European Spine Journal (2024) 33:185–197
https://doi.org/10.1007/s00586-023-07919-7

ORIGINAL ARTICLE

Risk factors for in-hospital mortality in geriatric patients aged 80 and older with axis fractures: a nationwide, cross-sectional analysis of concomitant injuries, comorbidities, and treatment strategies in 10,077 cases

Maximilian Kerschbaum[1] · Lisa Klute[1] · Leopold Henssler[1] · Markus Rupp[1] · Volker Alt[1] · Siegmund Lang[1]

Received: 5 May 2023 / Revised: 5 May 2023 / Accepted: 23 August 2023 / Published online: 15 September 2023

Abstract

Purpose To investigate the association between treatment, comorbidities, concomitant injuries, and procedures with in-hospital mortality in patients aged 80 years or older with axis fractures.

Methods Data were extracted from the German InEK (Institut für das Entgeltsystem im Krankenhaus) GmbH database (2019–2021) for patients aged 80 years or older with axis fractures and the in-hospital mortality rate was calculated. Differences in comorbidities and concomitant diseases and injuries were analyzed using the Chi-square test. In surgically treated patients, odds ratios (OR) with 95% confidence intervals (95% CI) were used to analyze potential risk factors for in-hospital mortality.

Results Among 10,077 patients, the in-hospital mortality rate was 8.4%, with no significant difference between surgically (9.4%) and non-surgically treated patients (7.9%; $p = 0.103$). The most common comorbidities were essential hypertension (67.3%), atrial fibrillation (28.2%), and chronic kidney disease (23.3%), while the most common concomitant injuries were head and face wounds (25.9%), concussions (12.8%), and atlas fractures (11.6%). In surgically treated patients, spinal cord injury (OR = 4.62, 95% CI: 2.23–9.58), acute renal failure (OR = 3.20, 95% CI: 2.26–4.53), and acute bleeding anemia (OR = 2.06, 95% CI: 1.64–2.59) were associated with increased in-hospital mortality (all $p < 0.01$). Screw-rod-system fixation of one segment (OR = 0.74, 95% CI: 0.56–0.97) and intraoperative navigation (OR = 0.45, 95% CI: 0.16–0.71) were identified as potential protective factors (both $p < 0.05$).

Conclusion Comprehensive geriatric assessment and optimization of comorbidities during treatment are crucial. The indication for surgical treatment must be carefully individualized. Future studies should focus on the choice of surgical technique, perioperative blood management, and intraoperative navigation as potential protective factors.

Keywords Axis fractures · Cervical spine · Geriatric population · In-hospital mortality · Risk factors

✉ Siegmund Lang
Siegmund.lang@ukr.de

Maximilian Kerschbaum
maximilian.kerschbaum@ukr.de

Lisa Klute
lisa.klute@ukr.de

Leopold Henssler
leopold.henssler@ukr.de

Markus Rupp
markus.rupp@ukr.de

Volker Alt
volker.alt@ukr.de

[1] Department of Trauma Surgery, University Hospital Regensburg, Franz-Josef-Strauß-Allee 11, 93053 Regensburg, Germany

Introduction

The rapidly aging population in the Western world presents a significant healthcare challenge, as this demographic is particularly susceptible to fractures and will undoubtedly play a pivotal role in shaping the future of medical care. According to the Global Burden of Disease Study females had an age-standardized rate of 92.2 vertebral fractures per 100,000 people, while males had a rate of 125.3 per 100,000 in Central Europe [1]. Recently, a staggering 94% increase in cervical spine fractures in Germany between 2009 and 2019 was demonstrated, with a notable shift in the age distribution of affected individuals, and patients aged 70 or older accounting for 70% of all cases [2]. In fact, axis fractures had an incidence rate of 8.2 per 100,000 inhabitants in Germany in 2019, with an 82.5% increase since 2009, and predominantly affected males and geriatric patients aged 80 years or older, accounting for 59.1% of cases [3]. The most common type of axis fracture of patients aged 80 years or older is the dens axis (odontoid) fracture, with type II fractures according to Anderson and D'Alonzo being the most prevalent, followed by type III fractures [4–8]. The current epidemiological trend has inspired a plethora of retrospective studies, reviews, and meta-analyses in the literature investigating the morbidity and mortality of geriatric patients. The optimal treatment strategy is an ongoing controversy and the discussion has been shifted in recent years primarily to patients older than 80 years [9–11]. While non-surgical management with external immobilization has been the traditional approach for type I and some type II fractures, recent evidence suggested that surgical intervention may provide better outcomes, particularly for unstable type II and type III fractures [10, 12]. However, surgery may be associated with higher risks of complications, such as infection and neurovascular injury, and may not be suitable for all patients, especially if “modifiers” like osteoporosis, a nonreducible fracture or a reverse fracture line among others are present [12, 13]. Therefore, a careful evaluation of the fracture type, patient factors, and potential risks and benefits of each treatment approach should be considered before making a decision [13, 14]. Despite the availability of up-to-date treatment guidelines and research efforts, the mortality of odontoid fractures in geriatric patients is still high and according to Venkatesan et al., it is even higher than hip joint-related fractures [9, 15]. Graffeo et al. recently suggested, that among octogenarian patients with type II odontoid fractures, frailty was associated with increased mortality, independent of the chosen treatment strategy [9]. Despite several meta-analyses that provide several risk factors for in-hospital mortality in geriatric patients with axis fractures, the general conclusions of most studies are limited by the low quality of evidence available, highlighting the need for randomized controlled trials and large register-based analyses [12, 16, 17].

To provide data with a high degree of generalizability we conducted a nationwide cross-sectional study, aiming (1) to identify risk factors for high in-hospital mortality in patients aged 80 and older with axis fractures. (2) The second aim was to identify factors that were associated with in-hospital mortality in the surgically treated patient cohort.

Methods

We conducted a cross-sectional nationwide study with pooled data from 2019 through 2021. In accordance with Section 17b of the German Hospital Financing Act, a universal, performance-based, and flat-rate remuneration system has been introduced for general hospital services. The basis for this is the German Diagnosis Related Groups system (G-DRG system), whereby each inpatient case of treatment is remunerated using a corresponding DRG lump sum payment. The Institut für das Entgeltsystem im Krankenhaus (InEK) GmbH provides detailed data on the main diagnoses based on “International Statistical Classification of Diseases and Related Health Problems, 10th Revision” (ICD-10) codes, age- and sex distribution, length of hospital stays, reasons for discharge (including “death”), coded concomitant diagnoses (based on ICD-10 codes) and coded procedures based on “Operationen- und Prozedurenschlüssel” (OPS) codes. The InEK browser enables analysis back to the year 2019. For the following comprehensive analysis, all cases from 2019 through 2021 were extracted and pooled. Based on the ICD-10 code for axis fracture (S12.1), data for total case numbers, the numbers of coded concomitant diagnoses, and the number of in-hospital deaths were extracted. In the second step, case combinations of the ICD-10 code S12.1 with any surgical procedure of the spine (OPS-codees 5–83.-; 5.030.-) for the years 2019 through 2021 were extracted and pooled to conduct the same analysis as mentioned above for surgically treated patients exclusively.

The study included only patients aged 80 years or older, for these have been in the recent focus of debate regarding the optimal treatment. The analysis was conducted on comorbidities that were documented in at least 1.0% of cases. The primary outcome parameter was the event of in-hospital death. To identify potential risk factors for the in-hospital mortality, the prevalence of comorbidities, concomitant injuries (each by ICD-10 code), and procedures (by OPS-codes) were compared between two groups: Group A (Survival Group) and Group B (Deceased Group). In the next step, cases with documented surgical procedures were further divided into these two groups (A and B) to investigate potential risk and protective factors for the in-hospital mortality in surgically treated patients.

Ethics statement

Informed Consent and Investigational Review Board (IRB) were not required for this cross-sectional study as it used data from an anonymous, de-identified, administrative database.

Statistical analysis

Data are presented as total numbers and as percentages of the total. The Chi-Square test was used for statistical comparison between groups (A and B). To analyze the association between potential risk factors and the outcome parameter of in-hospital mortality the odds ratios (OR) with 95% confidence intervals (95% CI) were calculated for the previously identified factors.

Results

Patient characteristics

In total, $N = 10{,}077$ hospital admissions cases were pooled from 2019 to 2021 and analyzed. Only patients aged 80 years or older were included. In total $n = 843$ cases of in-hospital deaths were documented, giving an in-hospital mortality rate of 8.4%. The proportion of male patients was 35.2% ($n = 3544$) and 64.8% ($n = 6533$) for female patients ($p < 0.001$). In the deceased group, 47.7% ($n = 402$) were male and 52.3% ($n = 441$) were female patients. Among all cases, $n = 201$ (2.0%) were classified as short-stay patients, $n = 8876$ (88.1%) as normal-stay patients, and $n = 1000$ (9.9%) as long-stay patients. Ten-point seven percent of cases ($n = 1076$) had severe motor function impairment (Barthel Index: 20–55 points). Mild to moderate motor function impairment (Barthel Index: 60–75) was documented in 4.1% of cases ($n = 417$) and 1.4% of cases ($n = 142$) had mild motor function impairment (Barthel Index: 80–95 points). A significantly higher proportion of cases were classified as having ´very severe´ motor function impairment (Barthel Index: 0–15 points), whereas significantly fewer cases with ´mild,´ ´moderate,´ and ´moderately severe´ motor function impairment were documented in the deceased group (all $p < 0.01$; Table 1).

Risk factors for in-hospital mortality

The most prevalent comorbidity was essential hypertension, which was reported in $n = 6731$ cases (67.3%). Codes for essential hypertension were significantly more often used in the survival group than in the deceased group ($p < 0.001$). In only $n = 34$ cases (0.3%) obesity and in $n = 1665$ (16.5%) cases a form of Type 2 Diabetes Mellitus was coded with no difference between the two groups (both $p > 0.05$). A code for atrial fibrillation was used in $n = 2837$ (28.2%) of cases and the proportion was significantly higher in the deceased group ($n = 315$; 37.4%; $p < 0.001$). Further, left-sided heart failure was significantly more prevalent in the deceased group ($n = 201$; 23.8% vs. $n = 1024$; 11.1%; $p < 0.001$). The frequencies of codes for volume deficiency ($n = 107$; 12.7%), hyperkalemia ($n = 59$; 7.0%), hypokalemia ($n = 197$; 23.4%), acute kidney failure ($n = 148$; 17.6%) and chronic kidney disease ($n = 257$; 30.5%) were significantly higher in the deceased group (all $p < 0.01$). Hospital-acquired pneumonia was documented in $n = 444$ (4.4%) of all cases and significantly more frequently in the deceased group ($n = 133$; 15.8%; $p < 0.001$). There was a statistically significant difference between the groups in the prevalence of acute anemia (due to hemorrhage) which was documented in the deceased group in $n = 193$ (21.3%) cases ($p < 0.001$). Similarly, a significantly higher portion of cases of hemorrhagic diathesis was found in the deceased group ($n = 78$; 9.3% vs. $n = 249$; 2.7%; $p < 0.001$). However, no difference in the frequency of long-term anticoagulant therapy was found between the groups ($p = 0.536$). The prevalence was 25.6% in all cases. Most codes for cognitive disorders and motor dysfunctions (according to the Barthel Index stratification) were more prevalent in the deceased group. Table 1 provides an overview of all analyzed comorbidities in the total cohort (A+B) and the deceased group (B).

The most common concomitant injuries were head and face wounds in 25.9% of all cases, followed by a concussion in 12.8% of all cases. Traumatic brain injuries were rare, traumatic subdural hemorrhage was documented in $n = 161$ (1.6%), and traumatic subarachnoidal hemorrhage in $n = 137$ cases (1.4%). Traumatic subdural hemorrhage was significantly more prevalent in the deceased group ($n = 29$; 3.4%; $p < 0.001$). The frequency of Cranium and facial skeleton fractures was documented in $n = 945$ (9.4%) cases and was significantly more frequent in the deceased group ($n = 127$; 15.1%; $p < 0.001$). Concomitant cervical fractures were documented in 11.6% of all cases represented by 1st cervical vertebra (atlas) fractures and 7.0% of all cases represented by subaxial cervical spine fractures. Atlas fractures were significantly more frequent in the deceased group compared to the survival group ($n = 147$; 17.4% vs. $n = 1020$; 11.0%; $p < 0.001$). There was a significant difference in the frequency of fractures of the rib cage which was documented in $n = 80$ (9.5%) cases of the deceased and $n = 324$ (3.5%) of the survival group ($p < 0.001$). Cervical Spinal cord injuries (SCI) were rare, but significantly more frequent in the group of deceased patients ($n = 64$; 0.7% in group A vs. $n = 17$; 2.0% in group B; $p < 0.001$). In Table 2, all analyzed

Table 1 Comparison of the prevalence of comorbidities in all patients with axis fractures and the deceased patient cohort

ICD-10 code	Condition	All patients (Group A + B)			Deceased patients (Group B)			*p*-value
		Number of cases	Cumulative cases	Percentage of all cases	Number of cases	Cumulative cases	Percentage of all cases	
S12.1	Fracture of 2nd cervical vertebra	10,077		100.00%	843		100.00%	
Coagulation								
D62	Acute bleeding anemia	905	905	9.0%	183	183	21.7%	0.000
D50.8	Other iron deficiency anemias	154	401	4.0%	9	38	4.5%	0.412
D63.8	Anemia due to other chronic diseases classified elsewhere	75			6			
D64.8	Other specifically stated anemias	133			11			
D64.9	Unspecified anemia	39			12			
D68.33	Hemorrhagic diathesis due to coumarins (vitamin K antagonists)	79	326	3.2%	16	78	9.3%	0.000
D68.35	Hemorrhagic diathesis due to other anticoagulants	69			13			
D68.4	Acquired deficiency of clotting factors	178			49			
Z92.1	Long-term anticoagulant therapy	2576	2576	25.6%	208	208	24.7%	0.536
Metabolic disease								
E11.20	Type 2 diabetes mellitus with renal complications	97	1665	16.5%	8	137	16.3%	0.825
E11.90	Type 2 diabetes mellitus without complications, without derailment	1416			106			
E11.91	Type 2 diabetes mellitus without complications, with derailment	152			23			
E66.00	Obesity grade I (WHO)	34	34	0.3%	5	5	0.6%	0.181
I10.00	Benign essential hypertension: Without mention of hypertensive crisis	5055	6781	67.3%	353	498	59.1%	0.000
I10.01	Benign essential hypertension: With mention of hypertensive crisis	716			73			
I10.90	Essential hypertension, unspecified: Without mention of hypertensive crisis	872			65			
I10.91	Essential hypertension, unspecified: With mention of hypertensive crisis	138			7			
Heart disease								
I25.0	Atherosclerotic cardiovascular disease as described	171	1327	13.2%	18	140	16.6%	0.002
I25.11	Atherosclerotic heart disease: Single-vessel disease	225			25			
I25.12	Atherosclerotic heart disease: Two-vessel disease	240			13			
I25.13	Atherosclerotic heart disease: Three-vessel disease	382			51			
I25.19	Atherosclerotic heart disease: Unspecified	309			33			
I25.22	Old myocardial infarction: 1 year or more ago	303	303	3.0%	31	31	3.7%	0.234
I34.0	Mitral valve insufficiency	245	245	2.4%	31	31	3.7%	0.014
I35.0	Aortic valve stenosis	138	138	1.4%	17	17	2.0%	0.091
I35.1	Aortic valve insufficiency	69	69	0.7%	0	0	0.0%	0.012
I36.1	Nonrheumatic tricuspid valve insufficiency	158	158	1.6%	20	20	2.4%	0.049
I48.0	Paroxysmal atrial fibrillation	1564	2837	28.2%	181	315	37.4%	0.000
I48.1	Persistent atrial fibrillation	341			39			
I48.2	Permanent atrial fibrillation	932			95			
I48.9	Atrial fibrillation and flutter, unspecified	342	342	3.4%	37	37	4.4%	0.096

Table 1 (continued)

ICD-10 code	Condition	All patients (Group A + B)			Deceased patients (Group B)			*p*-value
		Number of cases	Cumulative cases	Percentage of all cases	Number of cases	Cumulative cases	Percentage of all cases	
I50.12	Left-sided heart failure: With symptoms with greater stress	435	1225	12.2%	22	201	23.8%	0.000
I50.13	Left-sided heart failure: With symptoms with milder stress	471			79			
I50.14	Left-sided heart failure: With symptoms at rest	284			90			
I50.19	Left-sided heart failure: Unspecified	35			10			
Fluid and electrolyte imbalance. Kidney disease								
E86	Volume deficiency	776	776	7.7%	107	107	12.7%	0.000
E87.5	Hyperkalemia	262	262	2.6%	59	59	7.0%	0.000
E87.6	Hypokalemia	1850	1850	18.4%	197	197	23.4%	0.001
N17.91	Acute kidney failure, unspecified: Stage 1	228	381	3.8%	58	148	17.6%	0.000
N17.92	Acute kidney failure, unspecified: Stage 2	78			37			
N17.93	Acute kidney failure, unspecified: Stage 3	75			53			
N18.2	Chronic kidney disease, Stage 2	329	2352	23.3%	32	257	30.5%	0.000
N18.3	Chronic kidney disease, Stage 3	1488			137			
N18.4	Chronic kidney disease, Stage 4	401			61			
N18.5	Chronic kidney disease, Stage 5	134			27			
Infectious disease								
U69.01	Pneumonia acquired in the hospital	444	444	4.4%	133	133	15.8%	0.000
N30.0	Acute cystitis	156	1561	15.5%	6	134	15.9%	0.734
N39.0	Urinary tract infection	1405			128			
Cognitive disorders								
F00.1	Alzheimer's disease dementia with late onset (Type 1)	213	2011	20.0%	26	214	25.4%	0.001
F01.8	Other vascular dementia	213			22			
F03	Unspecified dementia	1585			166			
F05.0	Delirium without dementia	252	1201	11.9%	40	160	19.0%	0.000
F05.1	Delirium with dementia	462			61			
F05.8	Other forms of delirium	487			59			
R26.8	Other and unspecified disturbances of gait and mobility	916	2045	20.3%	49	126	14.9%	0.001
R29.6	Tendency to fall, not otherwise classified	1129			77			
Motor dysfunction								
U50.10	Mild motor dysfunction, Barthel Index: 80–95 points	142	142	1.4%	0	0	0.0%	0.004
U50.20	Moderate motor dysfunction, Barthel Index: 60–75 points	417	417	4.1%	0	0	0.0%	0.000
U50.30	Moderately severe motor dysfunction, Barthel Index: 40–55 points	941	941	9.3%	22	22	2.6%	0.000
U50.40	Severe motor dysfunction, Barthel Index: 20–35 points	1076	1076	10.7%	68	68	8.1%	0.010
U50.50	Very severe motor dysfunction, Barthel Index: 0–15 points	808	808	8.0%	109	109	12.9%	0.000

Table 1 (continued)

ICD-10 code	Condition	All patients (Group A + B)			Deceased patients (Group B)			*p*-value
		Number of cases	Cumulative cases	Percentage of all cases	Number of cases	Cumulative cases	Percentage of all cases	
Osteoporosis								
M81.00	Postmenopausal osteoporosis: Multiple locations	321	813	8.1%	13	23	2.7%	0.000
M81.09	Postmenopausal osteoporosis: Unspecified location	34			0			
M81.80	Other osteoporosis: Multiple locations	209			5			
M81.89	Other osteoporosis: Unspecified location	79			0			
M81.99	Osteoporosis, unspecified: Unspecified location	170			5			

Data are presented as total numbers, cumulative cases for condition groups, and percentages. Results of the Chi-square test for the comparison between the survival group and the deceased group are presented

concomitant injuries in the total cohort and the deceased group are listed.

Surgical procedures

A total of $n = 3178$ (31.5%) patients in this cohort were treated surgically. The in-hospital mortality rate in the surgically treated patients was 9.4% ($n = 298$ cases with in-hospital deaths vs. $n = 545$; 7.9% in the non-surgically treated group). The OR for in-hospital mortality depending on the surgical treatment was 1.13 (95% CI: 0.99–1.3; $p = 0.103$). In $n = 1954$ (61.5%) cases a dorsal approach was used and in n = 1266 (39.8%) cases a ventral approach was, which indicates, that a 360° approach was applied in $n = 42$ (1.3%) cases. Most frequently, screw fixation for one segment was applied ($n = 1404$ cases, 44.2%) followed by fixation with a screw-rod system for 1 segment ($n = 919$ cases; 28.9%). Multisegmented fixation with a screw-rod system of up to 5 segments was conducted in $n = 728$ (22.9%) cases. A dorsal fusion of 1–5 segments was coded in $n = 823$ (25.9%) cases. Decompression at one segment was only documented in $n = 62$ (2.0%) cases (Table 3).

Risk factors in surgically treated patients

In the group of surgically treated patients ($n = 3178$) the prevalence of hospital-acquired pneumonia had a high OR for in-hospital mortality among comorbidities, with 2.12 (95% CI: 1.60–2.80; $p < 0.001$). Hemorrhagic diathesis due to medication and congestive heart failure also had high ORs, with 1.98 (95% CI: 1.42–2.77) and 1.80 (95% CI: 1.37–2.37), respectively (both $p < 0.001$). Chronic kidney disease stage 3 or higher had a modestly elevated OR of 1.44 (95% CI: 1.09–1.89; $p = 0.02$). The other evaluated conditions, including dementia, diabetes, urinary tract infections, and coronary heart disease, showed ORs close to 1, indicating little to no association with in-hospital mortality (Fig. 1).

Considering the concomitant injuries and factors, we found the odds for the in-hospital mortality to be the highest in patients with SCI, although only prevalent in 1.1% ($n = 34$) of surgically treated patients (OR = 4.62, 95% CI: 2.23–9.58; $p < 0.001$). Further, acute renal failure (OR = 3.20, 95% CI: 2.26–4.53, $p = 0.000$) and acute bleeding anemia (OR = 2.06, 95% CI: 1.64–2.59, $p = 0.000$) were associated with a higher in-hospital mortality rate compared to cases without these conditions. Traumatic subdural hemorrhage (OR = 2.04, 95% CI: 1.16–3.61, $p = 0.080$) and concomitant atlas fracture (OR = 1.34, 95% CI: 1.00–1.80, $p = 0.147$) were not associated with statistically significant higher in-hospital mortality odds (Fig. 2).

The cases in which blood transfusion was indicated were associated with a significantly, 2.02-fold increased OR of in-hospital mortality (95% CI: 1.60–2.55, $p = 0.000$). Further, multi-segmental instrumentation using a screw-rod system with 4 or more segments was by tendency associated with 1.79-fold increased odds of in-hospital mortality (95% CI: 1.15–2.79, $p = 0.052$).

As seen in Fig. 3, most surgical techniques were not associated with a relevant change in the OR for in-hospital mortality. However, patients who were dependent on care level 3 had 1.39-fold increased odds (95% CI: 1.06–1.83, $p = 0.035$). Screw fixation for 1 segment as applied for anterior dens-screws was not associated with a significantly elevated OR of in-hospital mortality (OR 1.14; 95% CI: 0.92–1.40; $p = 0.260$). On the other hand, fixation by a screw-rod system of one segment, as used for encoding C1/C2 fusion procedures (e.g., Goel-Harms technique) showed a moderate negative association with in-hospital mortality (OR = 0.74, 95% CI: 0.56–0.97; $p = 0.044$).

Table 2 Comparison of the prevalence of concomitant injuries in all patients with axis fractures and the deceased patients cohort

ICD-10 code	Condition	All patients (Group A + B)			Deceased patients (Group B)			*p*-value
		Number of cases	Cumulative cases	Percentage of all cases	Number of cases	Cumulative cases	Percentage of all cases	
S12.1	Fracture of 2nd cervical vertebra	10,077		100.00%	843		100.00%	
Head and face wound								
S01.0	Open wound of hairy scalp	1024	2606	25.9%	101	246	29.2%	0.021
S01.1	Open wound of eyelid and periocular region	40			0			
S01.21	Open wound of external skin of nose	125			0			
S01.80	Unspecified open wound of other parts of head	691			50			
S01.84	Soft tissue injury, first degree, with closed fracture or dislocation of head	376			44			
S01.9	Open wound of head, part unspecified	350			51			
Cranium and facial skeleton fractures								
S02.1	Fracture of skull base	38	945	9.4%	12	127	15.1%	0.000
S02.2	Nasal bone fracture	701			87			
S02.3	Fracture of orbital floor	75			15			
S02.4	Fracture of zygomatic bone and maxilla	131			13			
Traumatic brain injury								
S06.0	Concussion	1293	1293	12.8%	97	97	11.5%	0.695
S06.5	Traumatic subdural hemorrhage	161	161	1.6%	29	29	3.4%	0.000
S06.6	Traumatic subarachnoidal hemorrhage	137	137	1.4%	17	17	2.0%	0.398
Spinal cord injury								
S14.12	Central cervical cord injury (incomplete cross-sectional injury)	23	81	0.8%	5	17	2.0%	0.000
S14.13	Other incomplete cross-sectional injuries of the cervical spinal cord	10			5			
S14.71	Injury of the spinal cord: C1	11			0			
S14.72	Injury of the spinal cord: C2	37			7			
Concomitant cervical fractures								
S12.0	Fracture of 1st cervical vertebra	1167	1167	11.6%	147	147	17.4%	0.000
S12.21	Fracture of 3rd cervical vertebra	241	704	7.0%	27	80	9.5%	0.031
S12.22	Fracture of 4th cervical vertebra	120			15			
S12.23	Fracture of 5th cervical vertebra	91			14			
S12.24	Fracture of 6th cervical vertebra	121			15			
S12.25	Fracture of 7th cervical vertebra	131			9			
Thoracic injury								
S22.01	Fracture of thoracic vertebrae T1 and T2	187	385	3.8%	20	40	4.7%	0.544
S22.02	Fracture of thoracic vertebrae T3 and T4	192			14			
S22.04	Fracture of thoracic vertebrae T7 and T8	6			6			
S22.20	Fracture of sternum, unspecified	6	404	4.0%	6	80	9.5%	0.000
S22.32	Fracture of other rib	85			8			
S22.43	Fracture of rib series, with involvement of three ribs	118			16			
S22.44	Fracture of rib series, with involvement of four or more ribs	195			50			

Data are presented as total numbers, cumulative cases for condition groups, and percentages. Results of the Chi-square test for the comparison between the survival group and the deceased group are presented

Table 3 Frequencies of surgical procedures by documented OPS-codes in n = 3178 surgically treated patients

OPS Code	Procedure	Number	Cumulative	Total number	Percentage
Approach					
5-030.1	Approach to the cranio-cervical junction and cervical spine: Cranio-cervical junction, posterior	413	Posterior approach	1954	61.5%
5-030.30	Approach to the cranio-cervical junction and cervical spine: Posterior cervical spine: 1 segment	717			
5-030.31	Approach to the cranio-cervical junction and cervical spine: Posterior cervical spine: 2 segments	356			
5-030.32	Approach to the cranio-cervical junction and cervical spine: Posterior, cervical spine: 2 segments or more	468			
5-030.70	Approach to the cranio-cervical junction and cervical spine: Anterior: 1 segment	1052	Anterior approach	1266	39.8%
5–030.71	Approach to the cranio-cervical junction and cervical spine: Anterior cervical spine: 2 segments	141			
5-030.72	Approach to the cranio-cervical junction and cervical spine: Anterior cervical spine: 2 segments or more	73			
Fusion					
5-836.30	Spinal fusion: posterior: 1 segment	526	Spinal fusion: posterior	823	25.9%
5-836.31	Spinal fusion: posterior: 2 segments	168			
5-836.32	Spinal fusion: posterior: 3 to 5 segments	90			
5-836.34	Spinal fusion: posterior: 3 segments	26			
5-836.35	Spinal fusion: posterior: 4 segments	13			
5-836.50	Spinal fusion: anterior: 1 segment	158	Spinal fusion: anterior	158	5.0%
Decompression					
5-839.60	Decompression: 1 segment	62	Decompression	62	2.0%
Fixation					
5-83b.20	Osteosynthesis (fixation): Screws: 1 segment	1404	Fixation: Screws: 1 segment	1404	44.2%
5-83b.30	Osteosynthesis (fixation): Anterior fixation by screw-plate-system: 1 segment	101	Anterior: Screw-plate system	101	3.2%
5-83b.50	Osteosynthesis (fixation): Screw-rod-system: 1 segment	919	Fixation: Screw-rod-system: 1 segment	919	28.9%
5-83b.51	Osteosynthesis (fixation): Screw-rod-system: 2 segments	332	Fixation: 2 segments or more	728	22.9%
5-83b.52	Osteosynthesis (fixation): Screw-rod-system: 3 segments	154			
5-83b.53	Osteosynthesis (fixation): Screw-rod-system: 4 or more segments	160			
5-83b.54	Osteosynthesis (fixation): Screw-rod-system: 4 segments	62			
5-83b.55	Osteosynthesis (fixation): Screw-rod-system: 5 segments	20			

Data are presented as total numbers, cumulative cases for procedure group and percentages

The use of intraoperative navigation was found to have an OR of 0.45 (95% CI: 0.16–0.71, $p = 0.001$) for in-hospital mortality. Figure 3 lists the ORs for in-hospital mortality depending on all analyzed procedures (by OPS code) for surgically treated patients.

Discussion

This nationwide cross-sectional register study on 10,077 geriatric patients aged 80 or older, that suffered axis

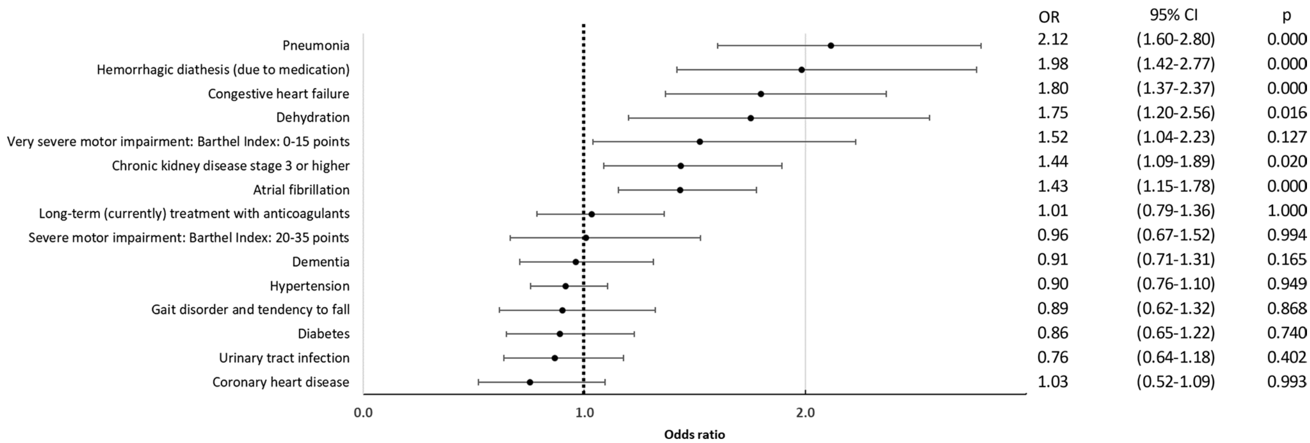

Fig. 1 Risk factors for in-hospital mortality in surgically treated patients: ORs for comorbidities are displayed with 95% CI and results of the Chi-squared test. Whiskers indicate the 95% CI. OR = 1.00 is indicated by the dotted vertical line

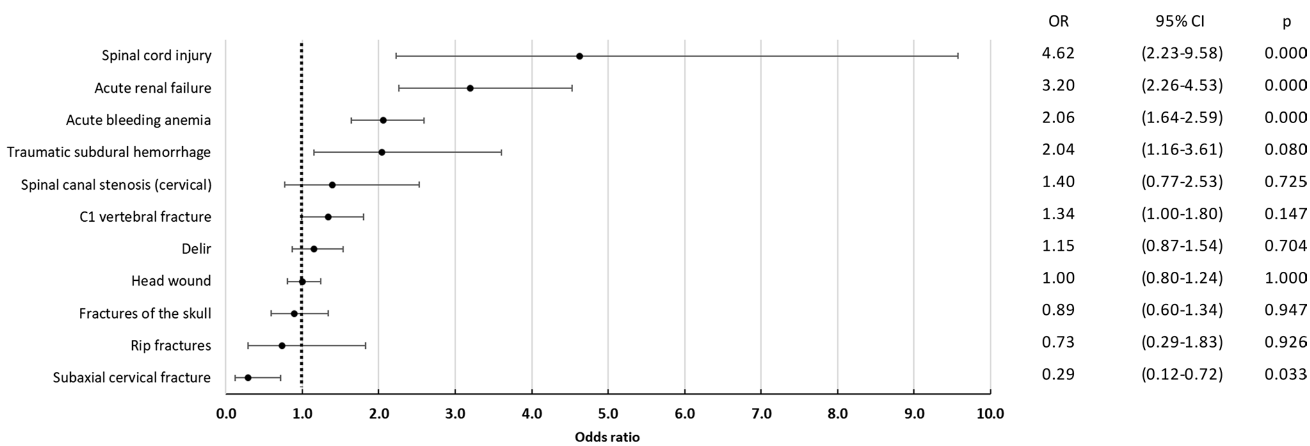

Fig. 2 Risk factors for in-hospital mortality in surgically treated patients: ORs for concomitant diseases, injuries and complications are displayed with 95% CI and results of the Chi-squared test. Whiskers indicate the 95% CI. OR = 1.00 is indicated by the dotted vertical line

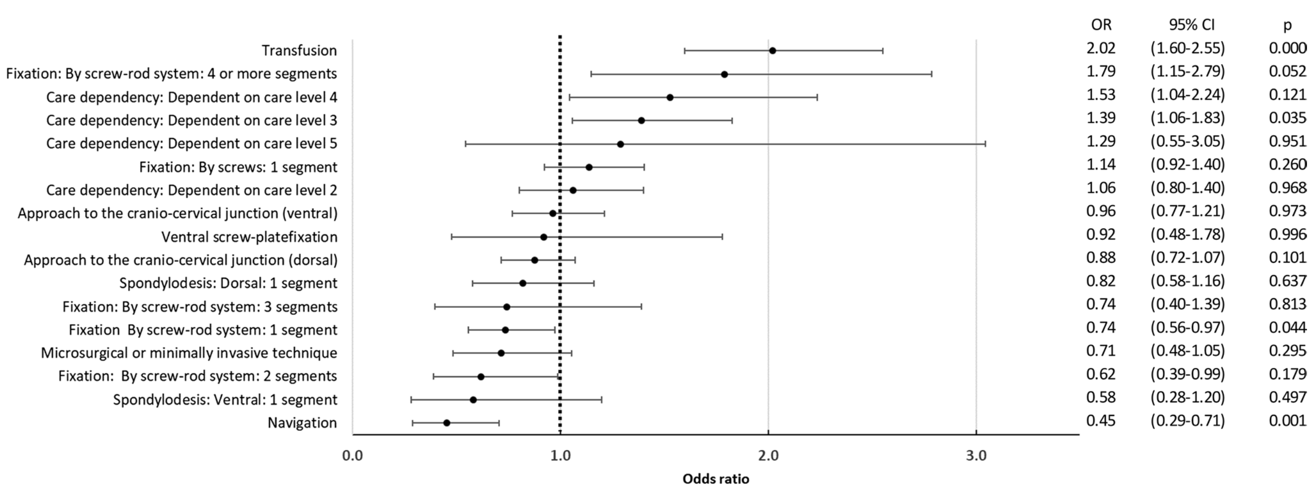

Fig. 3 Risk factors for in-hospital mortality in surgically treated patients: ORs for surgical procedures and interventions are displayed with 95% CI and results of the Chi-squared test. Whiskers indicate the 95%CI. OR = 1.00 is indicated by the dotted vertical line

fractures revealed an association between certain comorbidities and concomitant injuries with in-hospital mortality. In surgically treated patients, comorbidities played a less central role, but hospital-acquired pneumonia and acute renal failure are associated with a more than twofold OR.

General risk factors for in-hospital mortality in geriatric patients with axis fractures

Comorbidities indicating frailty and severe illness were associated with higher in-hospital mortality, such as essential hypertension, atrial fibrillation, left-sided heart failure, chronic kidney disease, dementia, and very severe motor dysfunction (Barthel index: 10–15 pts.). These findings are consistent with previous studies that have shown the importance of comorbidities and concomitant injuries in predicting mortality in elderly patients with axis fractures [6, 18]. In general, comorbidities are known to be associated with elevated risk for mortality after cervical spine fractures [19]. Concordant with our findings, chronic kidney disease is one of the key prognostic factors for early mortality in older patients with traumatic cervical spine injuries [20]. Shafafy et al. identified several predictors of mortality in elderly patients with fractures of the odontoid process [21]. They found that head injury and the presence of other spinal injuries increase the risk of mortality after 30 days [21]. Similarly, we revealed that concomitant injuriese such as SCI, traumatic brain injuries, atlas fractures, subaxial vertebral fractures, and rib cage fractures were indicators for high-risk in-hospital mortality. The knowledge of these factors can help to identify patients at risk, which should be monitored very carefully. Anyhow, there was no statistically significant difference in mortality rates between surgically treated (9.4%) and non-surgically treated patients (7.9%; $p = 0.103$) in the current cohort. Smith et al. retrospectively analyzed the complications of surgical versus conservative treatment of isolated type II odontoid fractures in octogenarians and found, that no relevant difference in the acute in-hospital mortality rate between 15.0% in the nonsurgical group and 12.5% in the surgical group [22]. These findings are in line with other retrospective studies [23]. Similarly, a meta-analysis by Deng et al. on the treatment of odontoid fractures in the octogenarians on 22 cases series and retrospective studies including 248 patients reports on a higher mortality rate of 10.1% for non-surgery vs. 5.4% for surgery, but without statistical significance [12]. Yang et al. conducted a meta-analysis to grade the evidence on conservative versus surgical treatment for type II odontoid fractures in the elderly. Analyzing twelve studies involving 730 patients aged 60 years or older, they did not find a difference with regard to the mortality between the two procedures [16]. In a prospective study on 336 patients, Rizvi et al. identified major comorbidities and older age as significant factors contributing to physicians' decision to refrain from the surgical fixation of odontoid fractures [6]. Prospective trials are emerging to better understand the outcomes associated with different treatment options. Currently Robinson et al. are conducting the Uppsala Study on Odontoid Fracture Treatment (USOFT) which is one of the first randomized controlled trials comparing non-surgical and surgical management of type II odontoid fractures in the elderly [24]. Regarding stability and fusion rates meta-analysis see an advantage for the surgical treatment [12].

Risk factors for the in-hospital mortality in surgically treated patients

In the current cohort 31.5% of the patients were treated surgically. Most frequently, a screw fixation for one segment was applied as used to encode for dens-screws or transarticular "Magerl" screws, followed by fixation with a screw-rod system for 1 segment as used to encode the dorsal Atlanto-axial fusion techniques. The role of comorbidities was less pronounced in this cohort of surgically treated patients. We revealed Pneumonia to be a relevant risk factor (OR = 2.12). The occurrence of pneumonia after surgery is a frequent complication that is linked with significant morbidity and mortality [25]. Aspiration may be partially accountable, which is associated with significantly greater length of stay, costs, and mortality and has been reported with an incidence of 5.3 cases of per 1000 cervical procedures [26]. The highest OR in this sudy of 4.62 for in-hospital mortality in surgically treated patients was associated with SCI, although it was only prevalent in 1.1% of the cases. SCI has been well recognized as a significant factor for a fatal outcome in cervical spine fractures, especially in the geriatric population [27, 28]. However, low case numbers of SCI in this cohort prevented statistical differentiation between complete and incomplete SCI. Furthermore, only SCI diagnoses coded as concomitant but not primary ICD-10 code could be analyzed. Acute renal failure was found to have an OR of 3.20 for mortality in our cohort and could potentially be suggested as another significant predictor. Acute renal failure is well-known to be associated with increased mortality and therefore should be meticulously screened for and treated as early as possible [29, 30]. The current analysis suggests that bleeding complications are likely to play a major role for the in-hospital mortality, with medication-induced hemorrhagic diathesis having a high OR of 1.98. The deceased group had a significantly higher prevalence of acute anemia due to hemorrhage and hemorrhagic diathesis compared with the survival group. The cases in which blood transfusion was indicated were associated with 2.02-fold increased odds of in-hospital mortality. However, no difference was found in the frequency of long-term anticoagulant therapy between the groups, which was present in 25.6% of all cases. It has been demonstrated, that massive intraoperative hemorrhage is an important risk factor for in-hospital mortality after spine surgery with a reported OR of 28.2 [31]. For planned spine surgery various guidelines on the perioperative management of anticoagulation have been published [32, 33]. The initial findings from the AO Spine Anticoagulation Global Survey recognized the challenge of offering consistent perioperative anticoagulation advice to patients due to the lack of universally acknowledged literature or guidelines [34]. Cutler et al. demonstrated, that next to age and white race the history of bleeding disorders were independently predictive of complications in the multivariate analysis in their retrospective cohort of 103 patients treated with anterior fixation for odontoid fractures with a significant OR of 4.4 [35]. Our results and the body of the literature suggest that investigating the peri-operative management of coagulopathies to mitigate adverse events and exploring the feasibility of bridging anticoagulants in the trauma setting should be further considered. Hemoglobin levels might be employed to identify high-risk patients for in-hospital mortality and could be integrated into a predictive score system [21].

The geriatric population is prone to an increased risk of complications during the peri-operative period caused by prevalent comorbidities and weak bone structure. Nonetheless, Robinson et al. propose, that surgical treatment improves survival of elderly with axis fracture based on their national population-based multi-registry cohort study on 3375 patients [37]. A systematic analysis of the literature on the morbidity and mortality related to odontoid fracture surgery in the elderly population showed that major complications after surgery include cardiac failure, deep vein thrombosis, stroke, pneumonia, respiratory failure, liver failure, and severe infection [38]. Notable, anterior surgery had a higher rate of site-specific complications such as non-union and revision surgery [38]. Longo et al. report a mortality rate of 7.6% and a complication rate of 9.1% in elderly patients treated with anterior odontoid screw fixation and described functional dependency as one predictor for mortality, which is in line with our findings [36]. Interestingly, we identified the fixation using a screw-rod system for one segment (e.g., as in "Goel/Harms" technique) to be associated with a significantly decreased risk for in-hospital mortality (OR = 0.74). Based on the results of their retrospective study of 70 patients above 75 years of age with odontoid fractures Faure et al. conclude, that the Harms technique showed lower risk of complications and better mechanical stability compared to anterior screw fixation [39]. In line, Cutler et al. report on a high complication rate (37.9%) and relevant mortality rate of 6.8% of anterior fixation of odontoid fractures in a retrospective analysis of 103 patients aged 73.9 years at average [35].

One further protective surgical factor was the use of intraoperative navigation. Due to substantial improvements and rapidly increasing availability, computer-assisted navigation is establishing itself as the gold standard for instrumentation at the cervical spine. It has been reviewed to increases the accuracy of pedicle screw placement, to reduce screw mispositioning and leading to fewer revision surgeries [40]. Ishak et al. retrospectively analyzed 35 patients suffering type II odontoid fractures with an average age of 86.5 years, that were treated with a navigated C1-C2 fusion. They found no in-hospital deaths and the overall major complication rate was 11%, leading to their conclusion, that Atlanto-axial fusion by using intraoperative spinal navigation is a safe and effective procedure [41].

Limitations

The findings of this study should be interpreted within the scope of its limitations. In general, registry studies are commonly not accepted by design to allow causative relationships to be made. The ICD-10 coding system does not allow for the differentiation of axis fractures (ICD10: S12.1) into odontoid or corpus or vertebral arch fractures. Furthermore, the InEK database does not provide any information about the fracture classification or dislocation. Thus, this study is based on the assumption, that the majority of axis fractures in the geriatric population are odontoid fractures. Further, the database employed did not enable to analyze the mid-to long-term results, but only in-hospital mortality. However, while focusing on risk factors in surgically treated patients this analysis adds important information to be considered for the indication for surgery. The retrospective character of this database study is prone to selection bias. The main statistical limitation is present in the analysis of frequency data, as it does not allow for the consideration of multiple variables affecting the outcome variable in-hospital mortality. Additionally, internal validity checks, such as bootstrapping or cross-validated estimates cannot be performed with this frequency data. The generalizability of this study's results may be limited due to its focus on German patients aged 80 years or older and the retrospective design. Differences in healthcare systems, clinical practices, and patient populations could impact the applicability of the findings to other settings or age groups. Therefore, it is important to carefully interpret the data and consider alternative approaches, such as prospective studies to gain a deeper understanding of the association between the tested risk factors and in-hospital mortality.

Conclusion

This study provides important insights into the factors associated with in-hospital mortality in geriatric patients aged 80 and older with axis fractures, which can aid in the identification of high-risk patients. The findings underscore the importance of comprehensive geriatric assessment and optimization of comorbidities prior and during treatment. The indication for surgical treatment must be carefully individualized, respecting the comorbidities and concomitant injuries and tailored treatment should be aimed for. We suggest, that prospective, multicentric studies should focus on the choice of the surgical technique, perioperative blood management and intraoperative navigation as potential protective factors to further improve the standard of care in the geriatric population.

Funding Open Access funding enabled and organized by Projekt DEAL. The authors declare that no funding was received for this article's research, authorship, and/or publication.

Declarations

Conflict of interest None of the authors has any potential conflict of interest.

References

1. Wu A-M, Bisignano C, James SL, Abady GG, Abedi A, Abu-Gharbieh E et al (2021) Global, regional, and national burden of bone fractures in 204 countries and territories, 1990–2019: a systematic analysis from the Global Burden of Disease Study 2019. The Lancet Healthy Longevity 2:e580–e592. https://doi.org/10.1016/S2666-7568(21)00172-0
2. Rupp M, Walter N, Pfeifer C, Lang S, Kerschbaum M, Krutsch W et al (2021) The incidence of fractures among the adult population of Germany. Dtsch Arztebl Int. https://doi.org/10.3238/arztebl.m2021.0238
3. Lang S, Walter N, Freigang V, Neumann C, Loibl M, Alt V, et al (2022) The epidemiology of vertebral fractures in the adult German population and an analysis of the socio-economic burden: trends from 2009 to 2019. https://doi.org/10.21203/rs.3.rs-1238169/v1
4. Deluca A, Wichlas F, Deininger C, Traweger A, Mueller EJ (2022) Reevaluation of a classification system: stable and unstable odontoid fractures in geriatric patients—a radiological outcome measurement. Eur J Trauma Emerg Surg 48:2967–2976. https://doi.org/10.1007/s00068-022-01985-0
5. Robinson A-L, Möller A, Robinson Y, Olerud C (2017) C2 fracture subtypes, incidence, and treatment allocation change with age: a retrospective cohort study of 233 consecutive cases. Biomed Res Int 2017:8321680. https://doi.org/10.1155/2017/8321680
6. Rizvi SAM, Helseth E, Rønning P, Mirzamohammadi J, Harr ME, Brommeland T et al (2020) Odontoid fractures: impact of age and comorbidities on surgical decision making. BMC Surg 20:236. https://doi.org/10.1186/s12893-020-00893-7
7. Anderson LD, D'Alonzo RT (1974) Fractures of the odontoid process of the axis. J Bone Joint Surg Am 56:1663–1674
8. Ryan MD, Henderson JJ (1992) The epidemiology of fractures and fracture-dislocations of the cervical spine. Injury 23:38–40. https://doi.org/10.1016/0020-1383(92)90123-a
9. Graffeo CS, Perry A, Puffer RC, Carlstrom LP, Chang W, Mallory GW et al (2017) Deadly falls: operative versus nonoperative management of Type II odontoid process fracture in octogenarians. J Neurosurg Spine 26:4–9. https://doi.org/10.3171/2016.3.SPINE151202
10. Nourbakhsh A, Shi R, Vannemreddy P, Nanda A (2009) Operative versus nonoperative management of acute odontoid Type II fractures: a meta-analysis. J Neurosurg Spine 11:651–658. https://doi.org/10.3171/2009.7.SPINE0991
11. Schnake KJ (2023) Operative Versorgung der Typ 2 Dens Fraktur bei >80j – synthese. Die Wirbelsäule 7:47–49. https://doi.org/10.1055/a-1964-6848
12. Deng H, Yue JK, Upadhyayula PS, Burke JF, Suen CG, Chan AK et al (2016) Odontoid fractures in the octogenarian: a systematic review and meta-analysis. J Neurosurg Sci 60:543–555
13. Gonschorek O, Vordemvenne T, Blattert T, Katscher S, Schnake KJ (2018) Treatment of odontoid fractures: recommendations of the spine section of the German Society for orthopaedics and trauma (DGOU). Global Spine Journal 8:12S-17S. https://doi.org/10.1177/2192568218768227
14. Konieczny MR, Gstrein A, Müller EJ (2012) Treatment algorithm for dens fractures: non-halo immobilization, anterior screw fixation, or posterior transarticular C1–C2 fixation. J Bone Joint Surg Am. https://doi.org/10.2106/JBJS.K.01616
15. Venkatesan M, Northover JR, Wild JB, Johnson N, Lee K, Uzoigwe CE et al (2014) Survival analysis of elderly patients with a fracture of the odontoid peg. Bone Joint J. https://doi.org/10.1302/0301-620X.96B1.32024
16. Yang Z, Yuan Z-Z, Ma J-X, Ma X-L (2015) Conservative versus surgical treatment for type II odontoid fractures in the elderly: grading the evidence through a meta-analysis. Orthop Traumatol Surg Res 101:839–844. https://doi.org/10.1016/j.otsr.2015.08.011
17. Pommier B, Ollier E, Pelletier J-B, Castel X, Vassal F, Tetard M-C (2020) Conservative versus surgical treatment for odontoid fracture: Is the surgical treatment harmful? Systematic review and meta-analysis. World Neurosurg 141:490-499.e2. https://doi.org/10.1016/j.wneu.2020.02.169
18. Schoenfeld AJ, Bono CM, Reichmann WM, Warholic N, Wood KB, Losina E et al (2011) Type II odontoid fractures of the cervical spine: Do treatment type and medical comorbidities affect mortality in elderly patients? Spine (Phila Pa 1976) 36:879–885. https://doi.org/10.1097/BRS.0b013e3181e8e77c
19. Harris MB, Reichmann WM, Bono CM, Bouchard K, Corbett KL, Warholic N et al (2010) Mortality in elderly patients after cervical spine fractures. J Bone Joint Surg Am 92:567–574. https://doi.org/10.2106/JBJS.I.00003

20. Kobayashi M, Yokogawa N, Kato S, Sasagawa T, Tsuchiya H, Nakashima H et al (2023) Risk factors for early mortality in older patients with traumatic cervical spine injuries-a multicenter retrospective study of 1512 cases. J Clin Med 12:708. https://doi.org/10.3390/jcm12020708
21. Shafafy R, Valsamis E, Luck J, Dimock R, Rampersad S, Kieffer W et al (2019) Predictors of mortality in elderly patients with fractures of the odontoid process - can we use non-spinal scoring systems? Bone Joint J. https://doi.org/10.1302/0301-620X.101B3.BJJ-2018-1004.R1
22. Smith HE, Kerr SM, Maltenfort M, Chaudhry S, Norton R, Albert TJ et al (2008) Early complications of surgical versus conservative treatment of isolated type II odontoid fractures in octogenarians: a retrospective cohort study. J Spinal Disord Tech 21:535–539. https://doi.org/10.1097/BSD.0b013e318163570b
23. Gembruch O, Lemonas E, Ahmadipour Y, Sure U, El Hindy N, Dodel R et al (2019) Treatment of odontoid type II fractures in octogenarians: balancing two different treatment strategies. Neurospine 16:360–367. https://doi.org/10.14245/ns.1836250.125
24. Robinson A-L, Schmeiser G, Robinson Y, Olerud C (2018) Surgical vs. non-surgical management of displaced type-2 odontoid fractures in patients aged 75 years and older: study protocol for a randomised controlled trial. Trials. https://doi.org/10.1186/s13063-018-2690-8
25. Chughtai M, Gwam CU, Mohamed N, Khlopas A, Newman JM, Khan R et al (2017) The epidemiology and risk factors for postoperative pneumonia. J Clin Med Res 9:466–475. https://doi.org/10.14740/jocmr.v9i6.3002
26. Fineberg SJ, Oglesby M, Patel AA, Singh K (2013) Incidence, risk factors, and mortality associated with aspiration in cervical spine surgery. Spine (Phila Pa 1976). https://doi.org/10.1097/BRS.0b013e31829cc19b
27. Ikpeze TC, Mesfin A (2017) Spinal cord injury in the geriatric population: risk factors, treatment options, and long-term management. Geriatr Orthop Surg Rehabil 8:115–118. https://doi.org/10.1177/2151458517696680
28. Wilson KV, McDonnell JM, O'Malley S, Lynch D, Larouche J, Cunniffe GM et al (2022) Morbidity and mortality of traumatic cervical spinal cord injuries in a geriatric cohort. Ir J Med Sci. https://doi.org/10.1007/s11845-022-03169-6
29. Jurawan N, Pankhurst T, Ferro C, Nightingale P, Coleman J, Rosser D et al (2017) Hospital acquired Acute Kidney Injury is associated with increased mortality but not increased readmission rates in a UK acute hospital. BMC Nephrol 18:317. https://doi.org/10.1186/s12882-017-0729-9
30. Ahmed N, Mathew RO, Kuo Y, Asif A (2021) Risk of in-hospital mortality in severe acute kidney injury after traumatic injuries: a national trauma quality program study. Trauma Surg Acute Care Open. https://doi.org/10.1136/tsaco-2020-000635
31. Kushioka J, Takenaka S, Makino T, Sakai Y, Kashii M, Iwasaki M et al (2019) Risk factors for in-hospital mortality after spine surgery: a matched case-control study using a multicenter database. The Spine J. https://doi.org/10.1016/j.spinee.2019.10.008
32. Porto GBF, Jeffrey Wessell D, Alvarado A, Arnold PM, Buchholz AL (2020) Anticoagulation and spine surgery. Global Spine J 10:53S-64S. https://doi.org/10.1177/2192568219852051
33. Steib A, Hadjiat F, Skibba W, Steib J-P (2011) Focus on perioperative management of anticoagulants and antiplatelet agents in spine surgery. Orthop Traumatol Surg Res 97:S102–S106. https://doi.org/10.1016/j.otsr.2011.07.005
34. Louie P, Harada G, Harrop J, Mroz T, Al-Saleh K, Brodano GB et al (2020) Perioperative anticoagulation management in spine surgery: initial findings from the AO spine anticoagulation global survey. Global Spine J 10:512–527. https://doi.org/10.1177/2192568219897598
35. Cutler HS, Guzman JZ, Lee NJ, Kothari P, Kim JS, Shin JI et al (2018) Short-term complications of anterior fixation of odontoid fractures. Global Spine J 8:47–56. https://doi.org/10.1177/2192568217698132
36. Longo M, Gelfand Y, De la Garza RR, Echt M, Kinon MD, Yanamadala V et al (2019) Perioperative complications and mortality following anterior odontoid screw fixation in elderly patients: a national database analysis. World Neurosurg 129:e776–e781. https://doi.org/10.1016/j.wneu.2019.06.022
37. Robinson A-L, Olerud C, Robinson Y (2018) Surgical treatment improves survival of elderly with axis fracture—a national population-based multiregistry cohort study. The Spine J 18:1853–1860. https://doi.org/10.1016/j.spinee.2018.03.021
38. White AP, Hashimoto R, Norvell DC, Vaccaro AR (2010) Morbidity and mortality related to odontoid fracture surgery in the elderly population. Spine (Phila Pa 1976) 35:S146-157. https://doi.org/10.1097/BRS.0b013e3181d830a4
39. Faure A, Graillon T, Pesenti S, Tropiano P, Blondel B, Fuentes S (2017) Trends in the surgical management of odontoid fractures in patients above 75 years of age: retrospective study of 70 cases. Orthop Traumatol Surg Res 103:1221–1228. https://doi.org/10.1016/j.otsr.2017.07.008
40. Lange N, Meyer B, Meyer HS (2021) Navigation for surgical treatment of disorders of the cervical spine – a systematic review. J Orthop Surg (Hong Kong) 29:23094990211012864. https://doi.org/10.1177/23094990211012865
41. Ishak B, Schneider T, Gimmy V, Unterberg AW, Kiening KL (2017) Early complications, morbidity, and mortality in octogenarians and nonagenarians undergoing posterior intra-operative spinal navigation-based C1/2 fusion for type II odontoid process fractures. J Neurotrauma 34:3326–3335. https://doi.org/10.1089/neu.2017.4968