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Epidemiology of C2 fractures and determinants of surgical management: analysis of a national registry

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ABSTRACT

Objective Operative management of axis fractures (C2) usually depend on the stability and location of the break and individual patient characteristics. We sought to describe the epidemiology of C2 fractures and hypothesized that determinants for surgery would differ by fracture diagnosis.

Methods Patients with C2 fractures were identified from the US National Trauma Data Bank from January 1, 2017, to January 1, 2020. Patients were classified by C2 fracture diagnosis: odontoid type II, odontoid types I and III, and non-odontoid fracture (hangman's fracture or fractures through base of the axis). The primary comparison was C2 fracture surgery versus non-operative management. Multivariate logistic regression was used to identify independent associations with surgery. Decision tree-based models were developed to identify determinants for surgery.

Results There were 38 080 patients; 42.7% had an odontoid type II fracture; 16.5% had an odontoid type I/III fracture; and 40.8% had a non-odontoid fracture. All examined patient demographics, clinical characteristics, outcomes, and interventions differed by C2 fracture diagnosis. Overall, 5292 (13.9%) were surgically managed (17.5% odontoid type II, 11.0% odontoid type I/III, and 11.2% non-odontoid; p<0.001). The following covariates increased odds of surgery for all three fracture diagnoses: younger age, treatment at a level I trauma center, fracture displacement, cervical ligament sprain, and cervical subluxation. Determinants of surgery differed by fracture diagnosis: for odontoid type II, age ≤80 years, a displaced fracture, and cervical ligament sprain were determinants; for odontoid type I/III, age ≤85 years, a displaced fracture, and cervical subluxation were determinants; for non-odontoid fractures, cervical subluxation and cervical ligament sprain were the strongest determinants for surgery, by hierarchy.

Conclusions This is the largest published study of C2 fractures and current surgical management in the USA. Odontoid fractures, regardless of type, had age and fracture displacement as the strongest determinants for surgical management, whereas associated injuries were determinants of surgery for non-odontoid fractures.

Level of evidence III.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Controversy exists in the management of fractures to the second vertebrae (C2 fractures), with wide variation in practice in part due to the location of the break and the frequency of these injuries among the elderly.

WHAT THIS STUDY ADDS

⇒ There were significant differences in demographics, injury patterns, outcomes, and surgical management based on C2 fracture diagnosis. Decision tree modeling identified similar determinants of surgery for type I, II, and III odontoid fractures being age and fracture displacement, whereas determinants of surgery for non-odontoid fractures were associated injuries of cervical subluxation and cervical ligament sprain.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ This is the largest published descriptive study of C2 fractures and surgical management in the USA to date. The findings from our models inform current management practices in the USA and may be used for additional study of outcomes based on determinants of surgery.

BACKGROUND

Fractures of the second vertebrae (C2), or axis, are the most common cervical spine injuries and typically result from motor vehicle collisions or falls that cause the neck and head to snap forward or backward or twist suddenly. These axis fractures are usually characterized into odontoid fractures and what is colloquially known as hangman's fractures. Odontoid fractures are further classified as type I (fractures through the tip), type II (fractures through the base), and type III (fractures through the body of the C2 vertebral body).[1] The overall incidence of C2 fractures has increased annually in the USA,[2] as well as in other countries.[3] This increase is driven largely by the aging population who are at increased risk of odontoid fractures specifically.[4 5]

Controversy exists in the management of C2 fractures. Historically, the overall gestalt of fracture management is that hangman's fractures and type I and III odontoid fractures are treated non-operatively with cervical orthoses, whereas there is wide variation in practice for the management of odontoid type II fractures[5 6] due to the frequency of these injuries among the elderly.[7 8] The degree to which the fracture is displaced and the age and frailty of the patient both play a role in whether surgical or non-operative management is the preferred approach. However, recent treatment guidelines are generally based on a review of the literature rather than taking a statistical approach for prediction and classification.[5 9–11]

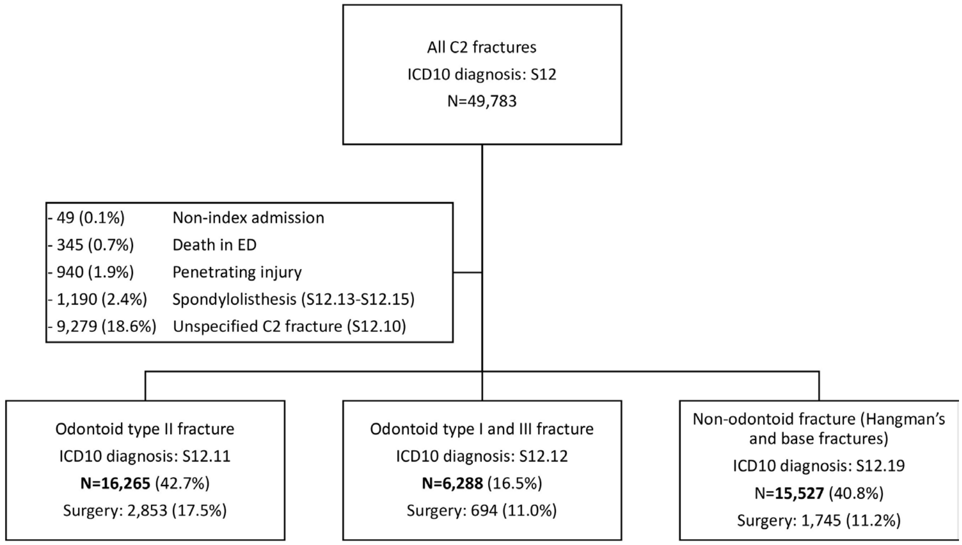

Figure 1 Patient disposition. ED, emergency department; ICD-10, International Classification of Diseases, 10th Revision.

Our study objectives are twofold: (1) to provide a detailed epidemiological evaluation of C2 fractures using a large national registry and (2) to analyze associations with operative intervention and model determinants of surgery using decision tree analysis. We hypothesized that determinants of surgery would differ by C2 fracture diagnosis.

METHODS

This national registry analysis used the American National Trauma Data Bank (NTDB), which is the largest aggregation of admissions due to traumatic injury.[12] Patients admitted for a C2 fracture from January 1, 2017, to January 1, 2020, were included (figure 1). Exclusions were patients who died in the ED (0.1% of C2 fracture admissions), subsequent, non-index admissions (0.7%), and penetrating injuries (1.9%).

Study groups were determined based on C2 fracture diagnosis using the International Classification of Diseases, 10th Revision, diagnosis code (figure 2): odontoid type II fracture (S12.11), odontoid type I or III fracture (S12.12), and other fractures (S12.19, used primarily for hangman's fracture but also includes fractures through the base of the axis; this group is defined as non-odontoid fractures in the table and text). Patients with other C2 diagnoses were excluded: traumatic spondylolisthesis without fracture (S12.13–S12.15) and unspecified fractures (S12.1 and S12.10; these fractures did not have sufficient information in the medical record to determine if it was an odontoid I, II, III, or non-odontoid fracture).

The dependent variable of interest was surgical intervention of the C2 fracture, identified using ICD-10 procedure codes for cervical fusion and internal fixation. ICD-10 diagnosis codes and procedure codes used throughout this study can be found in online supplemental table 1.

There were 26 covariates of interest, categorized as follows:

- Demographics: age in years (median and IQR; patients >89 years were coded as 90 years old); sex (male and female); race (non-Hispanic (NH) white, NH black, NH other, Hispanic, and unspecified); individual comorbidities with >10% incidence.
- Hospital characteristics: transferred in from another facility for definitive care (yes or no) and trauma level (level I or II or III/IV or unverified/not applicable), based on American College of Surgeons (ACS) verification; for hospitals unverified by the ACS but state designated I or II, the state designation was used.
- Injury characteristics, in addition to fracture type: fracture displacement (displaced or non-displaced, based on ICD-10 diagnosis codes); cause of injury (ground-level fall, fall from height, motor vehicle crash or motorcycle crash (MVC), all other causes); abnormal emergency department (ED) vital signs of systolic blood pressure (SBP <90 mm Hg), heart rate (HR <60 or >120 beats/min), and respiratory rate (RR

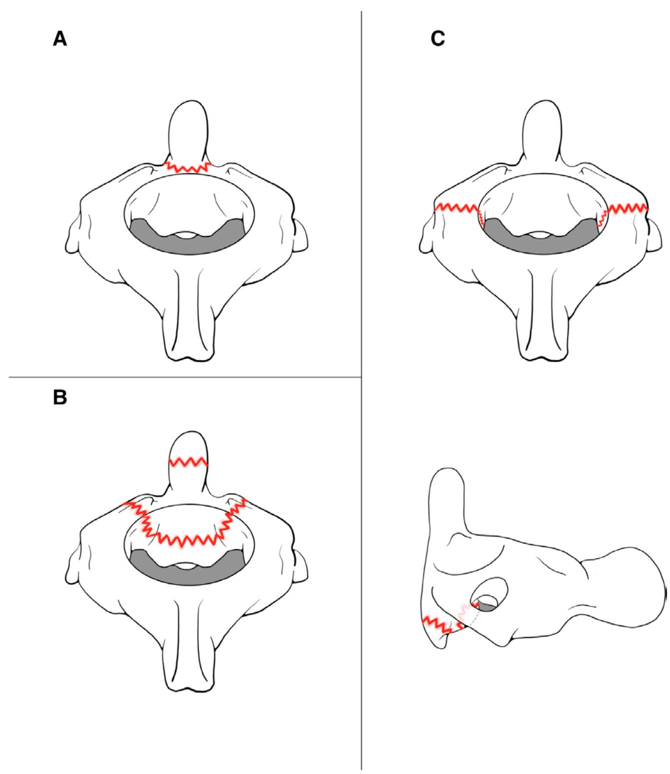

Figure 2 C2 fracture diagnoses. (A). Odontoid type II fracture (ICD-10 diagnosis: S12.11). (B) Odontoid type I/III fracture (ICD-10 diagnosis: S12.12). (C) Other, non-odontoid fracture (hangman's fracture and C2 base fracture, ICD-10 diagnosis: S12.19). ICD-10, International Classification of Diseases, 10th Revision.

<12 or >20 breaths/min); ED Glasgow Coma Scale (GCS) motor component (median and IQR, scores range from 1 (worst) to 6 (best); severe concomitant injury to the head/neck, face, thorax, abdomen/pelvis, or extremities (defined with the Abbreviated Injury Scale region and score ≥3); and associated injury diagnoses for cervical ligament sprain, vertebral subluxation and dislocation, and intracranial injury (defined by ICD-10 diagnosis codes).

In-hospital outcomes of mortality (%), intensive care unit (ICU) admission, hospital length of stay (LOS), ICU LOS, and development of a complication in-hospital (yes or no) are also reported.

Statistical analysis

Analyses were performed with SAS V.9.4. A conservative alpha of <0.01 was used for statistical significance based on the large sample size. χ^2 tests (categorical variables, reported using %, n) and Wilcoxon rank-sum tests (continuous variables, reported using medians and IQR) were used to examine differences between study covariates and fracture diagnosis, as well as operative management. Collinearity was assessed with Spearman's rank correlation; values ≥0.4 had moderate-to-strong correlation. Intracranial injury and pre-existing hypertension were collinear with severe head/neck injury and age, respectively, and were not used in the models, but all remaining covariates were analyzed. For both regression models and decision trees, model fit was assessed with c-statistics.

Multivariate logistic regression with backward selection and exit criteria of p value of <0.01 determined independent associations with operative management for each fracture diagnosis. ORs and the associated 99% CIs were calculated from the regression models.

For decision trees, the high-performance split procedure(PROC HPSPLIT) was used to build a tree-based statistical model for classifying patients into operative versus non-operative management for each fracture diagnosis. Candidate splits for each node were based on criteria for impurity (entropy), which uses an entropy score from 0 to 1 to determine how to grow the tree based on how similar or impure the data were within each 'branch'. Cost complexity pruning was used to ensure the complexity (number of branches) was reduced to prevent overfitting.

RESULTS

There were 38 080 patients; 42.7% had an odontoid type II fracture; 16.5% had an odontoid type I/III fracture; and 40.8% had a non-odontoid fracture (figure 1). Among the odontoid fractures, the majority (72.1%) were type II fractures. The population median age was 74 (58 to 85) years; ground-level falls and MVCs were the most common causes of injury (31.9% and 31.4%, respectively); patients frequently presented with severe injuries besides the C2 fracture, including head/neck injuries (29.7%), extremity injuries (25.2%), and thoracic injuries (22.7%), and nearly half of the patients (45.6%) were treated at a level I trauma center.

As shown in table 1, there were statistically significant differences in all demographics, comorbidities, and presenting clinical characteristics by fracture diagnosis (p<0.001), with the exception of similar rates of mental/personality disorder comorbidities (p=0.63). For example, compared with odontoid type I/IIII and non-odontoid fractures, patients with odontoid type II fractures were older (median age: 80 years vs. 75 years and 65 years, respectively), were injured in a ground-level fall (44.8% vs. 31.0% and 18.6%), and were more likely to present with comorbidities but less likely to present with abnormal ED vital signs and concomitant injuries.

There were also significant differences in outcomes by fracture diagnosis (table 2). Compared with patients with odontoid

Table 1 Characteristics of patients with C2 fracture by fracture diagnosis

Characteristic, % or median (IQR)	Odontoid type II (n=16 265)	Odontoid types I and III (n=6288)	Non-odontoid* (n=15 527)	P value
Age (years), median (IQR)	80 (69–88)	75 (59–85)	65 (47–79)	**<0.001**
Female sex	52.0	53.6	47.7	**<0.001**
Race/ethnicity				**<0.001**
NH white	83.7	80.7	74.9	
NH black	4.8	6.0	9.1	
Hispanic	4.1	5.1	7.7	
NH other	2.7	3.7	4.7	
Unspecified	4.8	4.6	4.1	
Comorbidities†				
Anticoagulant use preinjury	18.5	14.7	11.3	**<0.001**
Dementia	16.0	11.8	7.1	**<0.001**
Diabetes	19.3	17.1	16.0	**<0.001**
Functional dependence	19.8	15.4	9.9	**<0.001**
Hypertension	61.4	52.8	44.2	**<0.001**
Mental/personality disorder	10.9	11.1	10.6	0.63
Smoker	10.2	14.4	17.9	**<0.001**
Interfacility transfer	48.3	42.4	36.7	**<0.001**
Trauma level				**<0.001**
Level I verified/designated	54.4	58.1	58.2	
Level II verified/designated	35.8	32.7	33.9	
Level III/IV verification	5.5	4.9	4.1	
Unverified by ACS	4.2	4.3	3.7	
Cause of injury				**<0.001**
MVC	18.0	32.5	45.0	
Fall from height	31.4	28.3	24.8	
Ground-level fall	44.8	31.0	18.6	
Other cause	5.7	8.1	11.6	
GCS motor score, median (IQR)	6 (6–6)	6 (6–6)	6 (6–6)	**<0.001**
Abnormal ED vital signs				
SBP <90 mm Hg	2.3	3.2	3.8	**<0.001**
HR <60 or >120	8.9	9.0	10.0	**0.004**
RR <12 or >20	16.1%	19.0%	21.8%	**<0.001**
Severe concomitant injury, AIS score ≥3				
Head/neck injury	21.8	30.0	37.7	**<0.001**
Facial injury	8.2	7.3	9.0	**<0.001**
Thoracic injury	13.9	23.0	21.7	**<0.001**
Abdomen/pelvic injury	3.4	6.0	8.7	**<0.001**
Extremity injury	17.9	26.6	32.4	**<0.001**
Other associated Injuries				
Displaced C2 fracture	73.7	71.3	67.8	**<0.001**
Cervical ligament sprain	3.9	5.2	7.4	**<0.001**
Vertebral subluxation/dislocation	3.2	2.8	3.9	**<0.001**
Intracranial injury	13.1	17.2	21.5	**<0.001**

Bold values denotes statistical significance with alpha <0.01.
*Non-odontoid fractures are other C2 fractures (S12.19) including hangman's fracture and fractures through the base of the axis.
†Comorbidities with at least 10% incidence are tabulated.
ACS, American College of Surgeons; AIS, Abbreviated Injury Scale; ED, emergency department; GCS, Glasgow Coma Scale; HR, heart rate; MVC, motor vehicle crash or motorcycle crash; NH, non-Hispanic; RR, respiratory rate; SBP, systolic blood pressure.

Table 2 Procedures and outcomes of patients with C2 fracture

Variable, % or median (IQR)	Odontoid type II (n=16 265)	Odontoid types I and III (n=6288)	Non-odontoid* (n=15 527)	P value
Operative management	17.5	11.0	11.2	**<0.001**
Spinal fusion only	36.9	41.9	52.5	
Internal fixation without fusion	32.3	23.5	12.2	
Internal fixation with fusion	30.7	34.6	35.3	
Other procedures				
Cervical joint/disc	1.3	1.3	3.2	**<0.001**
Cervical spinal cord	0.6	0.6	1.0	**<0.001**
Neurosurgery	0.7	1.4	2.1	**<0.001**
Mechanical ventilation	9.2	11.2	13.0	**<0.001**
Tracheostomy	2.5	3.4	4.5	**<0.001**
In-hospital outcomes				
Complication	11.8	13.0	13.0	**0.002**
In-hospital mortality	7.8	7.6	6.5	**<0.001**
ICU admission	42.7	45.6	51.2	**<0.001**
ICU LOS	3 (2–6)	3 (2–7)	3 (2–7)	**<0.001**
Hospital LOS	5 (3–8)	5 (3–9)	5 (3–9)	**0.01**
Disposition home/ home health	37.1	39.1	47.2	**<0.001**

*Non-odontoid fractures are other C2 fractures (S12.19) including hangman's fracture and fractures through the base of the axis.
ICU, intensive care unit; LOS, length of stay.

type II or type I/IIII fractures, patients with non-odontoid fractures had the lowest mortality rate (7.8%, 7.6%, and 6.5%, respectively; p<0.001) as well as the most favorable rate of hospital discharge disposition home (37.1%, 39.1%, and 47.2%, p<0.001), but the highest ICU admission rate (42.7%, 45.6%, and 51.2%, p<0.001).

Operative management

Overall, 5292 (13.9%) were operatively managed. The rate of operative management of C2 fractures differed by fracture diagnosis and was 17.5% for patients with odontoid type II fractures, 11.0% for odontoid type I/III fractures, and 11.2% for non-odontoid fractures. Most patients (76%) who were operatively managed had cervical fusion, and 24% had internal fixation without fusion.

As shown in table 3, the operative management group was younger than non-operatively managed patients (median age: 68 years vs. 75 years, p<0.001), less likely to be female (42.5% vs. 51.8%, p<0.001), less likely to be white (77.7% vs. 79.9%, p<0.001), less likely to be injured from a ground-level fall (29.0% vs. 32.3%, p<0.001), more likely to be transferred in (46.3% vs. 42.0%, p<0.001), more likely to be treated at a level I trauma center (61.1% vs. 55.9%, p<0.001), more likely to have a displaced C2 fracture (86.5% vs. 68.4%, p<0.001), more likely to have associated injuries of cervical ligament sprain (13.3% vs. 4.3%, p<0.001) and vertebral subluxation (9.6% vs. 2.4%, p<0.001), and to have concomitant head/neck injuries (33.0% vs. 29.1%, p<0.001) but less likely to have concomitant extremity injuries (23.0% vs. 25.6%, p<0.001). There were no differences for the operative and non-operative management groups in abnormal ED vital signs of GCS, SBP, RR, and HR and concomitant injuries to the face, thorax, abdomen, and pelvis. Compared with the non-operative group, the operative group had lower mortality (3.9% vs. 7.8%) but otherwise had worse outcomes (table 3).

Table 3 Characteristics of patients with C2 fracture by operative management

Characteristics, n (%) or median (IQR)	Nonoperative (32 788)	Operative (5292)	P value
Age, median (IQR)	75 (59–86)	68 (52–78)	**<0.001**
Female sex	51.8	42.5	**<0.001**
Race/ethnicity			**<0.001**
NH white	79.9	77.7	
NH black	6.5	8.2	
Hispanic	5.4	6.1	
NH other	3.6%	4.1%	
Unspecified	4.6%	3.8%	
Comorbidities*			
Anticoagulant use preinjury	15.6	10.7	**<0.001**
Dementia	12.6	5.9	**<0.001**
Diabetes	17.7	16.5	0.03
Functional dependence	15.9	9.9	**<0.001**
Hypertension	53.7	48.2	**<0.001**
Mental/personality disorder	10.6	12.1	**0.002**
Smoker	13.1	20.0	**<0.001**
Interfacility transfer	42.0	46.3	**<0.001**
Trauma level			
Level I verification/designation	55.9	61.1	**<0.001**
Level II verification/designation	34.7	33.3	
Level III/IV verification	5.2	3.1	
Unverified by ACS	4.3	2.6	
Cause of injury			**<0.001**
MVC	31.2	32.5	
Fall from height	28.3	27.9	
Ground-level fall	32.3	29.0	**<0.001**
Other cause	8.2	10.7	
GCS motor component score, median (IQR)	6 (6–6)	6 (6–6)	0.03
Abnormal ED vital signs			
SBP <90 mm Hg	3.1	2.6	0.04
HR <60 or >120	9.5	8.8	0.15
RR <12 or >20	18.9	18.9	0.87
Severe concomitant injury, AIS score ≥3			
Head/neck injury	29.1	33.0	**<0.001**
Facial injury	8.2	9.2	0.02
Thoracic injury	22.7	22.5	0.80
Abdomen/pelvic injury	6.0	6.2	0.65
Extremity injury	25.6	23.0	**<0.001**
Other associated Injuries			
Displaced C2 fracture	68.4	86.5	**<0.001**
Cervical ligament sprain	4.3	13.3	**<0.001**
Vertebral subluxation/dislocation	2.4	9.6	**<0.001**
Intracranial injury	17.4	15.8	**0.004**
C2 fracture diagnosis			
Odontoid type II	40.9	53.9	**<0.001**
Odontoid types I and III	17.1	13.1	
Non-odontoid† fracture	42.0	33.0	
In-hospital outcomes			
Complication	11.2	20.7	**<0.001**
In-hospital mortality	7.8	3.9	**<0.001**
ICU admission	43.0	68.9	**<0.001**
Median ICU LOS (days)	3 (2–6)	5 (3–10)	**<0.001**
Median hospital LOS (days)	5 (3–8)	9 (6–15)	**<0.001**
Disposition home/home health	42.0	38.7	**<0.001**

*Comorbidities with at least 10% incidence are tabulated.
†Non-odontoid fractures are other C2 fractures (S12.19) including hangman's fracture and fractures through the base of the axis.
ACS, American College of Surgeons; AIS, Abbreviated Injury Scale; ED, emergency department; GCS, Glasgow Coma Scale; HR, heart rate; ICU, intensive care unit; LOS, length of stay; MVC, motor vehicle crash or motorcycle crash; NH, non-Hispanic; RR, respiratory rate; SBP, systolic blood pressure.

Table 4 Multivariate logistic regression analysis of operative management for patients with C2 fracture

Covariate of interest	Odontoid type II (n=16 265) C-statistic: 0.72		Odontoid types I and III (n=6288) C-statistic: 0.71		Non-odontoid* (n=15 527) C-statistic: 0.73	
	AOR (99% CI)	P value	AOR (99% CI)	P value	AOR (99% CI)	P value
Age, 10-year increment	0.82 (0.78 to 0.85)	**<0.001**	0.85 (0.80 to 0.91)	**<0.001**	0.90 (0.87 to 0.93)	**<0.001**
Male vs. female sex	1.21 (1.07 to 1.36)	**<0.001**	–	–	1.27 (1.09 to 1.47)	**<0.001**
Fall, height vs. same-level fall	1.05 (0.92 to 1.21)	0.34	0.98 (0.72 to 1.33)	0.85	–	–
MVC vs. same-level fall	0.79 (0.65 to 0.97)	**0.003**	0.60 (0.42 to 0.84)	**<0.001**	–	–
Other cause vs. same-level fall	1.14 (0.89 to 1.47)	0.17	0.98 (0.63 to 1.52)	0.89	–	–
GCS motor score, 1-point increment	1.11 (1.05 to 1.18)	**<0.001**	1.14 (1.03 to 1.26)	**<0.001**	–	–
SBP ≤90 mm Hg vs. >90 mm Hg	0.62 (0.39 to 0.98)	**0.008**	–	–	–	–
Pulse >120 vs. ≤120 beats/min	–	–	–	–	0.78 (0.61 to 1.00)	**0.01**
Thoracic injury (AIS score ≥3) vs. no	0.80 (0.66 to 0.96)	**0.002**	–	–	–	–
Displaced vs. non-displaced	3.11 (2.63 to 3.68)	**<0.001**	2.48 (1.82 to 3.38)	**<0.001**	2.50 (2.07 to 3.00)	**<0.001**
Cervical ligament sprain vs. no	2.48 (1.95 to 3.17)	**<0.001**	3.07 (2.14 to 4.41)	**<0.001**	3.14 (2.58 to 3.83)	**<0.001**
Cervical subluxation vs. no	2.32 (1.77 to 3.05)	**<0.001**	3.74 (2.35 to 5.95)	**<0.001**	4.98 (3.88 to 6.39)	**<0.001**
Transferred in vs. no	1.19 (1.05 to 1.35)	**<0.001**	–	–	–	–
Level I TC vs. ACS non-verified	1.70 (1.20 to 2.39)	**<0.001**	2.29 (1.12 to 4.69)	**0.003**	2.11 (1.30 to 3.44)	**<0.001**
Level II TC vs. ACS non-verified	1.85 (1.31 to 2.62)	**<0.001**	2.05 (0.99 to 4.27)	0.012	1.88 (1.15 to 3.09)	**0.001**
Level III/IV TC vs. ACS non-verified	1.33 (0.86 to 2.06)	0.09	0.98 (0.36 to 2.67)	0.96	1.07 (0.54 to 2.12)	0.79
Comorbidities						
Anticoagulant vs. no	0.76 (0.64 to 0.90)	**<0.001**	–	–	0.72 (0.55 to 0.96)	**0.003**
Dementia vs. no	0.56 (0.45 to 0.69)	**<0.001**	–	–	0.44 (0.28 to 0.68)	**<0.001**
Functionally dependent vs. no	0.75 (0.63 to 0.90)	**<0.001**	0.51 (0.34 to 0.79)	**<0.001**	–	–
Mental/personality disorder vs. no	1.23 (1.03 to 1.47)	**0.003**	–	–	–	–
Smoker vs. no	1.33 (1.12 to 1.58)	**<0.001**	1.63 (1.23 to 2.17)	**<0.001**	–	–

Bolding denotes adjusted p≤0.01, statistically significant. The following covariates were not significantly associated with surgery in any of the three models after adjustment and are not presented in the table: race/ethnicity, diabetes comorbidity, abnormal respiratory rate, abdominal/pelvic injury (AIS score ≥3), head/neck injury (AIS score ≥3), facial injury (AIS score ≥3), and extremity injury (AIS score ≥3).
*Non-odontoid fractures are other C2 fractures (S12.19) including hangman's fracture and fractures through the base of the axis.
ACS, American College of Surgeons; AIS, Abbreviated Injury Scale; AOR, adjusted OR; GCS, Glasgow Coma Scale; MVC, motor vehicle or motorcycle collision; SBP, systolic blood pressure; TC, trauma center.

Multivariate models

The logistic regression models identified covariates that were independently associated with operative management by fracture diagnosis (table 4). For all three fracture diagnoses, the following covariates were independently associated with increased odds of operative management: younger age, admission to a level I trauma center (vs. unverified/not applicable trauma centers), a displaced C2 fracture, and associated injuries of cervical ligament sprain and vertebral subluxation. The following covariates were not significantly associated with surgery in any of the three models, by fracture diagnosis: race/ethnicity, diabetes comorbidity, abnormal RR, and severe injuries to the head/neck, abdomen/pelvis, face, or extremities.

For patients with odontoid type II fractures, the odds of surgery also increased with higher ED GCS motor scores, transfer in for definitive care, for men, and for comorbidities of mental/personality disorder and smoking; whereas there were decreased odds of surgery with severe thoracic injury, ED SBP of ≤90 mm Hg, MVC cause of injury, and comorbidities of chronic anticoagulant use, dementia, and functional dependence.

For patients with odontoid type I or III fractures, the odds of surgery also increased with higher ED GCS motor scores, for men, and for smokers, whereas there were decreased odds of surgery for patients with MVC cause of injury and patients who were functionally dependent.

For patients with non-odontoid fracture, the odds of surgery also decreased with comorbidities of chronic anticoagulant use and dementia, for women, and for patients with an abnormal ED pulse of >120 beats/min.

The decision tree analysis identified different determinants for operative management based on fracture diagnosis. For patients with a type II odontoid fracture, age was the most important determinant of surgery; patients >80 years old were only estimated to be surgically managed in 9% of cases (figure 3). A displaced odontoid type II fracture and a cervical ligament sprain were the two remaining determinants of surgical management. The estimated surgery rate was 24.9% for patients ≤80 years old and increased to 29.3% if the fracture was displaced, and was 49.2% if there was also cervical ligament sprain.

The decision tree for odontoid type I/III fractures similarly identified age as the most important determinant for surgery (figure 4). Patients >85 years were rarely estimated to have surgery (<4%). A displaced odontoid type II fracture and a cervical subluxation were the two remaining determinants of surgical management. The estimated surgery rate was 13.7% for patients ≤85 years old, increased slightly to 16.3% if the fracture was displaced, and was 46.7% if there was also cervical subluxation.

The decision tree for non-odontoid fractures had more nodes, but many of these nodes had small patient groups sizes of <5% of the total sample (figure 5). The presence of cervical subluxation was the most important determinant for surgery of non-odontoid fractures, although only 10% of patients had cervical subluxation with an estimated rate of surgery of 13.7%. Among

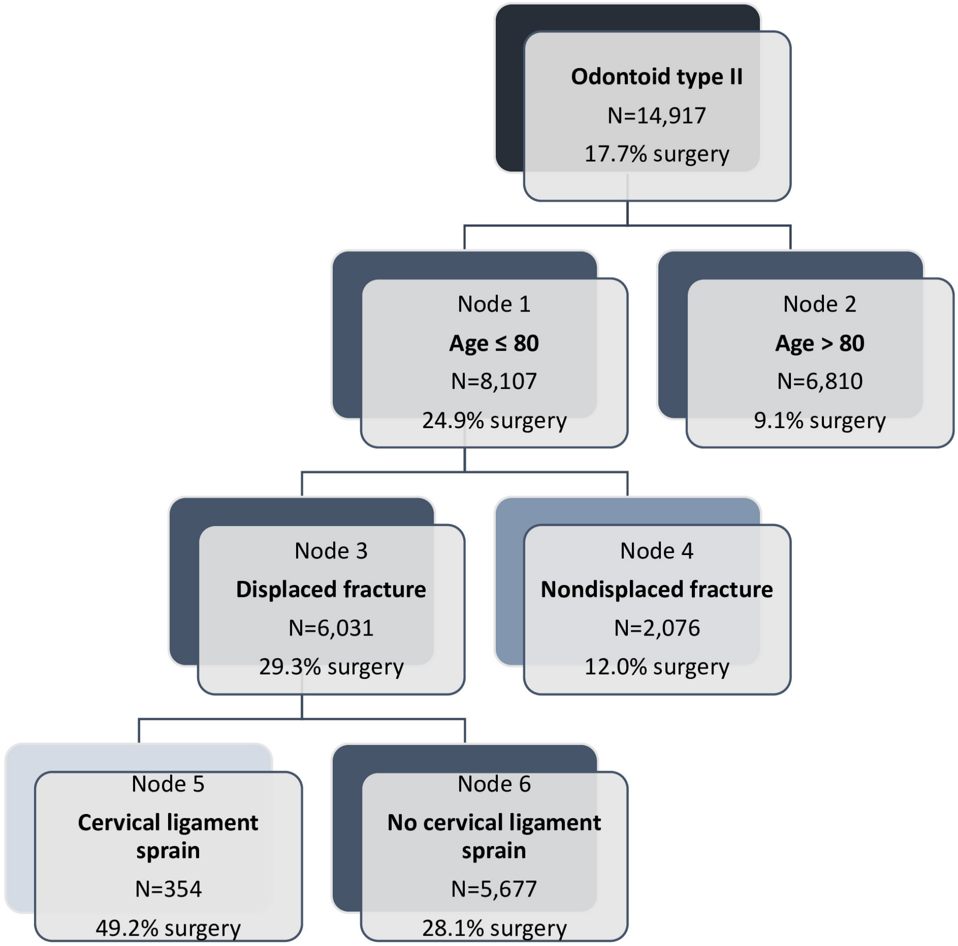

Figure 3 Decision tree for operative intervention of odontoid type II fractures. Shading indicates largest (darkest) to smallest (lightest, <5% of total N) patient group size. Misclassification rate=17.1%, area under the receiver operating characteristic (AUROC) curve=0.68.

patients without cervical subluxation (90% of patients), determinants of surgery were cervical ligament sprain and age. The estimated rate of surgery was 8.8% in patients without a cervical ligament sprain and 29.7% for patients with cervical ligament sprain who were ≤80 years old. A displaced fracture was not a consideration for surgery in this fracture diagnosis.

The regression models had model fit statistics indicating fair fit, with area receiver operating characteristic (AUROC) values of 0.71 to 0.73. The decision tree models had slightly poorer fit with AUROC values of 0.68 for odontoid type II and type I/III fractures and 0.62 for non-odontoid fractures.

DISCUSSION

This population-based study identified significant differences in demographics, injury patterns, and outcomes based on fracture diagnosis for patients with fractures to the second vertebrae. These variations in injuries and populations are indicative of differences in surgical management of the fracture. Our regression analysis identified between 9 and 16 variables that were independently associated with operative intervention. When considering decision tree modeling, only three covariates were determinants of surgical management for odontoid type II and odontoid I/III fractures, and these determinants were similar, by hierarchy: patient age, whether the fracture was displaced, and associated cervical injuries of either cervical subluxation or ligament sprain. The decision tree for non-odontoid fractures had more determinants for surgery, but most patients did not have cervical subluxation and were differentiated by presence of cervical ligament sprain and age. Thus, the overarching determinants for surgery of C2 fractures were the patient's age and the cervical injuries themselves, and not more general injury characteristics such as the cause of injury, presenting vital signs, and severe concomitant injuries (polytrauma), nor patient demographics like sex, race, and comorbidities, nor hospital characteristics like trauma level and transfer status.

This large registry analysis illustrates the epidemiology of C2 fractures in the USA. Radovanovic *et al* previously described patterns of C2 fracture in geriatric patients treated in London, England.[13] Odontoid type II fractures were the majority of fractures (57%), which is higher than the 43% we reported, possibly due to their studies' older age inclusion criteria. Also contrary to our findings, they reported few differences between fracture types with respect to cause of injury, demographics, and outcomes. They also reported only 10.6% were injured in an MVC, which is lower than the 31% rate in our population and lower than a prior NTDB analysis of octogenarians where 17% were injured by MVC. Using the Swedish national registry, Robinson *et al* report that in geriatric patients, approximately 63% of C2 fractures are odontoid type II and 26% are odontoid type III, and in younger patients, approximately 34% are odontoid type II, 17% are odontoid type III, and 24% are hangman's fractures.[3] Our C2 population was 43% odontoid type II fractures, which were within the range of these Swedish studies.

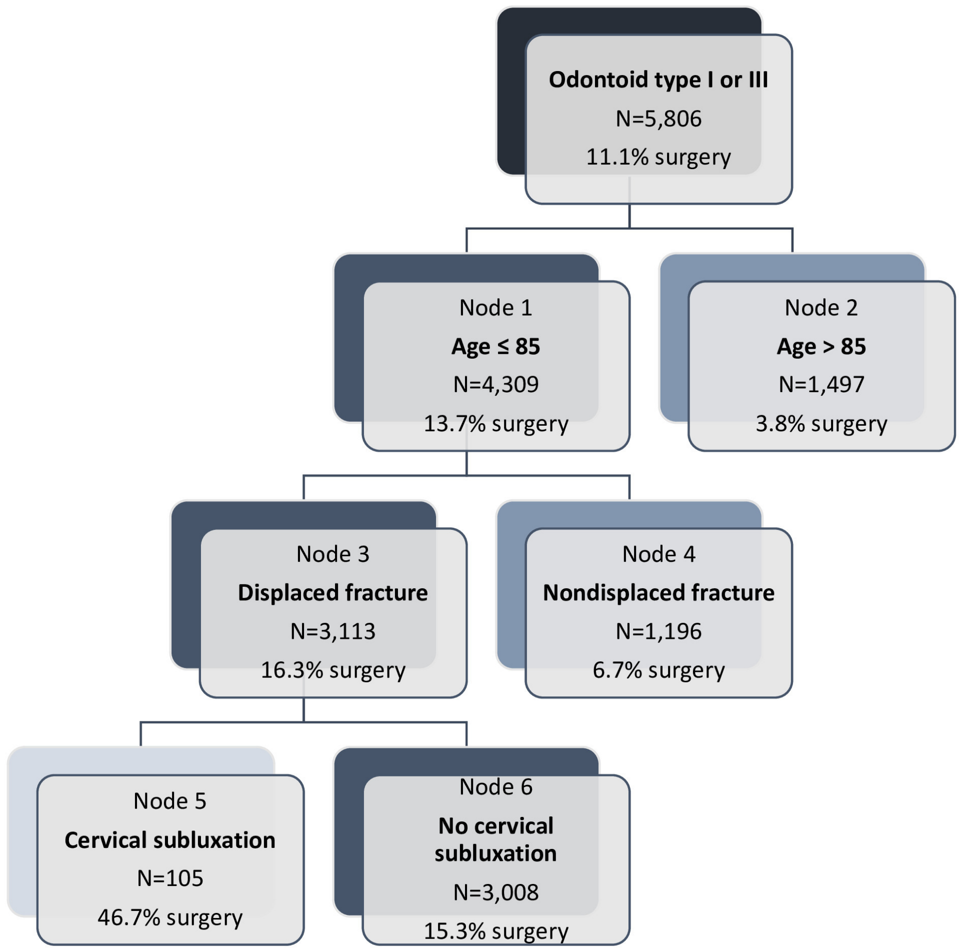

Figure 4 Decision tree for operative intervention of odontoid type I/III fractures. Shading indicates largest (darkest) to smallest (lightest, <5% of total N) patient group size. Misclassification rate=10.5%, area receiver operating characteristic=0.68.

Surgical rates of C2 fractures vary widely. Regarding age, in Sweden, the surgical rate was 22% among ≥70 years[14]; in England, it was 27% among ≥65 years[13]; in New Zealand, it was 11% among ≥70 years,[15] and in the NTDB, it was previously reported to be 10% for octogenarians.[16] The surgical rate among non-geriatric patients in Sweden was higher, at approximately 35%.[17] In our population, surgical management peaked in patients aged 50–69 years at 18% and was lowest in patients ≥80 years old (8% surgically managed).

Few studies have compared the surgical rate by fracture diagnosis. In the Swedish registry, the surgical rate was 40% across all C2 fractures but was 53% with odontoid type II injuries.[3] A Norwegian study of 336 patients reported surgical rates of 32% with odontoid type II fractures but only 4% with odontoid type III fractures.[18] The surgical rate in our study was low at 14%, and the disparity with our data compared with other regions may be driven by the lower rate of surgical management for patients with odontoid type II fractures, at only 17.5%.

We used regression analysis and decision tree modeling to determine surgical versus non-operative management, as opposed to other studies that describe preferred treatment guidelines based on a review of the literature. Carvalho *et al* recommend surgical treatment for type III fractures with >5 mm displacement and type II fractures with >4 mm to 6 mm displacement and who are non-geriatric.[9] Nourbakhsh and Hanson prefer conservative management for type I and III fractures regardless of age, and surgical management of type II fractures with >4 mm displacement.[11] Wagner *et al* take a more general approach and prefer surgical management of geriatric patients with odontoid type II fractures.[5] Rizvi *et al* examined compliance with their recommendation to operate on younger patients with displaced odontoid type II fractures, older patients with type II fractures regardless of displacement, and all displaced type III fractures regardless of age; the non-compliance rate of 36% was largely driven by age, and the authors conclude that age should play a larger consideration in decision trees for treatment choice.[18] Our findings agree with the aforementioned studies, that displacement of the odontoid fracture and the patients' age both play a role in whether surgical or non-operative management is preferred. The most favored age cut-off in our study was <80 years old for odontoid type II fractures and <85 years old for odontoid type I/III fractures, which is older than geriatric age in the aforementioned studies (often described as the 'old old' or octogenarians). Our analysis was more specific than prior studies because it modeled each fracture diagnosis separately and analyzed age continuously.

The gestalt that odontoid type II fractures are surgically managed, and hangman's fractures and odontoid type I/III fractures are non-operatively managed does not appear to be supported by our analysis, as seen in the overall surgical rates were 17.5% and 11.1%, respectively. Still, when comparing the decision trees for odontoid type II and type I/III fractures, the estimated surgical rates were approximately twofold higher for odontoid type II fractures compared with odontoid type I/III

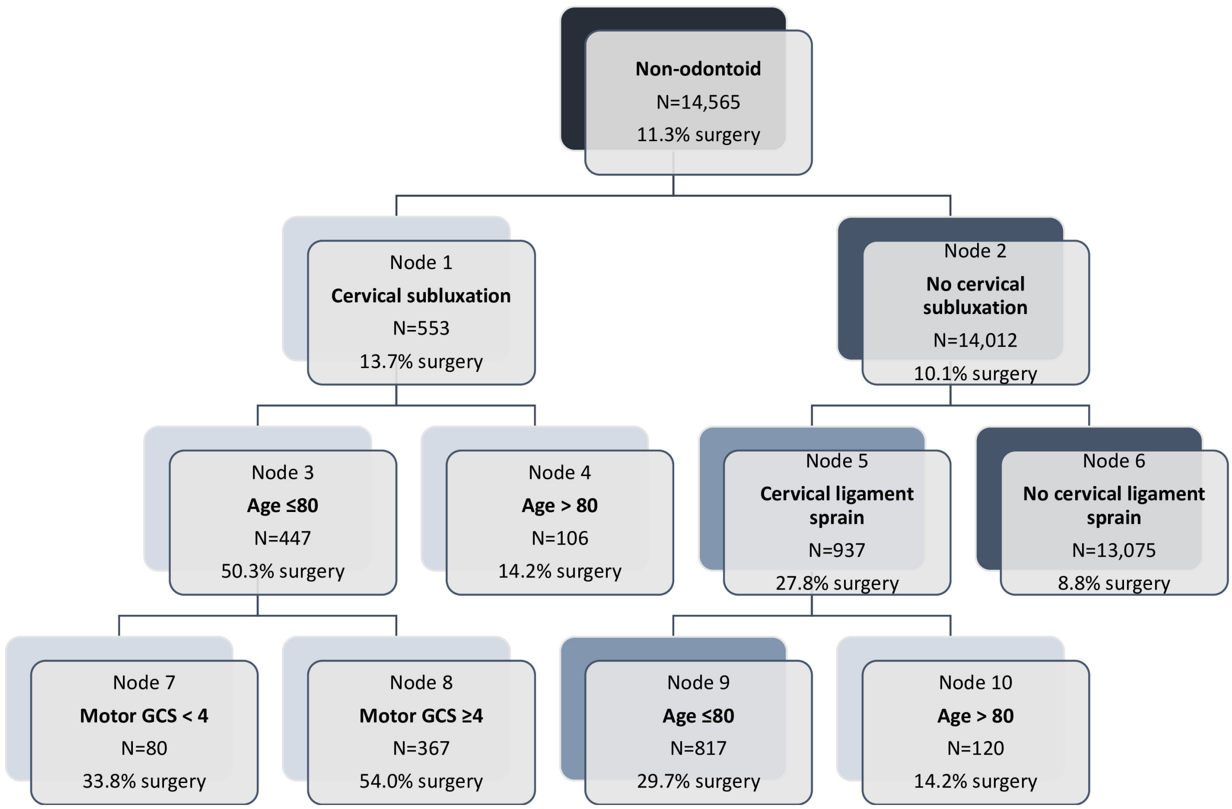

Figure 5 Decision tree for operative intervention of non-odontoid fractures. Shading indicates largest (darkest) to smallest (lightest, <5% of total N) patient group size. Misclassification rate=10.6%, area receiver operating characteristic=0.62. GCS, Glasgow Coma Scale.

fractures in the old old cohort, 9.1% versus 3.8% surgery, and in the younger cohort, 24.9% versus 13.7% surgery; as well as in the younger cohort who had a displaced fracture, 29.3% versus 16.3% surgery.

One of the studies' biggest limitations is that the models' findings should not be considered the standard of care or to guide optimal treatment decisions. Rather, these models demonstrate current practice patterns in the USA by C2 fracture diagnosis. This study is limited in determining whether patients were mismanaged or inappropriately selected for surgery, in part because there are no long-term (postdischarge) outcomes in the NTDB. Additional study is needed to compare outcomes by surgical management of C2 fractures based on the variables identified in this study (fracture diagnosis, fracture displacement, patients' age, and associated cervical injuries), but also to adjust for variables that would influence outcomes in trauma patients such as abnormal vital signs, severe concomitant injuries, and comorbidities.

Second, the degree of fracture displacement was not available. Other studies recommended surgery based on whether the fracture was displaced >4, 5, or 6 mm. Displacement was a significant determinant for classifying into operative management, and our model fit statistics would likely have been improved had we been able to examine the degree of displacement. However, it should be noted that displacement of C2 fractures can be difficult to assess because it may change with the patient's position and posture and even with respiration.[9] Third, nearly 20% of patients with C2 fracture did not have more detailed diagnoses and were considered 'unspecified', and these patients were excluded from our analysis comparing types of C2 fractures. Fourth, 3% of patients had more than one C2 fracture diagnosis; patients with an odontoid type II fracture were characterized in that group even when there was also an odontoid type I/III or non-odontoid fracture, and patients with an odontoid type I/III fracture were characterized in that group even when they also had a non-odontoid fracture. We performed a sensitivity analysis to exclude the 3% of patients with more than one C2 fracture diagnosis, and there were no differences in the decision tree models (order and variables of nodes) or the model fit statistics (data not shown). Finally, the NTDB only includes data from contributing trauma centers, and these results might not be generalizable to non-participating hospitals. There were 183 of approximately 198 (93%) level I trauma centers contributing data and 206 of approximately 252 (82%) level II trauma centers contributing data, but far fewer III/IV and non-ACS verified centers contributed data.

CONCLUSIONS

At nearly 40 000 patients, this is the largest published descriptive study of C2 fractures and current management in the USA to date. There were significant differences in demographics, injury patterns, surgical procedures, and outcomes based on C2 diagnosis. The hierarchy (order) that was identified in the decision trees suggests age is the predominant determinant of surgery for patients with an odontoid fracture, regardless of type, followed by fracture displacement. On the contrary, associated cervical diagnoses of subluxation/dislocation and cervical ligament sprain were the predominant determinants of operative intervention for patients with non-odontoid fractures in US trauma centers. Our findings reflect other authors' suggested criteria for operative intervention of odontoid fractures that they based on review of the literature, but our findings are based on statistical modeling of a large US database and provide more specific age criterion. The model performance for surgical management was similarly adequate for decision tree modeling and logistic regression modeling. The findings from our analysis may be used for studying outcomes by surgical management, especially when examined by fracture displacement, fracture location, and age. These findings could also be used as a reference to inform current management practices in the USA.

Contributors All authors made substantial contributions to the manuscript as follows: KS is responsible for conceptualization, methodology, software, formal analysis, and drafting of the manuscript. AB, KLB, DA, RP, and CHP are responsible for verification and critical revisions of the manuscript. DB-O is responsible for project administration, writing the manuscript, and is responsible for the overall content as guarantor. All authors provided final approval of the submitted manuscript.

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Competing interests None declared.

Patient consent for publication Not applicable.

Ethics approval National Trauma Database review is not applicable. This study did not require institutional review board approval because the analysis of secondary, deidentified, publicly available data does not constitute research involving human subjects under the federal Common Rule, 45 CFR Part 46.

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Data availability statement Data are available in a public, open access repository. The datasets used and/or analyzed during the current study are publicly available. The NTDB remains the full and exclusive copyrighted property of the American College of Surgeons. The American College of Surgeons is not responsible for any claims arising from works based on the original Data, Text, Tables, or Figures. Data are available via https://www.facs.org/quality-programs/trauma/tqp/center-programs/ntdb/datasets. The authors did not have any special access privileges to this data.

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