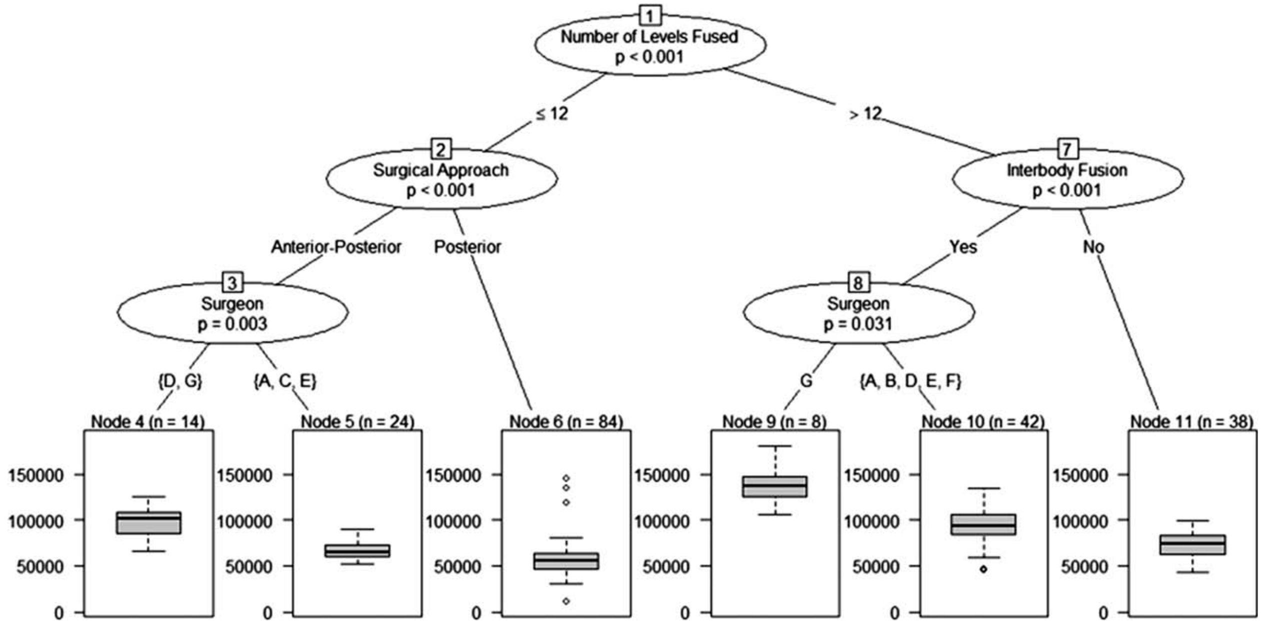

Figure 5. Ninety-day cost conditionally unbiased regression tree for direct costs of adult spinal deformity surgery (2010 US dollars). Each node represents a decision rule extracted from the predictive model, and if it is satisfied, the subsequent left node is followed until exhaustion of nodes. Node [1] references number of vertebral levels fused in the surgery [1], and if the number of levels is >12, then the interbody fusion node follows [3]. If no interbody was performed, the model predicts that the direct cost of surgery will be approximately 75,000 US dollars.

that the vast majority of cost is associated with the index procedure and reoperations. Owing to the limited number of sites, we could not evaluate specific hospital center factors such as setting (urban versus rural), teaching status, ownership (profit versus not-for-profit), center region, and center volume, which could impact cost. Although specific surgeon was associated with cost, the interpretation can only be related to unobserved factors constant at a surgeon level, which implies that the present study cannot be used to meaningfully compare cost between surgeons, as this would

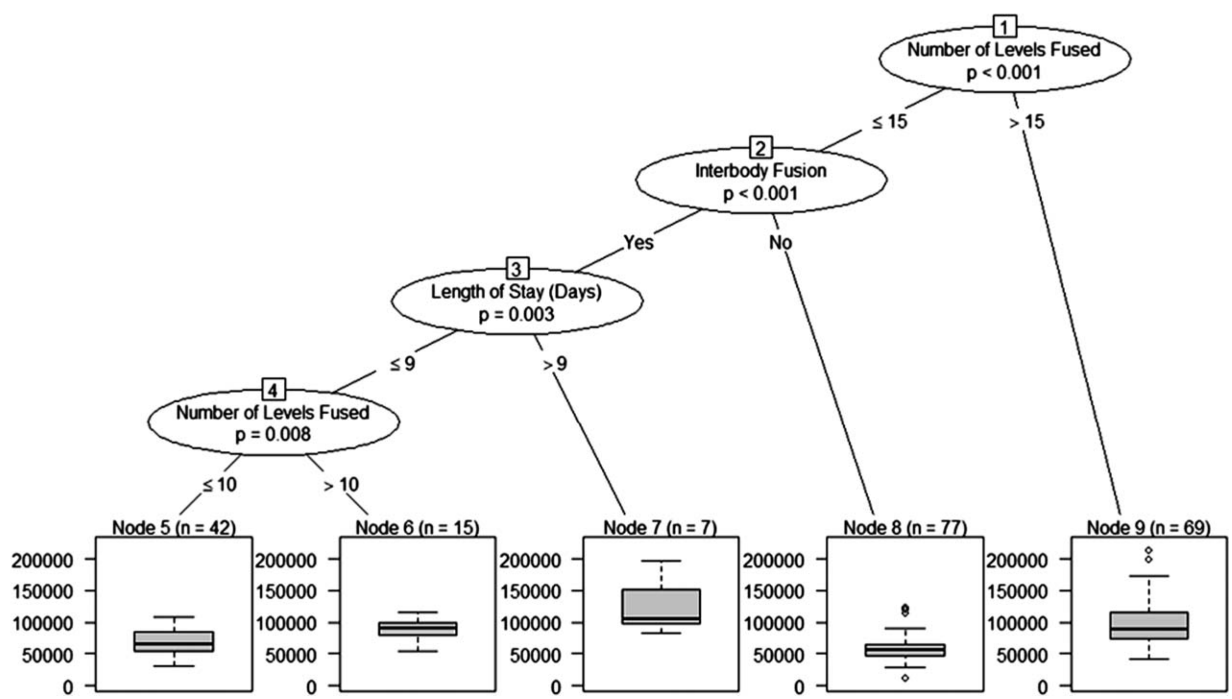

Figure 6. Two-year cost conditionally unbiased regression tree for direct costs of adult spinal deformity surgery (2010 US dollars). Each node represents a decision rule extracted from the predictive model, and if it is satisfied, the subsequent left node is followed until exhaustion of nodes. Higher nodes denote higher predictive ability and hierarchy.

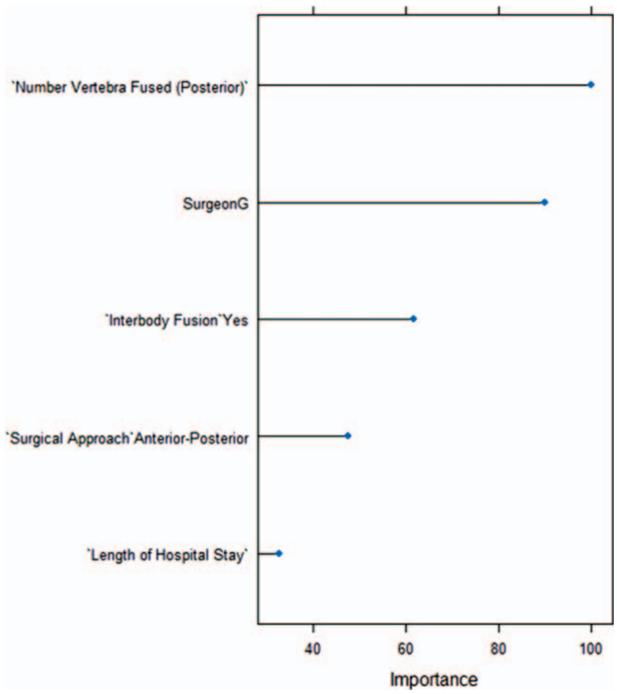

Figure 7. Relative variable importance for random forest model of 90-day direct cost for adult spinal deformity surgery.

require random allocation of patients to surgeons. Lastly, it is important to highlight that associations covered in this study cannot be interpreted as causal.

CONCLUSION

The present study demonstrates that direct cost in ASD surgery can be accurately predicted. Top predictors of direct cost included number of levels fused, surgical approach, surgeon, IBF, and LOS. The CC threshold at index surgery and 90-day and 2-year follow-up was exceeded by 11.9%, 14.8%, and 19.1% of patients, respectively. Collectively, these findings may not only prove useful for bundled care initiatives, but also may provide insight into means to reduce and better predict cost of ASD surgery outside of bundled payment plans.

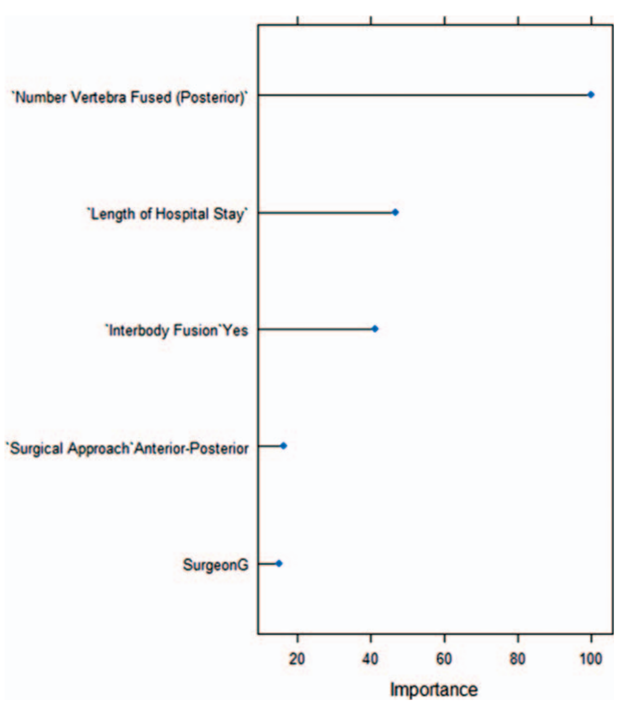

Figure 8. Relative variable importance for random forest model of 2-year direct cost for adult spinal deformity surgery.

➢ Key Points

- ❑ There is wide variability surrounding the cost for ASD surgery, including a subset of outlier patients that exceed CC.
- ❑ The ability to predict cost associated with ASD surgery and to predict which patients may exceed CC could prove useful for bundled care initiates and provide insight into means to reduce cost of ASD surgery.
- ❑ The present study demonstrates that direct cost in ASD surgery can be accurately predicted.
- ❑ Top predictors of CC were number of fused levels, surgical approach (anterior-posterior versus posterior-alone), surgeon, use of IBF, and LOS.
- ❑ The ability to accurately estimate cost and to identify patients that are likely to fall outside of risk sharing warranties could make 90-day bundled payment models feasible for ASD and may facilitate self-insurance by large corporations for this challenging condition.

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