

Adherence to Chest Wall Trauma Guidelines Reduces Critical Care Burden Across Ventilation Phenotypes: A Two-Era Cohort Study

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Abstract

Purpose

To determine whether a structured, guideline-informed chest wall trauma pathway was associated with lower ICU burden, and whether this differed by the indication for ventilation.

Methods

We retrospectively compared ICU-managed patients at a single center in Era 1 (2013–2017; mainly nonoperative care) and Era 3 (2023–2025; after pathway implementation), excluding the COVID-19-affected transitional Era 2. The primary outcome, restricted mean ICU time through day 28, was analyzed by adjusted pseudo-observation regression. Ventilation phenotype (chest-wall related vs extrathoracic) was the predefined effect modifier; surgical stabilization of rib fractures (SSRF) was modeled as a time-dependent exposure.

Results

Among 181 ICU-managed patients, median ICU stay was 7 days in both eras, but Era 3 was associated with 3.42 fewer adjusted ICU days (95% CI, – 5.96 to – 0.88; $p = 0.008$) despite more severe thoracic injury. The reduction was – 6.23 days with chest-wall related ventilation ($n = 67$; $p = 0.001$) and – 2.29 days with extrathoracic ventilation ($n = 100$; $p = 0.170$); the era $\times$ phenotype interaction was significant for ventilator days ($p = 0.040$) but not ICU time ($p = 0.067$). SSRF associations were also phenotype-dependent (interaction $p = 0.003$ for ICU time, $p = 0.010$ for ventilator days); in the chest-wall related phenotype, SSRF was associated with faster ICU exit (HR, 2.50; $p = 0.014$), faster ventilator liberation (HR, 3.35; $p = 0.002$) and less pneumonia (46.7% vs 75.7%; $p = 0.022$). Blinded phenotype re-adjudication ($\kappa = 0.84$) did not materially change the interaction estimates.

Conclusion

The pathway was associated with lower adjusted ICU burden, concentrated in patients ventilated because of chest wall injury. It cannot be attributed to SSRF alone, and ventilation phenotype merits prospective evaluation.

Background

Multiple rib fractures can impair chest wall mechanics, promote pain-related hypoventilation and pulmonary complications, and contribute to prolonged critical care use and mortality. These risks are heavily modified by age, overall injury severity, fracture burden, flail morphology, pulmonary contusion, and the adequacy of analgesic and respiratory support. Contemporary management therefore

increasingly combines structured risk assessment, aggressive multimodal analgesia, respiratory physiotherapy, selective critical care, and surgical stabilization in appropriately selected patients¹⁻³.

Over the last two decades, surgical stabilization of rib fractures (SSRF) has evolved from an uncommon intervention used mainly for ventilator-dependent flail chest into a selective component of contemporary chest wall trauma care.⁴ Randomized trials and meta-analyses suggest that, in selected patients, SSRF can reduce mechanical ventilation duration, pneumonia, tracheostomy, and intensive care unit (ICU) length of stay, although outcomes depend heavily on patient selection, injury pattern, timing, and institutional expertise⁵⁻⁸. Current consensus documents and guidelines position SSRF within a broader multidisciplinary management strategy rather than as an isolated surgical intervention⁹⁻¹².

Implementation of contemporary chest wall trauma care remains heterogeneous across institutions¹³⁻¹⁶. Differences in trauma-system organization, ICU capacity, access to dedicated chest wall expertise, and thresholds for ICU admission may influence the real-world effect of structured pathways. At our Central European trauma center, chest wall trauma care progressively evolved toward a structured, guideline-informed pathway. This comprehensive strategy comprises systematic assessment of chest wall instability, protocolized multimodal and regional analgesia, structured respiratory support, multidisciplinary decision-making, and guideline-based selection and timing for SSRF⁹⁻¹².

From a critical care perspective, the principal question is whether the incorporation of a guideline-informed chest wall trauma pathway is associated with reduced ICU and ventilator burden. ICU length of stay is a vital metric because prolonged critical care occupies substantial clinical capacity and incurs high costs^{17,18}.

The primary objective of this study was to determine whether the transition to a structured, guideline-informed chest wall trauma pathway was associated with lower adjusted ICU burden. Secondary objectives were to evaluate changes in mechanical ventilation and clinical outcomes, and to examine whether these associations differed according to the physiological indication for mechanical ventilation. We hypothesized that the contemporary era would carry lower adjusted ICU burden, that this reduction would be greatest when respiratory failure was driven by the chest wall injury itself, and that the association of SSRF with ICU and ventilator recovery would differ by ventilation phenotype.

Methods

Study Design and Setting

We conducted a retrospective, single-center observational cohort study at a Hungarian level-one trauma center, screening consecutive patients with traumatic rib fractures managed between January 1, 2013, and December 31, 2025. The study was approved by the Institutional Review Board of Aladar Petz University Teaching Hospital (PAEOK IKEB: 76-1-1/2026) and is reported in accordance with the STROBE statement.

The anonymized analysis dataset supporting these analyses is provided as Online Resource 1, and the phenotype codebook, the Era 3 protocol summary, supplementary tables and supplementary figure as Online Resource 2.

Treatment Eras

Chest wall trauma care at our institution passed through three consecutive eras, each defined by the state of the institutional pathway rather than by any single calendar event. Patients were assigned to an era by the date of the trauma-related admission. The components of care in each era are summarized in Table 1.

Table 1
Components of institutional chest wall trauma care across the three treatment eras

Component of care	Era 1 (2013–2017)	Era 2 (2018–2022)	Era 3 (2023–2025)
Model of care	historical; reactive, ICU-centered	transitional; excluded from analysis	contemporary; guideline-informed
Institutional guideline or protocol	none	none	guideline-informed, protocol-driven
Systematic CT chest wall assessment	no	inconsistent	routine
Dedicated chest wall consultation	no	no	routine
Operative decision-making	at the bedside, case by case	case by case	multidisciplinary review with ICU
Analgesia	intravenous, individualized	mixed, individualized	protocolized multimodal; paravertebral catheter in all SSRF patients, epidural if inadequate
Respiratory support and physiotherapy	individualized	individualized	structured protocol, dedicated physiotherapist
Dietetic input	not routine	not routine	routine
Protocolized critical care	no	no	yes
SSRF indication	rescue; mainly ventilator-dependent flail chest	selected cases, individually identified	contemporary guideline indications
SSRF implant	Judet struts	mixed	locking plates and screws
ICU-managed episodes analyzed, n	115	0 (100 in era)	66

CT, computed tomography; ICU, intensive care unit; SSRF, surgical stabilization of rib fractures. Era boundaries correspond to institutional changes in the chest wall trauma pathway rather than to any single calendar event. Era 2 is shown to document the transition and to make the contrast between the compared eras explicit; it was excluded from all analyses because it coincided with the COVID-19 pandemic and an altered ICU case-mix bearing directly on the primary outcome, and none of its 100 admission episodes entered any calculation. Episode counts in the final row are ICU-managed admission episodes in the analytic cohort.

- **Era 1 (2013–2017):** Preceded any structured pathway. Management was predominantly nonoperative (intravenous analgesia, case-by-case respiratory support). SSRF was performed sporadically as a rescue procedure using Judet struts for ventilator-dependent flail chest patients.

- **Era 2 (2018–2022):** A transitional phase characterized by increasing awareness of contemporary indications and systematic fracture assessment, but without a formal critical care protocol. Because this era overlapped the COVID-19 pandemic—which fundamentally altered ICU case-mix, admission thresholds, and resource utilization for reasons unrelated to trauma^{18,19} — it was excluded from outcome comparisons.
- **Era 3 (2023–2025):** The fully implemented, guideline-informed pathway. Instability and fracture burden were routinely assessed on admission CT. Management included protocolized multimodal analgesia (routine paravertebral catheters for SSRF patients), structured respiratory physiotherapy, dedicated dietetic input, multidisciplinary review, and guideline-indicated SSRF utilizing modern anatomically contoured locking plates. The operational sequence of this pathway, from the emergency department to discharge from critical care, is summarized in Online Resource 2, Table S1.

Participants and Inclusion/Exclusion Summary

Screening identified 3,119 patients admitted with traumatic rib fractures. Patients with blunt chest wall injury of qualifying severity (≥ 3 fractured ribs or thoracic Abbreviated Injury Scale [AIS] ≥ 3) were assessed for eligibility.

The primary analytic cohort consisted exclusively of eligible patients who required ICU management in Era 1 or Era 3, irrespective of whether they underwent SSRF. Patients managed entirely outside the ICU were excluded from all primary and secondary analyses.

For descriptive completeness, patients from Era 1 and Era 3 who underwent SSRF without ICU admission were retained in the institutional source cohort and are shown in the study flow, but they did not contribute to any ICU-burden, ventilation, phenotype, or outcome analysis.

The institutional source cohort comprised 318 eligible admission episodes across the full study period. Of these, 181 ICU-managed episodes from Era 1 and Era 3 constituted the primary analytic cohort. An additional 37 patients underwent SSRF without ICU admission in these two eras and are reported descriptively only. The construction of the cohort is shown in Fig. 1.

Retrospective Adjudication of SSRF Indications

All included patients were retrospectively assessed against contemporary World Society of Emergency Surgery (WSES) and Chest Wall Injury Society (CWIS) guideline-based indications for SSRF^{9–12}. Patients were considered to meet indications if they had clinical/radiographic flail chest, ≥ 3 severely displaced fractures, severe chest wall deformity, or failure of optimal nonoperative management. Three trauma surgeons applied these criteria, resolving disagreements by consensus. We acknowledge that retrospective adjudication introduces potential classification bias.

Definition of Endpoints and Censoring

The primary outcome was ICU length of stay among ICU-managed patients, measured from admission to ICU exit. ICU exit was defined as discharge or in-ICU death. While a shorter stay ending in death is clinically unfavorable, it is utilized here strictly as a resource-focused endpoint to measure critical care bed utilization. Clinical outcomes (mortality, complications) are analyzed separately. Open-ended ICU stays (patients transferred with continued intensive care) were treated as right-censored at the last documented ICU day. Pneumonia occurring during the index admission was recorded when a clinical diagnosis was supported either by a positive respiratory culture or by a new or progressive pulmonary infiltrate on chest radiography or computed tomography. This pragmatic definition reflects routine institutional practice, was applied identically in both eras, and was not subjected to independent re-adjudication.

Care-Pathway Classification and Timing of ICU Admission

ICU-managed patients were assigned to one of three mutually exclusive care pathways: (A) ICU management without SSRF; (B) SSRF with ICU admission before operation; or (C) SSRF with ICU admission beginning only after operation. Categories B and C were distinguished from the recorded dates of ICU admission and of surgery; where both fell on the same calendar day, documented preoperative invasive ventilation determined the assignment. Category C describes the sequence of admission relative to surgery and not the indication for admission: postoperative ICU admission for protocol-driven monitoring was not institutional practice in either era, and patients in this category were admitted because ventilatory support was still required. Care-pathway category was used as a sensitivity covariate in the adjusted analysis of ICU time.

For each ICU-managed patient we recorded whether ICU admission occurred directly from the emergency department or after a period of ward care. Delayed ICU admission denotes the latter, and pre-ICU ward days denotes the number of ward days preceding ICU admission. Both variables were entered as sensitivity covariates to establish that the era contrast was not produced by a shift in the time origin of the ICU clock.

Mechanical Ventilation Variables

Invasive mechanical ventilation was recorded in whole calendar days during the index hospitalization. Intubation solely for the conduct of surgery was not counted as mechanical ventilation for respiratory failure. In operated patients, ventilation before SSRF was counted inclusively through the day of operation and ventilation after SSRF exclusively thereafter; one recorded preoperative ventilator day therefore denotes surgery on the first calendar day of ventilation rather than 24 hours of preoperative support. The same preoperative ventilation day defined the change of state of the time-dependent SSRF exposure in the analysis of liberation from mechanical ventilation.

Ventilation Phenotype Classification

The indication for invasive mechanical ventilation was classified as chest-wall related (respiratory failure directly attributable to instability, pain, or pulmonary contusion) or extrathoracic (support required for traumatic brain injury, hemorrhagic shock, etc.). This classification was made retrospectively from the clinical record.

Because the ventilation indication is a post-baseline adjudicated variable, its robustness was assessed by independent re-adjudication. Two clinicians experienced in trauma critical care independently classified all 167 invasively ventilated patients from a structured extract restricted to documentation from the first 24 hours after admission or intubation, from which operative documentation was withheld; both were blinded to SSRF status, extubation timing and all subsequent outcomes. A predefined codebook (Codebook S1) defined chest-wall related, extrathoracic and indeterminate-mixed categories, the last being used when thoracic and extrathoracic contributions were both major and no dominant indication could be assigned. Raw agreement and Cohen's κ were calculated before any consensus discussion, and disagreements were resolved only after the independent classifications had been locked. The interaction analyses were then repeated with the final consensus phenotype, excluding indeterminate-mixed cases (Table S2).

Statistical Analysis and Alpha Control

Continuous variables are summarized as mean with standard deviation and median with interquartile range; categorical variables as counts and proportions. Because the number of available observations differed between variables, outcome-specific denominators are reported throughout; analyses of total ventilator days were restricted to completely observed ventilation courses, and comparisons of hospital length of stay to completely observed hospital stays. Continuous variables were compared using the Mann–Whitney test. Era-level categorical comparisons used the chi-square test with Yates' continuity correction for 2×2 tables; the phenotype-specific comparisons of SSRF against nonoperative management, in which expected cell counts were small, used Fisher's exact test.

For outcome-specific analyses, patients were excluded only when the relevant exposure, covariate, or outcome variable was missing or non-interpretable. Missing data were handled by complete-case analysis for each endpoint; no imputation was performed in the primary analyses. For the baseline-predicted phenotype sensitivity analysis only, the single missing head AIS value was imputed at the cohort median.

ICU length-of-stay values recorded as open-ended represented patients transferred to another institution with an incompletely observed subsequent ICU course. All such transfers represented continued intensive care at the receiving institution; these observations were therefore treated as right-censored at the last documented ICU day, and the observed ICU durations in these patients represent a lower bound. Exact values were treated as observed ICU-exit events.

The primary adjusted analysis estimated the restricted mean ICU time through day 28 by pseudo-observation regression with an identity link and robust sandwich standard errors, adjusted for treatment era, age, sex, ISS, thoracic AIS and flail chest; the Era 3 versus Era 1 contrast, with Era 1 as reference, was the primary comparison, and this estimate was re-examined with a nonparametric bootstrap resampling patients and recomputing the pseudo-observations within each resample. Sensitivity analyses replaced ISS with NISS, added pulmonary contusion burden, timing of ICU admission and care-pathway category, and included a propensity-score matched comparison in which the propensity score was estimated by logistic regression on standardized baseline covariates and patients were matched 1:1 without replacement on the logit of the score within a caliper of 0.2 standard deviations, balance being assessed by standardized mean differences. Two distinct Cox proportional hazards models were fitted and are reported separately. The first was a secondary analysis of the era effect on time to ICU exit, containing treatment era and the same baseline covariates and no SSRF term. The second, used only for the phenotype-specific SSRF analyses, entered SSRF as a time-dependent exposure changing state on the recorded day of fixation, with robust standard errors clustered at the patient level.

Effect modification by the ventilation indication was evaluated for restricted mean ICU time through day 28 and for total ventilator days: stratum-specific estimates were obtained from the same models fitted separately within each phenotype, and the interaction was then tested formally in a pooled model containing era or SSRF, phenotype, their interaction and the same covariates. Because the ventilation indication is a post-baseline adjudicated variable, the interaction models were re-estimated using the blinded consensus phenotype, and two further sensitivity analyses used definitions containing no outcome information: a baseline-only surrogate phenotype derived by logistic regression from age, sex, ISS, thoracic AIS, flail chest, head AIS and total rib-fracture count, and an a priori phenotype defined as thoracic AIS of 4 or greater or clinical flail chest.

Liberation from mechanical ventilation was analyzed on the ventilation clock, with time measured from the initiation of ventilation and SSRF entered as a time-dependent exposure changing state on the recorded pre-operative ventilation day. Patients who died within 30 days were censored at their last ventilator day in the primary analysis; a sensitivity analysis instead treated death as never liberated.

Inference followed a fixed hierarchy. The primary contrast was Era 3 versus Era 1 for restricted mean ICU time through day 28. One effect modifier – the indication for mechanical ventilation – was defined on clinical and guideline grounds rather than selected from the data, and its assignment was verified by independent re-adjudication blinded to treatment and outcome; it was tested by formal interaction on restricted mean ICU time and on total ventilator days. No other effect modifier was examined; the remaining variables were collected for description and for covariate adjustment only. All remaining analyses were exploratory. The primary contrast and the two interaction tests are therefore reported without multiplicity correction; the exploratory analyses are descriptive and were not used for inference. Analyses were performed in Python 3.12 using pandas, numpy and scipy, with pseudo-observation, Cox, logistic regression and matching routines implemented directly rather than taken from a survival or

regression library; because ICU and ventilation times were recorded in whole calendar days, tied event times were frequent and the Cox partial likelihood was evaluated with the Efron approximation.

Use of large language models

During the preparation of this work, the authors used Claude (Anthropic) solely for limited language editing, readability improvement, and formatting assistance. No patient-level data were provided to the tool, and it was not used for data analysis, statistical calculations, interpretation of results, or scientific decision-making. All content was reviewed and approved by the authors, who take full responsibility for the publication.

Results

Cohort Composition and Baseline Characteristics

Of the 318 admission episodes in the institutional source cohort, 218 fell within Eras 1 and 3. Of these, 181 met the ICU-management criterion and constitute the primary analytic cohort (115 in Era 1; 66 in Era 3; Fig. 1). Baseline characteristics (Table 2) showed similar age (median 51 vs 52 years) and overall injury severity (median ISS 27 vs 29; $p = 0.119$). However, chest injury was significantly more severe in Era 3, with higher thoracic AIS ($p = 0.009$), more fractured ribs ($p = 0.005$), and higher NISS ($p = 0.027$). The route into critical care (emergency department vs delayed ward transfer) did not differ between eras.

Table 2
Baseline demographic, injury and care-entry characteristics

Variable	Era 1 (n = 115)	Era 3 (n = 66)	p value
Age, median [IQR], years	51 [37–63.5]	52 [41–62.8]	0.547
Male sex, n/N (%)	90/115 (78.3)	49/66 (74.2)	0.665
Thoracic AIS, median [IQR]	3 [3–3.5]	3 [3–4.8]	0.009
ISS, median [IQR]	27 [22–37]	29 [24–38]	0.119
NISS, median [IQR]	34 [27–41]	34 [27–48]	0.027
Fractured ribs, median [IQR]	5 [4–8]	7 [5–9]	0.005
Flail segment, n/N (%)	40/115 (34.8)	30/66 (45.5)	0.207
Flail chest, n/N (%)	27/115 (23.5)	19/66 (28.8)	0.540
Delayed ICU admission, n/N (%)	25/115 (21.7)	16/66 (24.2)	0.839
Pre-ICU ward days, mean	0.54	0.67	0.738
Invasively ventilated, n/N (%)	102/115 (88.7)	65/66 (98.5)	0.037
Chest-wall related ventilation, n/N (%)	39/115 (33.9)	28/66 (42.4)	0.326
AIS, Abbreviated Injury Scale; ICU, intensive care unit; IQR, interquartile range; ISS, Injury Severity Score; NISS, New Injury Severity Score. Denominators differ between variables because of missing data and are reported as n/N. Delayed ICU admission denotes ICU admission after a period of ward care. The ventilation indication was not applicable in 13 Era 1 and 1 Era 3 patients who did not receive invasive mechanical ventilation; percentages for chest-wall related ventilation are of all ICU-managed patients. Continuous variables were compared using the Mann–Whitney test and categorical variables using the chi-square test.			

Care-Pathway Composition and SSRF Utilization

The composition of the ICU population changed markedly (Table 3). SSRF among ICU-managed patients rose from 12.2% in Era 1 to 39.4% in Era 3 ($p < 0.001$). The Era 3 ICU population was highly ventilator-dependent, with invasive mechanical ventilation rising from 88.7% to 98.5% ($p = 0.037$). An additional 37 patients underwent SSRF without ever being admitted to intensive care (3 in Era 1; 34 in Era 3); these patients are excluded from the ICU-burden analyses.

Table 3
Care-pathway composition, treatment characteristics and clinical outcomes

Variable	Era 1 (n = 115)	Era 3 (n = 66)	p value
A. ICU, no SSRF, n (%)	101 (87.8)	40 (60.6)	< 0.001
B. SSRF, ICU before operation, n (%)	12 (10.4)	20 (30.3)	
C. SSRF, ICU after operation only, n (%)	2 (1.7)	6 (9.1)	
Invasively ventilated share of ICU patients, %	88.7	98.5	0.037
SSRF among ICU patients, n/N (%)	14/115 (12.2)	26/66 (39.4)	< 0.001
Time from injury to SSRF, median [IQR], d	1 [0–4.2]	2 [1–4]	0.293
ICU stay, mean ± SD (median), days	10.8 ± 10.8 (7)	9.4 ± 8.4 (7)	0.646
Invasive ventilation, mean ± SD (median), d	7.5 ± 9.1 (3)	6.5 ± 6.9 (5)	0.655
Hospital stay, median [IQR], days	24 [14–44]	21 [12–45.5]	0.780
Pneumonia, n (%)	43 (37.4)	31 (47.0)	0.269
Reintubation, n/N (%)	11/115 (9.6)	9/66 (13.6)	0.552
Tracheostomy, n/N (%)	20/115 (17.4)	13/66 (19.7)	0.852
30-day mortality, n/N (%)	14/93 (15.1)	12/51 (23.5)	0.299
1-year survival, n/N (%)	58/79 (73.4)	25/38 (65.8)	0.526

ICU, intensive care unit; SSRF, surgical stabilization of rib fractures. Care-pathway categories A to C are mutually exclusive and were compared in a single 3×2 chi-square test ($\chi^2=18.5$; $p < 0.001$); the p value is reported once for the block. Category C denotes ICU admission beginning after operation and does not represent protocol-driven monitoring: restricted mean ICU time in this category was 14.88 days, the longest of the three pathways, and all six Era 3 patients remained ventilated for extrathoracic reasons. Denominators differ because of missing data: exact ICU stay was available in 163 patients, exact hospital stay in 137, 30-day status in 144 and 1-year status in 117. Ventilation data were complete in 167 patients, comprising 153 invasively ventilated patients with a completely observed ventilation course and 14 patients who were never invasively ventilated; ventilator-day analyses are therefore estimated in 153 patients. Crude ICU-stay summaries and the Mann–Whitney comparison use the observed ICU durations; for transferred patients these observed durations represent lower bounds. Censoring-aware inference is based on restricted mean ICU time.

ICU Burden Across Treatment Eras: Adjusted vs Crude Differences

An exact ICU length-of-stay value was available for 163 of the 181 ICU-managed patients; 18 were right-censored because of transfer with continued intensive care elsewhere (14 in Era 1 and 4 in Era 3). Crude median ICU stay was 7 days in both eras and the unadjusted comparison was not significant ($p = 0.646$), but unadjusted restricted mean ICU time through day 28 fell from 11.52 to 9.66 days — the change lies in the long tail of the distribution, not in the typical patient.

After adjustment for age, sex, ISS, thoracic AIS and flail chest, Era 3 was associated with a reduction in restricted mean ICU time through day 28 of – 3.42 days (95% CI, – 5.96 to – 0.88; $p = 0.008$) compared with Era 1. The same contrast estimated by nonparametric bootstrap was of similar magnitude and direction.

The estimate was stable across predefined sensitivity analyses (Table 4): replacing ISS with NISS, adding pulmonary contusion burden, adding the timing of ICU admission as either a continuous or a binary covariate, adjusting for care-pathway category, and extending the endpoint to the interval from hospital admission to ICU exit all yielded adjusted differences between – 3.07 and – 3.56 days, each significant.

Table 4
Adjusted analyses of ICU stay among ICU-managed patients

Analysis	Adjusted effect	95% CI	p
28-day restricted mean ICU time, ISS-adjusted	–3.42 days	–5.96 to – 0.88	0.008
NISS-adjusted sensitivity	–3.52 days	–6.05 to – 1.00	0.006
Adding pulmonary contusion (BPC18), n = 149	–3.56 days	–6.33 to – 0.79	0.012
Adding pre-ICU ward days	–3.32 days	–5.89 to – 0.76	0.011
Adding delayed ICU admission	–3.31 days	–5.86 to – 0.75	0.011
Adding care-pathway category	–3.28 days	–5.89 to – 0.66	0.014
Hospital admission to ICU exit	–3.07 days	–5.60 to – 0.54	0.017
Propensity-matched, 56 pairs (unadjusted)	–5.04 days	–8.34 to – 1.73	0.003
Cox model, time to ICU exit	HR 1.43	1.02–2.01	0.037
CI, confidence interval; HR, hazard ratio; ICU, intensive care unit; ISS, Injury Severity Score; NISS, New Injury Severity Score. All estimates are the Era 3 versus Era 1 contrast. Models were adjusted for age, sex, ISS (or NISS where indicated), thoracic Abbreviated Injury Scale score and flail chest, with Era 1 as reference. Negative differences indicate fewer restricted mean ICU days through day 28. Hazard ratios above 1 indicate a higher rate of ICU exit and therefore a shorter ICU stay; because ICU exit was defined as discharge or in-ICU death, these estimates describe bed-day utilization rather than clinical benefit. The primary model included all 181 patients, complete covariate data being available in every case. A nonparametric bootstrap of the primary estimate gave a median of – 3.38 days (95% CI, – 6.01 to – 0.70), with 99.5% of replicates below zero. After propensity matching all standardized mean differences were below 0.05.			

In a secondary Cox analysis Era 3 was associated with a higher rate of ICU exit than Era 1 (adjusted HR, 1.43; 95% CI, 1.02–2.01; $p = 0.037$). Unadjusted Kaplan–Meier curves are shown in Fig. 2; the curves are superimposed up to the median and separate only in the tail, consistent with a reduction in the frequency and duration of prolonged ICU courses rather than a uniform shortening of ICU treatment.

Because the proportion of censored observations differed between eras, a tipping-point analysis was performed over the plausible range of unobserved post-transfer ICU time (Online Resource 2: Table S3). The estimate remained significant across the entire range, from – 2.60 days ($p = 0.029$) if transferred patients required only three further ICU days to – 3.94 days ($p = 0.003$) if they remained in intensive care to day 28. In a propensity-score matched comparison (56 pairs; all standardized mean differences below 0.05 after matching), restricted mean ICU time was 9.10 versus 14.14 days (– 5.04 days; 95% CI, – 8.34 to – 1.73; $p = 0.003$), consistent in direction with the regression estimate although matching discarded half of the Era 1 patients.

Ventilation Phenotype and Effect Modification

Of the 181 ICU-managed patients, 167 (92.3%) received invasive mechanical ventilation: 67 for chest-wall related and 100 for extrathoracic indications; the remaining 14 patients were never invasively ventilated and were assigned to neither phenotype. The two phenotypes showed distinct critical care trajectories, with longer median ICU stay (12 vs 6 days) and ventilation duration (8 vs 2 days) in the chest-wall related group.

The era effect differed markedly by ventilation phenotype (Table 5; Fig. 3). In patients with chest-wall related ventilation, adjusted restricted mean ICU time decreased from 16.76 days in Era 1 to 11.88 days in Era 3, corresponding to a reduction of – 6.23 days (95% CI, – 9.79 to – 2.67; $p = 0.001$). Median ventilation duration decreased from 10.5 to 6 days, while SSRF utilization increased from 28% to 68%. In contrast, among patients ventilated for extrathoracic indications, the adjusted reduction in ICU time was smaller and imprecisely estimated (– 2.29 days; 95% CI, – 5.55 to 0.98; $p = 0.170$). Thus, the overall adjusted reduction of – 3.42 ICU days represents an average across two clinically distinct phenotypes, with the greatest reduction observed when ventilatory failure was driven by the chest wall injury.

Table 5
Critical care outcomes by ventilation indication and treatment era

Variable	Era 1	Era 3
Chest-wall related ventilation, n	39	28
SSRF, n (%)	11 (28)	19 (68)
Restricted mean ICU time, days	16.76	11.88
Median ICU stay, days	15	8.5
Median ventilation, days	10.5	6
Pneumonia, %	59	68
Adjusted difference vs Era 1, days	reference	-6.23 (p = 0.001)
Extrathoracic ventilation, n	63	37
SSRF, n (%)	2 (3)	7 (19)
Restricted mean ICU time, days	9.65	8.24
Median ICU stay, days	6	6
Median ventilation, days	2	3
Pneumonia, %	27	32
Adjusted difference vs Era 1, days	reference	-2.29 (p = 0.170)
ICU, intensive care unit; SSRF, surgical stabilization of rib fractures. Restricted mean ICU time is calculated through day 28 with right-censoring of incompletely observed stays. Median ventilation duration is reported among patients whose ventilation course was completely observed, the convention used throughout. Adjusted differences derive from pseudo-observation regression including age, sex, ISS, thoracic AIS and flail chest, fitted separately within each stratum; the 95% confidence intervals were - 9.79 to - 2.67 in the chest-wall related stratum and - 5.55 to 0.98 in the extrathoracic stratum. The formal era × phenotype interaction, estimated in a pooled model, is reported in the text and in Online Resource 2: Table S3. Fourteen ICU-managed patients (13 in Era 1 and 1 in Era 3) did not receive invasive mechanical ventilation and are not shown. The two strata comprise all 167 invasively ventilated ICU patients.		

Formal interaction testing supported this phenotype dependence, particularly for ventilatory burden. The Era 3 × chest-wall related interaction was - 4.79 ventilator days (95% CI, - 9.35 to - 0.22; p = 0.040) and - 4.69 restricted mean ICU days (95% CI, - 9.71 to 0.34; p = 0.067), the latter not reaching statistical significance. Within the pooled model, the implied Era 3 effect on ICU time was - 6.60 days in the chest-wall related phenotype (p = 0.001) and - 1.92 days in the extrathoracic phenotype (p = 0.227). Alternative severity adjustment and outcome-independent phenotype definitions yielded interactions of similar magnitude (Table S3).

SSRF Associations by Ventilation Phenotype

The predefined SSRF × phenotype interaction was significant for both restricted mean ICU time through day 28 (– 11.79 days; 95% CI, – 19.60 to – 3.97; $p = 0.003$; Table 6; Fig. 4) and total ventilator days (– 8.48 days; 95% CI, – 14.91 to – 2.05; $p = 0.010$). Within the chest-wall related stratum, SSRF was associated with substantially fewer ventilator days than nonoperative management (adjusted difference, – 8.72 days; 95% CI, – 15.41 to – 2.02; $p = 0.011$), whereas no significant association was observed in the extrathoracic stratum (+ 3.64 days; 95% CI, – 3.54 to 10.83; $p = 0.321$), where only seven operated patients had complete ventilation data.

Table 6
Effect modification of SSRF associations by indication for mechanical ventilation

Analysis	Chest-wall related ventilation	Extrathoracic ventilation
Patients, n	67	100
SSRF, n (%)	30 (44.8)	9 (9.0)
Median ICU stay, days	12	6
Median ventilation, days	8	2
Ventilator days, SSRF vs no SSRF, mean	7.6 vs 13.9	8.7 vs 5.1
adjusted difference, days	-8.72 (- 15.41 to - 2.02); p = 0.011	+ 3.64 (- 3.54 to 10.83); p = 0.321
ICU exit, time-dependent SSRF	HR 2.50 (1.20–5.18); p = 0.014	HR 0.58 (0.27–1.25); p = 0.166
Liberation from ventilation, time-dep. SSRF	HR 3.35 (1.55–7.27); p = 0.002	HR 0.30 (0.09–1.02); p = 0.055
Pneumonia, SSRF vs no SSRF	46.7% vs 75.7%; p = 0.022	55.6% vs 26.4%; p = 0.116
Baseline ISS, SSRF vs no SSRF	34.8 vs 25.8	36.2 vs 30.6
Baseline thoracic AIS, SSRF vs no SSRF	4.27 vs 3.43	4.44 vs 3.15
Flail chest, SSRF vs no SSRF	67% vs 27%	56% vs 11%
Head AIS ≥ 3 , SSRF vs no SSRF	13% vs 19%	56% vs 38%

AIS, Abbreviated Injury Scale; HR, hazard ratio; ICU, intensive care unit; ISS, Injury Severity Score; SSRF, surgical stabilization of rib fractures. Formal interaction tests were adjusted for age, sex, ISS, thoracic AIS and flail chest and used an outcome-specific analysis population. Restricted mean ICU time through day 28 was estimated in all 167 invasively ventilated patients, right-censored ICU stays being accommodated by the pseudo-observation method: SSRF $\times$ chest-wall related indication - 11.79 days (95% CI, - 19.60 to - 3.97; p = 0.003). Total ventilator days were estimated in the 153 patients with a completely observed ventilation course: -8.48 days (95% CI, - 14.91 to - 2.05; p = 0.010). Hazard ratios above 1 indicate faster ICU exit or faster liberation from mechanical ventilation. Baseline comparisons are shown to establish the direction of confounding by indication. Head AIS was not determinable in one patient in the extrathoracic stratum, who is excluded from the corresponding percentage. The 39 operated patients shown here are those of the 40 ICU-managed patients undergoing SSRF who received invasive mechanical ventilation and therefore have a ventilation phenotype; the remaining operated patient was never invasively ventilated and belongs to neither stratum. Estimates in the extrathoracic stratum rest on nine operated patients, seven of whom had a completely observed ventilation course. Neither extrathoracic hazard ratio reached nominal significance; the liberation estimate is additionally unstable, moving between 0.22 and 0.70 when any single operated patient is omitted, and it is not interpretable as an effect of fixation on the ventilatory course.

Modeled as a time-dependent exposure, SSRF was associated with faster ICU exit in the chest-wall related phenotype (HR, 2.50; 95% CI, 1.20–5.18; p = 0.014), but not in the extrathoracic phenotype (HR,

0.58; 95% CI, 0.27–1.25; $p = 0.166$). In the chest-wall related stratum, inclusion of time-dependent SSRF attenuated the Era 3 association with ICU exit, consistent with SSRF contributing to, but not formally mediating, part of the era effect. Pneumonia followed the same pattern, occurring in 46.7% of operated versus 75.7% of nonoperatively managed patients ($p = 0.022$); the corresponding difference was not significant in the extrathoracic stratum.

These associations should be interpreted cautiously because SSRF was not randomized. Importantly, within the chest-wall related phenotype, operated patients had more severe overall and thoracic injury, including higher ISS, thoracic AIS and prevalence of clinical flail chest, yet experienced shorter ICU and ventilator courses and fewer pulmonary complications. In contrast, patients in the extrathoracic phenotype required ventilation primarily for non-thoracic injuries, particularly traumatic brain injury; therefore, chest wall stabilization would not be expected to eliminate the dominant indication for ventilatory support.

Liberation from Mechanical Ventilation

SSRF was modeled as a time-dependent exposure on the ventilation clock in the 153 ventilated patients with a completely observed ventilation course and complete covariate data; 37 of them were operated and 25 died within 30 days. Fixation was associated with faster liberation from mechanical ventilation (HR, 2.16; 95% CI, 1.14–4.08; $p = 0.018$). Within the chest-wall related stratum the estimate was HR 3.35 (95% CI, 1.55–7.27; $p = 0.002$; Figure S1). Within the extrathoracic stratum the estimate lay in the opposite direction (HR, 0.30; 95% CI, 0.09–1.02; $p = 0.055$), but it rests on seven operated patients, six of whom were fixed before ICU admission and therefore counted as exposed from the first ventilator day, and it is not stable: omitting any single operated patient moves the estimate between 0.22 and 0.70, and the same model with model-based rather than robust standard errors gives 95% CI 0.09 to 1.06.

Ventilation in that stratum was dictated by the extrathoracic injury, and this estimate should not be read as evidence that fixation prolonged ventilation. When death was treated as never liberated, the overall estimate was HR 2.03 (95% CI, 1.08–3.83; $p = 0.028$).

Pulmonary Complications and Other Clinical Outcomes

Total invasive ventilation irrespective of indication was 7.5 ± 9.1 days in Era 1 and 6.5 ± 6.9 days in Era 3 ($p = 0.655$), and median hospital stay 24 days (IQR, 14–44) versus 21 days (IQR, 12–45.5; $p = 0.780$). Pneumonia occurred in 43 of 115 (37.4%) and 31 of 66 (47.0%; $p = 0.269$), reintubation in 11 of 115 (9.6%) and 9 of 66 (13.6%; $p = 0.552$), and tracheostomy in 20 of 115 (17.4%) and 13 of 66 (19.7%; $p = 0.852$).

Thirty-day mortality was 14 of 93 (15.1%) and 12 of 51 (23.5%) ($p = 0.299$), and 1-year survival among patients with known status was 58 of 79 (73.4%) and 25 of 38 (65.8%) ($p = 0.526$). Survival status was missing for 37 patients at 30 days and 64 patients at 1 year, and these comparisons should therefore be interpreted with caution.

Discussion

Effect of the Pathway on ICU Burden

In this 13-year analysis, the transition from a reactive, ICU-centered management model to a structured, guideline-informed chest wall trauma pathway was associated with lower adjusted ICU burden. While crude median ICU stays were unchanged, adjusted models accounting for the more severely injured case-mix in Era 3 revealed a reduction of approximately 3.42 ICU days per patient. Crucially, this reduction was not distributed evenly: it was heavily concentrated (-6.23 adjusted days) in patients whose respiratory failure was driven directly by their chest wall injury.

This magnitude is consistent with the limited previous experience of pathway-level intervention in chest wall trauma. Todd and colleagues reported a reduction of approximately 2.4 ICU days following implementation of a multidisciplinary clinical pathway in high-risk patients with rib fractures³, and the present estimate extends that observation to a Central European trauma system in which surgical stabilization formed an explicit, guideline-indicated component of the pathway rather than a rescue procedure.

One structural consequence of the pathway shapes every era-level comparison reported here. Thirty-four patients underwent SSRF in Era 3 without ever requiring intensive care, against three in Era 1. Patients whose chest wall injury could be managed outside the ICU were therefore progressively removed from the denominator, and those who remained were, by selection, the patients in whom the injury could not be managed any other way. That is the arithmetic behind the near-universal invasive ventilation rate of the Era 3 ICU cohort (98.5% versus 88.7%; $p = 0.037$) and behind its higher thoracic AIS, rib fracture count and NISS. Era-level rates of ventilation and of pulmonary complications in this study are consequently rates within an increasingly concentrated population, and any comparison that ignores this shift will understate rather than overstate the association with the pathway.

Role of SSRF Within the Pathway

In this heterogeneous, guideline-selected cohort, SSRF utilization increased substantially (from 12.2% to 39.4% in the ICU) and may have contributed to improved pathway performance.

The parallel phenotype dependence of the SSRF outcomes strengthens the biological coherence of our findings. Within the chest-wall related stratum, SSRF was associated with faster ICU exit, faster ventilator liberation, and reduced pneumonia^{20,21}. Conversely, in patients ventilated for extrathoracic reasons (e.g., severe traumatic brain injury), SSRF predictably showed no respiratory benefit. This supports the prospective evaluation of physiological, rather than exclusively anatomical, selection criteria for SSRF, as broadly grouping all patients with multiple rib fractures may dilute the measurable benefits of fixation⁵⁻⁸.

Operative timing did not differ materially between eras. This should be interpreted cautiously, as retrospective timing analyses are particularly susceptible to confounding by indication: patients operated earlier may differ systematically in physiological readiness and concomitant injury burden. Registry

studies have demonstrated similar selection effects in SSRF timing analyses^{22,23} and our whole-calendar-day data do not allow these time-varying clinical factors to be reconstructed reliably.

Phenotype Dependence and Its Physiological Basis

The SSRF associations run parallel to the era effect. Stabilization was associated with better critical care trajectories when chest wall dysfunction contributed directly to respiratory failure, but not when ventilatory dependence was governed by injuries outside the chest, and blinded re-adjudication left that pattern materially unchanged (Online Resource 2: Table S2). Within the chest-wall related stratum, adjustment for time-dependent SSRF attenuated the era association with ICU exit – consistent with, but not proving, a contribution of increased fixation to the pathway association. The phenotype-specific pattern is less consistent with a purely uniform secular improvement, although residual time-varying confounding cannot be excluded.

Ventilation phenotype may also help explain heterogeneity in the randomized literature. Trials focused on patients with severe clinical flail chest have generally reported reductions in ventilatory support or critical care use^{5,6,20} whereas trials enrolling broader chest wall injury populations have produced less consistent results^{7,21}. One possible explanation is dilution of a phenotype-specific treatment association when patients whose ventilation is chest-wall related are analyzed together with those ventilated for extrathoracic reasons. This remains hypothesis-generating, but supports prospective evaluation of physiological rather than exclusively anatomical selection criteria.⁴

This interpretation is physiologically plausible. Stabilization may improve chest wall mechanics and reduce pain-related impairment of ventilation and secretion clearance.^{9,24} When these factors contribute substantially to respiratory failure, correcting chest wall instability could plausibly facilitate ventilator liberation. Conversely, when mechanical ventilation is required predominantly for traumatic brain injury, shock or other extrathoracic injury, stabilization of the chest wall would not be expected to determine the ventilatory trajectory. It is important to interpret this on a case-by-case basis, however, because even if the reason for ventilation is not directly related to chest wall injury, SSRF may still benefit these patients and should not be withheld from them if there is a potential benefit. One important indication for SSRF specifically in the traumatically brain injured patient may be to avoid the secondary insult which can come from hypoxia.¹⁰

Potential Economic Implications (Hypothesis-Generating)

ICU bed-days and mechanical ventilation are resource-intensive components of trauma care²⁵. Previous economic models of SSRF from North America suggest that the upfront costs of surgery may be offset by reduced postoperative resource utilization^{26–30}. While our study lacks patient-level micro-costing data, an adjusted reduction of three ICU days per patient—and over six days in the chest-wall phenotype—represents highly relevant critical care capacity release. We frame this finding as hypothesis-generating: while it suggests substantial operational benefits (e.g., freeing beds for other critically ill

patients), institution-specific economic analyses are required to determine true cost-effectiveness in a European healthcare framework.

The Case for a Dedicated Chest Wall Injury Program

What separated the two compared eras was not a single operation. It was the way chest wall injury was recognized, discussed and treated: Era 1 offered analgesia and supportive care with fixation held back as a rescue maneuver, whereas Era 3 delivered the defined package summarized in Table 1. The reduction in critical care burden was observed at the level of that package, and it was largest exactly where the package is mechanistically supposed to act.

We therefore read these findings as an argument for establishing dedicated chest wall injury programs in centers managing a meaningful volume of blunt thoracic trauma, rather than for adopting SSRF as an isolated technical addition: the program, not the implant, is the unit of implementation, and its components are interdependent. Consistent with the importance of separating program-level effects from individual technical components, our recent multicenter CIID study found that the technique used for hemothorax evacuation during SSRF was not independently associated with ICU or hospital length of stay after adjustment for injury severity and pulmonary contusion burden.³¹ Our data are observational and single-center, and cannot apportion the association between components; what they describe is what happened to critical care utilization when a Central European trauma center moved from the first model of care to the second.

Mortality and Pulmonary Complications

Mortality did not differ significantly between eras, although interpretation is limited by incomplete follow-up and the more selective composition of the Era 3 ICU cohort. As increasing numbers of patients underwent SSRF without ICU admission, the later ICU population became concentrated toward more severe thoracic injury and near-universal mechanical ventilation. Accordingly, the observed reduction in ICU burden should not be interpreted as evidence of a survival benefit, but neither do the mortality data provide evidence of harm.

Pneumonia deserves separate comment, because its frequency in this cohort is high. Among nonoperatively managed patients ventilated for chest-wall related respiratory failure, 75.7% were recorded as having pneumonia. Set beside the era-level figures of 37.4% and 47.0%, that number looks extreme, but the comparison is not like for like: it describes intubated patients whose respiratory failure was driven by the chest wall itself, and rates of this order are what has been reported in that population. In the randomized trial of Tanaka and colleagues, in which every patient had severe flail chest and required prolonged ventilatory support, pneumonia occurred in 77% of patients managed without fixation and in 24% of those stabilized⁵. Among ventilated trauma patients with multiple rib fractures unselected for flail morphology, Park and colleagues recorded ventilator-associated pneumonia in 45.5%, with severe pulmonary contusion identified as an independent risk factor³². Our 75.7% therefore sits close to

the historical nonoperative benchmark rather than outside it, and the 46.7% observed after fixation sits close to the operative one.

Pneumonia did not decrease at the era level, despite its lower incidence among SSRF-treated patients within the chest-wall related phenotype. This is what the concentration of the Era 3 ICU population would predict, and it reinforces the phenotype-specific nature of the observed treatment associations. Overall, the pathway was associated with shorter ICU and ventilator courses without a demonstrable era-level reduction in infectious complications.

Limitations

Our study has several limitations that must be acknowledged:

- **Design and confounding:** As a retrospective, sequential-era design, causality cannot be definitively established. Secular changes in critical care, ventilation strategies, and institutional learning curves over the 13-year period may confound the observed pathway effects.
- **Selection and generalizability:** We excluded the transitional Era 2 (COVID-19 pandemic) to avoid direct confounding of ICU endpoints. Furthermore, non-ICU patients managed nonoperatively were excluded. Consequently, this study cannot assess whether the pathway prevented ICU admissions altogether.
- **Outcome measurement:** ICU exit was defined as "discharge or death," which serves as a metric for bed utilization but is not a pure measure of clinical recovery. Furthermore, retrospective adjudication of SSRF indications introduces classification bias. Finally, "ICU length of stay" is recognized as a complex, multifactorial endpoint. The causes of prolonged ICU treatment are rarely due to a single factor (like chest wall instability) and are heavily influenced by concurrent injuries (e.g., TBI), nosocomial infections, and system-level discharge barriers. Pneumonia was likewise ascertained from the clinical record using a culture- or radiology-based definition rather than by blinded adjudication, and in the presence of pulmonary contusion such a definition is expected to overcall infection; the resulting misclassification should be non-differential between eras, but it limits comparison of our absolute rates with those of studies applying stricter microbiological criteria.
- **Mortality and follow-up:** Survival status was incomplete (37 patients at 30 days, 64 at 1 year), and the study was neither designed nor powered for a mortality comparison. The numerically higher 30-day mortality in Era 3 is compatible with the more concentrated and more severely injured ICU population of that era, but it cannot be resolved with the follow-up available.
- **The effect modifier is a post-baseline variable:** Ventilation phenotype was adjudicated retrospectively rather than assigned at intubation. Blinded re-adjudication restricted to documentation from the first 24 hours gave high inter-rater agreement ($\kappa = 0.84$) and left the interaction estimates materially unchanged, which reduces but does not eliminate the potential for misclassification. Estimates resting on small operated subgroups, in particular the extrathoracic liberation estimate, were unstable to omission of single patients and should not be read as evidence of harm.

Conclusions

In this single-center cohort, the transition to a guideline-informed chest wall trauma pathway was associated with a significant reduction in critical care burden, heavily concentrated in patients ventilated specifically for chest-wall related respiratory failure. While SSRF utilization increased substantially, the observed reduction in ICU days cannot be attributed to SSRF alone. These findings support prospective evaluation of dedicated multidisciplinary chest wall injury programs and of physiological ventilation phenotypes for patient selection.

Abbreviations

AIS

Abbreviated Injury Scale

BPC18

Blunt Pulmonary Contusion 18 score

CI

Confidence interval

CT

Computed tomography

CWIS

Chest Wall Injury Society

HR

Hazard ratio

ICU

Intensive care unit

IQR

Interquartile range

ISS

Injury Severity Score

NISS

New Injury Severity Score

OR

Odds ratio

SD

Standard deviation

SSRF

Surgical stabilization of rib fractures

STROBE

Strengthening the Reporting of Observational Studies in Epidemiology

WSES

World Society of Emergency Surgery

Declarations

Supplementary Information

Online Resource 1. File name: ESM_1.xlsx. File format: Microsoft Excel spreadsheet (.xlsx). Title of data: Anonymized analysis dataset and variable codebook. Description of data: one row per ICU-managed admission episode for the 181 patients of the primary analytic cohort, containing every variable used in the analyses reported here, a codebook defining each variable and its permitted values, and a notes sheet describing the censoring conventions and the handling of missing data.

Online Resource 2. File name: ESM_2.pdf. File format: Portable Document Format (.pdf). Title of data: Phenotype codebook, supplementary tables and supplementary figure. Description of data: Table S1, a summary of the Era 3 institutional chest wall trauma protocol; Codebook S1, the operational criteria used for blinded adjudication of the ventilation phenotype; Table S2, blinded re-adjudication of the ventilation phenotype and the re-estimated interaction analyses; Table S3, formal interaction tests and sensitivity analyses; and Figure S1, liberation from mechanical ventilation within the chest-wall related stratum.

Competing interests

DS is an educational consultant for KLS Martin.

Ethics approval

This retrospective observational cohort study was approved by the Institutional Review Board of Aladar Petz University Teaching Hospital, Győr, Hungary (PAEOK IKEB:76-1-1/2026). The study was performed in accordance with the ethical standards of the 1964 Declaration of Helsinki and its later amendments. The study was conducted using a prospectively maintained institutional trauma database. The same approval covers publication of the anonymized patient-level analysis dataset provided as Online Resource 1; the dataset carries no direct or indirect identifiers, contains no dates and no free-text fields, and identifies patients only by an arbitrary study code.

Consent to participate

Because of the retrospective design and the use of routinely collected clinical data, the requirement for individual informed consent was waived by the Institutional Review Board.

Consent to publish

Not applicable. Online Resource 1 contains no identifiable individual data and no individual is identifiable from any part of this article.

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Author Contribution

DS: concept and project. DS, LZ, LSE, PZ, BS: article processing, data collection, and analysis of the data. IAH: statistical analysis and data visualization. DS, ZMB: writing. TWW, ZMB, LSE: review and editing. ZMB, TWW: editing and language correction. CS: project overview. All authors read and approved the final manuscript.

Data Availability

The anonymized dataset used for the analyses reported in this study is available in Additional file 1. The ventilation phenotype codebook and supplementary methodological materials are provided in Additional file 2. The underlying institutional source data are not publicly available due to patient confidentiality and institutional restrictions. Requests for access may be directed to the corresponding author and are subject to institutional approval and applicable data protection requirements.

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Figures

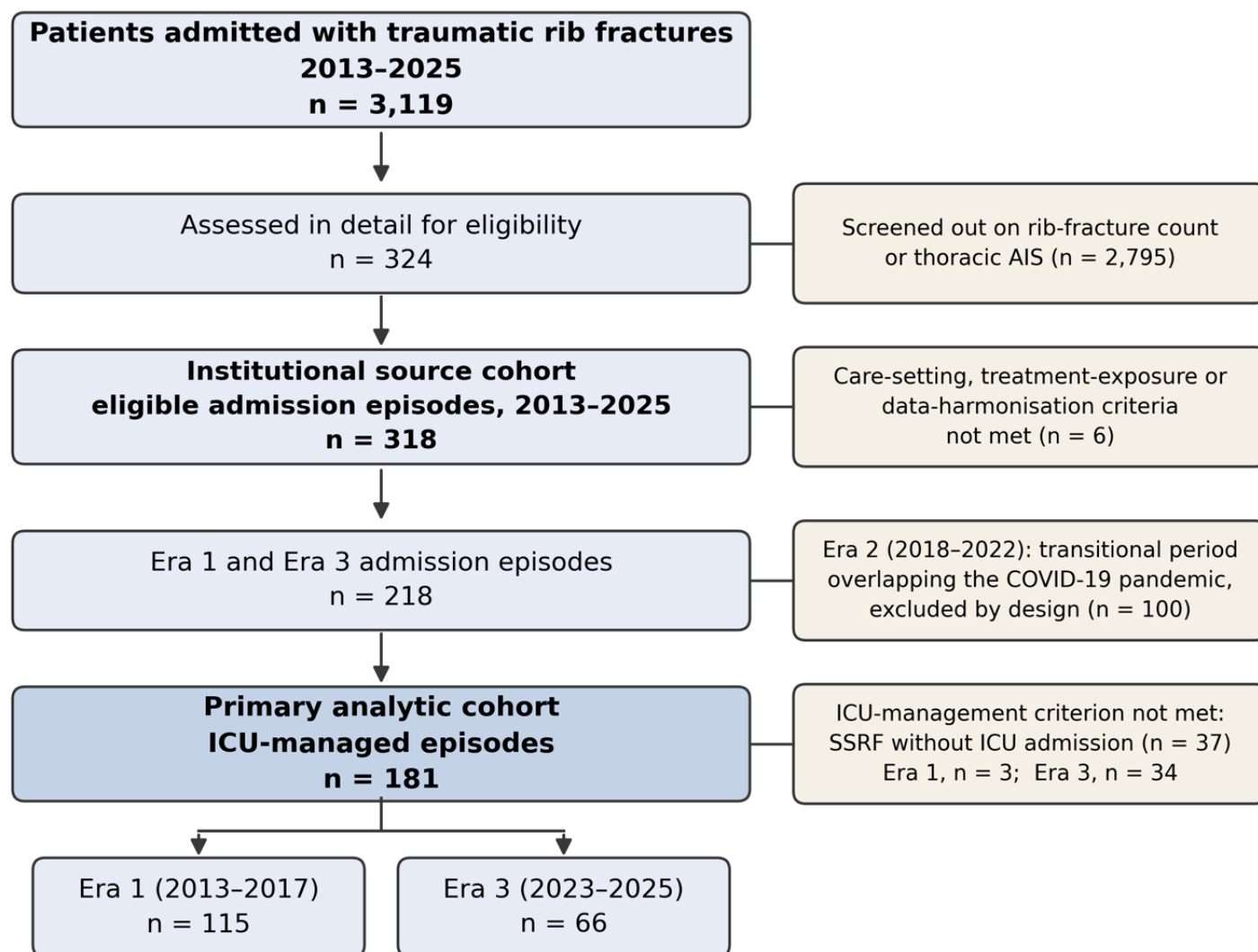
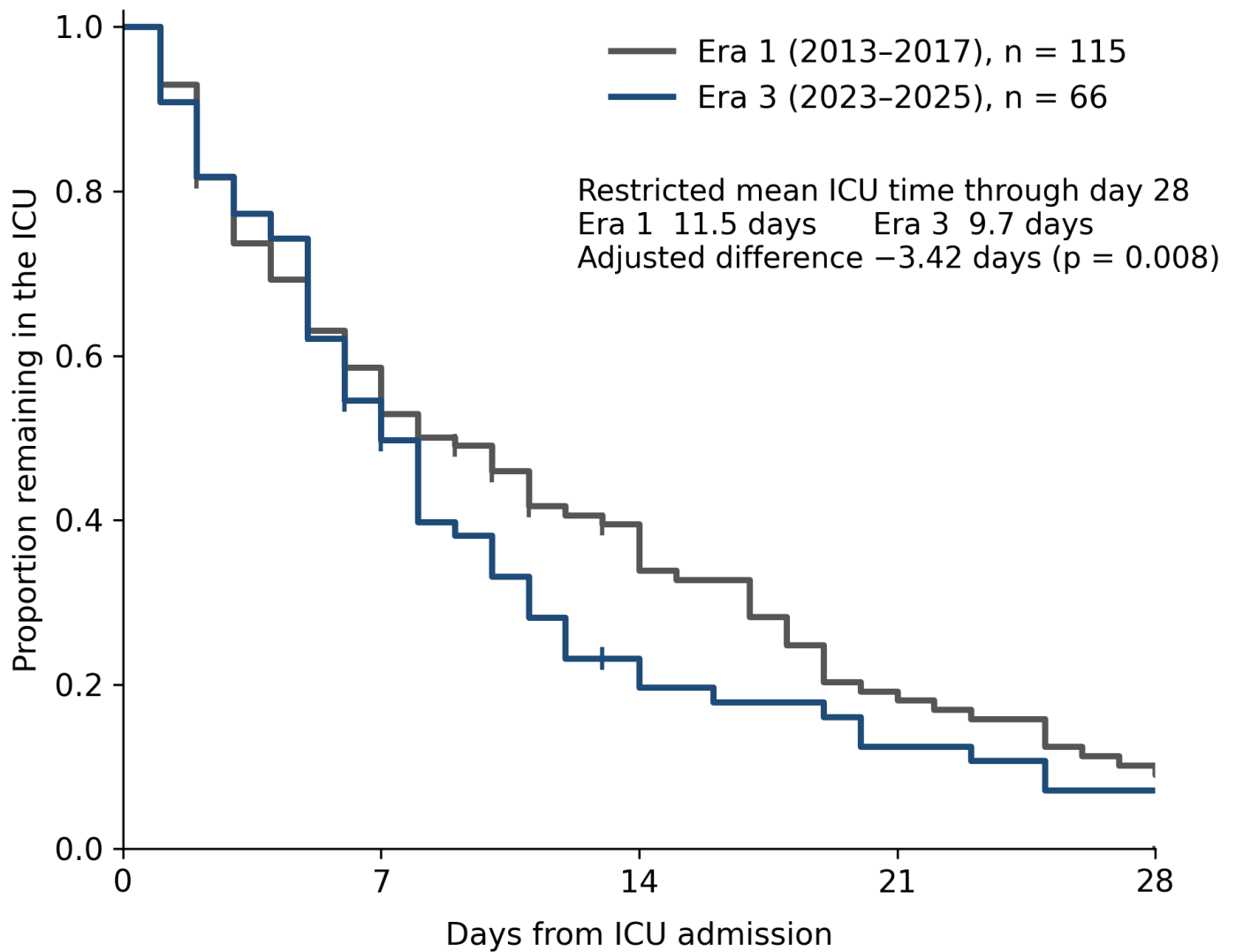


Figure 1

Patient selection and construction of the primary analytic cohort. Flow from 3,119 patients admitted with traumatic rib fractures between 2013 and 2025, through the 324 patients assessed in detail for eligibility and the institutional source cohort of 318 eligible admission episodes, to the primary analytic cohort of 181 ICU-managed episodes. Era 2 was excluded by design because it overlapped the COVID-19 pandemic and an altered ICU case-mix. The 37 patients who underwent SSRF without ICU admission did not meet the ICU-management inclusion criterion; their distribution across the two compared eras is shown for information, as they accrued no intensive care time in either era



At risk

Era 1	115	62	35	17	9
Era 3	66	34	13	7	4

Figure 2

Unadjusted Kaplan–Meier estimates of time to ICU exit by treatment era. Time from ICU admission to ICU exit, defined as ICU discharge or in-ICU death, among the 181 ICU-managed patients. Vertical ticks denote patients right-censored at the last documented ICU day because of transfer with continued intensive care elsewhere (Era 1, 14 of 115; Era 3, 4 of 66). Crude median ICU stay was 7 days in both eras and the curves are superimposed to that point, separating only in the tail. The area under each curve through day 28 corresponds to the restricted mean ICU time: 11.52 and 9.66 days. Numbers at risk are given below the horizontal axis

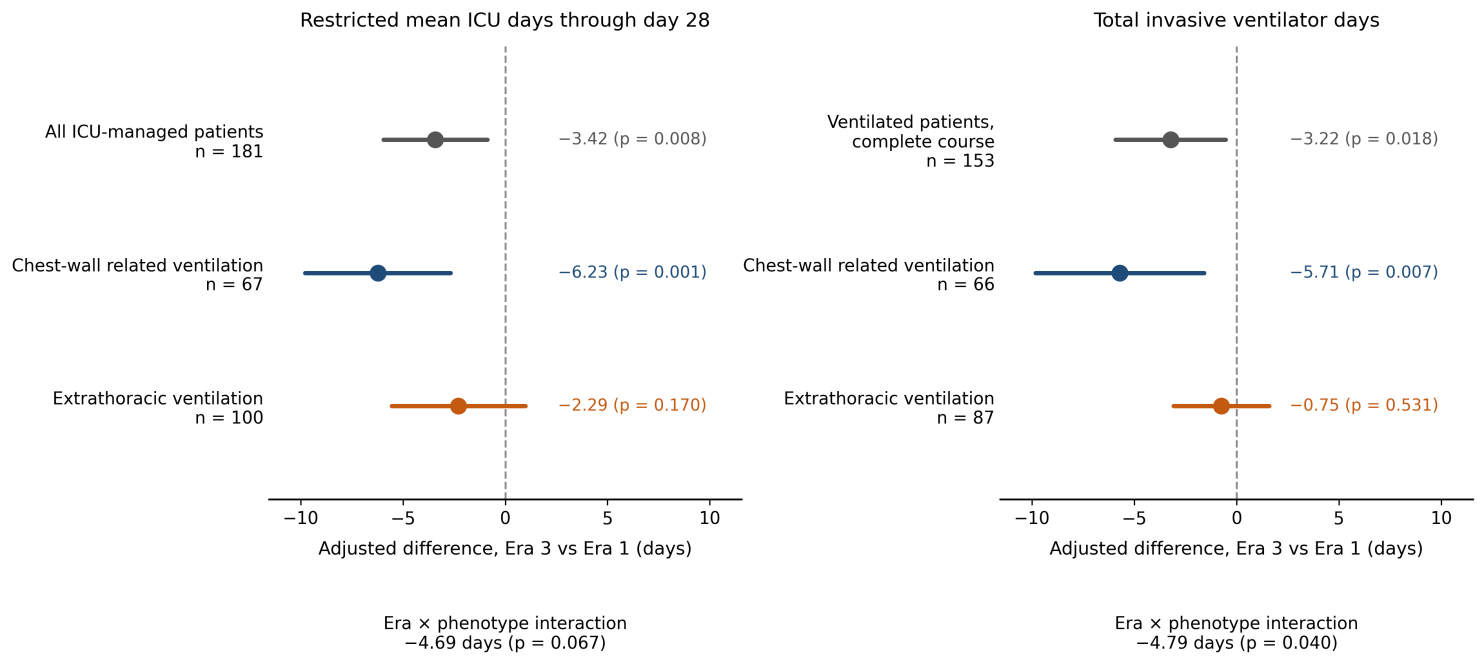


Figure 3

The era effect on critical care burden by ventilation phenotype. Adjusted differences with 95% confidence intervals for Era 3 versus Era 1, shown for restricted mean ICU time through day 28 (left) and total invasive ventilator days (right), in the relevant outcome-specific analysis population and within each ventilation phenotype. Analysis populations were: overall ICU-time estimate, n=181; phenotype-specific ICU-time estimates, n=167 invasively ventilated patients; ventilator-day analyses, n=153 invasively ventilated patients with a completely observed ventilation course. Estimates derive from models fitted separately within each stratum and are adjusted for age, sex, ISS, thoracic AIS and flail chest; they therefore do not sum arithmetically to the pooled interaction terms shown beneath each panel. The figure illustrates the central finding of the study: the overall estimate is a diluted average across a heterogeneous ICU population, with a substantial reduction in patients ventilated because of the chest wall injury and no detectable change in patients ventilated for extrathoracic reasons

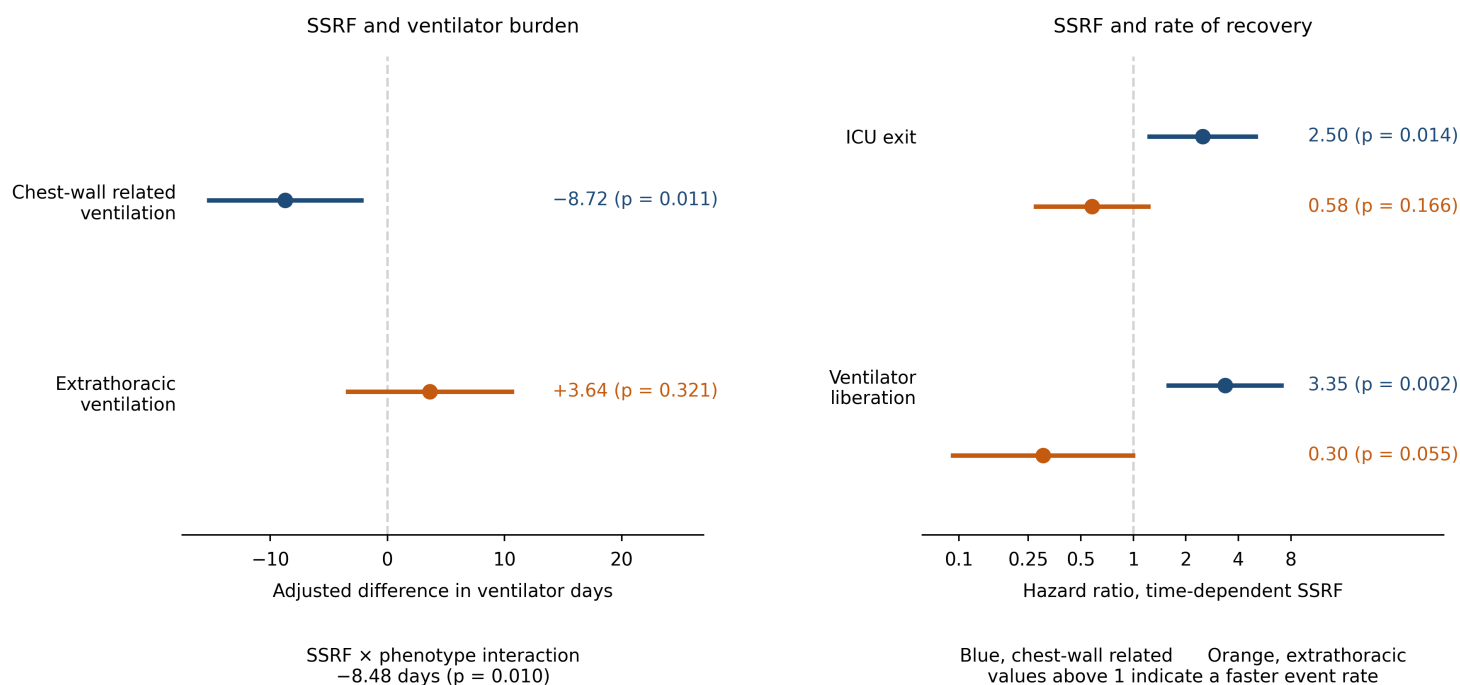


Figure 4

SSRF and critical care outcomes by indication for mechanical ventilation. Left panel: adjusted differences in total ventilator days within each phenotype, with the p value of the formal SSRF × indication interaction. Right panel: hazard ratios for ICU exit and for liberation from mechanical ventilation, with SSRF entered as a time-dependent exposure; values above 1 indicate a faster event rate. All estimates are adjusted for age, sex, ISS, thoracic AIS and flail chest. Estimates in the extrathoracic stratum rest on nine operated patients, seven of whom had a completely observed ventilation course; neither hazard ratio reached nominal significance, and the liberation estimate is not stable to the omission of any single operated patient. That stratum is defined by the reason ventilation was required rather than by the reason the chest wall was fixed, and its operated patients carried a far greater burden of head injury (head AIS ≥ 3 in 56% versus 38%) in addition to a chest wall injury that met operative indications

Supplementary Files

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