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Age-Associated Complications Following Anterior Cervical Discectomy and Fusion: A Systematic Review and Meta-Analysis

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Shaheryar Asad [1], Jean Shanaa [2], Guneet S. Bindra [2], Kevin Tang [2], Sarah Lateef [3], Ferhan Asghar [4]

1. Orthopaedic Surgery, University of Alabama at Birmingham, Birmingham, USA 2. Medicine, California Northstate University, Elk Grove, USA 3. Ophthalmology, New York Institute of Technology College of Osteopathic Medicine, Jonesboro, USA 4. Orthopaedic Surgery, University of Cincinnati Medical Center, Cincinnati, USA

Corresponding author: Shaheryar Asad, sasad@berkeley.edu

Abstract

With the aging population increasing surgical demand for degenerative cervical spine disease, this systematic review and meta-analysis evaluated postoperative outcomes of anterior cervical discectomy and fusion (ACDF) in older versus younger patients, hypothesizing that older age is associated with increased postoperative complications. PubMed, Embase, and Scopus were searched for comparative studies reporting postoperative outcomes of ACDF in older versus younger patients; the ⩾65-year threshold served as a screening criterion, and the age boundary defining the older cohort varied across included studies (from ⩾61 to ⩾80 years). In total, 10 studies (n=141,168; 49.0% male subjects, 51.0% female subjects; published 2016-2025) met the inclusion criteria. Random-effects meta-analyses (DerSimonian-Laird) pooled odds ratios (OR) for total complications, readmissions, mortality, and dysphagia; a sensitivity analysis restricted to studies sharing an identical age cutoff explored heterogeneity, and certainty of evidence was assessed using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) framework. Elderly patients demonstrated significantly higher rates of total complications (OR 1.64, 95% confidence interval (CI) 1.52-1.77), mortality (OR 5.06, 95% CI 2.97-8.65), and dysphagia (OR 2.18, 95% CI 2.02-2.36) than younger patients. No significant difference was observed for total readmissions (OR 1.35, 95% CI 0.61-2.98). Heterogeneity was moderate for total complications and mortality (I^2=44.7% and 44.2%), absent for dysphagia (I^2=0.0%), and high for readmissions (I^2=95.4%); the matched-cutoff sensitivity analysis yielded concordant estimates with no residual heterogeneity (total complications OR 1.49, mortality OR 5.55, dysphagia OR 2.10; all I^2=0.0%). Older age is a significant risk factor for poorer outcomes following ACDF. These findings highlight the importance of age-specific preoperative assessment and tailored postoperative management, though certainty of evidence was very low for all four outcomes owing to the retrospective study designs, and future research should standardize age-cutoff definitions and outcome reporting to guide targeted interventions.

Categories: Geriatrics, Orthopedics
Keywords: acdf, aging, anterior cervical discectomy, anterior cervical discectomy and fusion, dysphagia, geriatric spine surgery, meta-analysis, mortality, postoperative complications, systematic review

Introduction And Background

Populations worldwide are growing older, and with that shift comes a rising clinical burden of age-related disease. Adults aged 60 years and older now outnumber children younger than five years globally, according to the World Health Organization [1]. Degenerative change in the cervical spine is one of the more consequential problems in this older group; it frequently gives rise to cervical spinal stenosis (CSS), and anterior cervical discectomy and fusion (ACDF) is the procedure performed most often for degenerative cervical disease, especially in these patients [2].

Through an anterior approach, the procedure decompresses the cervical disc space and is followed by grafting and fusion [3], which suits it particularly well for compressive osteophytes, retro-pulsed bone fragments, and herniated discs. First described in 1955 as a less invasive alternative to posterior cervical surgery [4], ACDF has proven dependable, carries few immediate postoperative complications [5], and is usually the treatment of choice after nonoperative management has failed [6]. Most published outcomes nonetheless derive from younger cohorts, even though an estimated 70% of adults 65 years and older are affected by CSS and are correspondingly more vulnerable to the gait disturbance, spasticity, and falls that can make ACDF necessary [7,8]. The present systematic review and meta-analysis examines overall and individual postoperative outcomes of ACDF in geriatric patients, testing the hypothesis that older age carries a greater burden of total and individual postoperative complications.

Review

Materials and methods

This systematic review and meta-analysis was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement [9].

Search Strategy and Eligibility Criteria

The primary hypothesis held that older age (⩾65 years) is associated with higher rates of postoperative total complications, readmissions, mortality, and dysphagia after ACDF relative to younger patients, tested against a null hypothesis of no between-group difference. PubMed, Embase, and Scopus were searched in December 2025 using the Boolean terms ("anterior cervical discectomy and fusion" OR ACDF) AND (aging OR octogenarian OR old); the database-specific strategies and the records retrieved from each source are given in Table *1*.

Database (platform)	Date of last search	Records retrieved	Search terms
PubMed (MEDLINE)	December 2025	20	("anterior cervical discectomy and fusion" OR ACDF) AND (aging OR octogenarian OR old)
Embase (Elsevier)	December 2025	153	('anterior cervical discectomy and fusion' OR acdf) AND (aging OR octogenarian OR old)
Scopus (Elsevier)	December 2025	20	TITLE-ABS-KEY("anterior cervical discectomy and fusion" OR ACDF) AND TITLE-ABS-KEY(aging OR octogenarian OR old)

TABLE 1: Database-specific search strategies

The same Boolean search was applied across all three databases and adapted to each database's native syntax; the search was limited to English-language records. The combined yield (193 records) and the subsequent selection process are shown later.

ACDF: anterior cervical discectomy and fusion; MEDLINE: Medical Literature Analysis and Retrieval System Online.

Two reviewers (S.A. and G.B.) independently screened titles and abstracts for studies reporting postoperative outcomes of ACDF in patients aged ⩾65 years. This ⩾65-year threshold was applied at screening to identify studies reporting an older ACDF cohort. It was not imposed as a uniform analysis cutoff, because the included studies defined their older groups using varying thresholds, and the handling of those thresholds in the pooled analysis is described under statistical analysis. Eligibility was restricted to primary-data, peer-reviewed, English-language articles; case reports, case series, narrative reviews, conference abstracts, editorials, posters, and letters were excluded, as were non-comparative studies and any study that did not report complications as explicit numerical event counts. Remaining articles were confirmed by full-text review, and the reference lists of the included studies were hand-searched for additional eligible reports. The protocol was prospectively registered with the International Prospective Register of Systematic Reviews (PROSPERO; CRD42024561187), where any subsequent amendments are recorded.

Data Extraction and Quality Assessment

Extraction proceeded first at the title and abstract level and then at full text, capturing sex, the age groups compared, body mass index (BMI), infection rate, readmission rate, length of stay, revision rate, operative time, preoperative risk factors, and postoperative complications. Methodological quality was appraised with the Methodological Index for Non-randomized Studies (MINORS) [10], a validated instrument developed specifically for non-randomized surgical studies and well suited to the comparative cohort designs included here; its more limited handling of confounding by indication relative to tools such as the Risk Of Bias In Non-randomized Studies of Interventions (ROBINS-I) [11] is addressed in the limitations. Each item was scored 0 (not reported), 1 (reported but inadequate), or 2 (reported and adequate) for a maximum of 24 points in comparative studies. Total scores below 16 were taken to indicate high risk of bias, 16-20 moderate risk, and 21-24 low risk.

Statistical Analysis

Where reported, descriptive statistics (mean, percentage, standard deviation (SD), range, median, 95% confidence intervals (CIs), and correlation coefficients) were summarized. Postoperative outcomes were compared between older and younger cohorts using random-effects meta-analysis; for studies reporting more than two age strata, the oldest stratum was treated as "elderly" and the remaining strata combined as "younger." Because the ⩾65-year eligibility threshold was a screening criterion rather than a common analysis cutoff, the age boundary separating the older and younger cohorts varied across the included

studies, from ≥61 to ≥80 years; the resulting composition of the pooled elderly group and the effect of this variation are examined in the Results and in the sensitivity analysis described below. An outcome was pooled only when reported by at least four studies. Odds ratios were pooled on the natural-log scale using the DerSimonian-Laird random-effects estimator, with a 0.5 continuity correction applied to any study containing a zero cell and double-zero studies (no events in either arm) excluded from that outcome; between-study heterogeneity was quantified with the I^2 statistic and the variance estimate (τ^2), and a 95% prediction interval was derived for each pooled effect.

A pooled estimate was considered statistically significant when its 95% CI did not include 1. Small-study effects were assessed with funnel plots and the Egger regression test for any outcome informed by at least 10 studies. For the sensitivity analysis, each outcome was re-pooled within the subset of studies that applied an identical <70 versus ≥70-year cutoff, to gauge how much of the heterogeneity in the primary analyses was attributable to between-study variation in the age threshold. Certainty of evidence for each pooled outcome was then rated with the Grading of Recommendations Assessment, Development and Evaluation (GRADE) framework [12], weighing risk of bias, inconsistency, indirectness, imprecision, and magnitude of effect. Analyses were conducted in Python 3.9.6 (Python Software Foundation, Fredericksburg, VA, US) (NumPy version 1.26.4, NumPy Developers and SciPy version 1.13.1, Scipy Developers, both hosted by NumFOCUS, Austin, TX, USA). The completed PRISMA 2020 checklist is provided in the Appendix.

Results

The search identified 193 articles; after removing duplicates, 156 unique articles remained, of which 10 met inclusion criteria (Figure *1*).

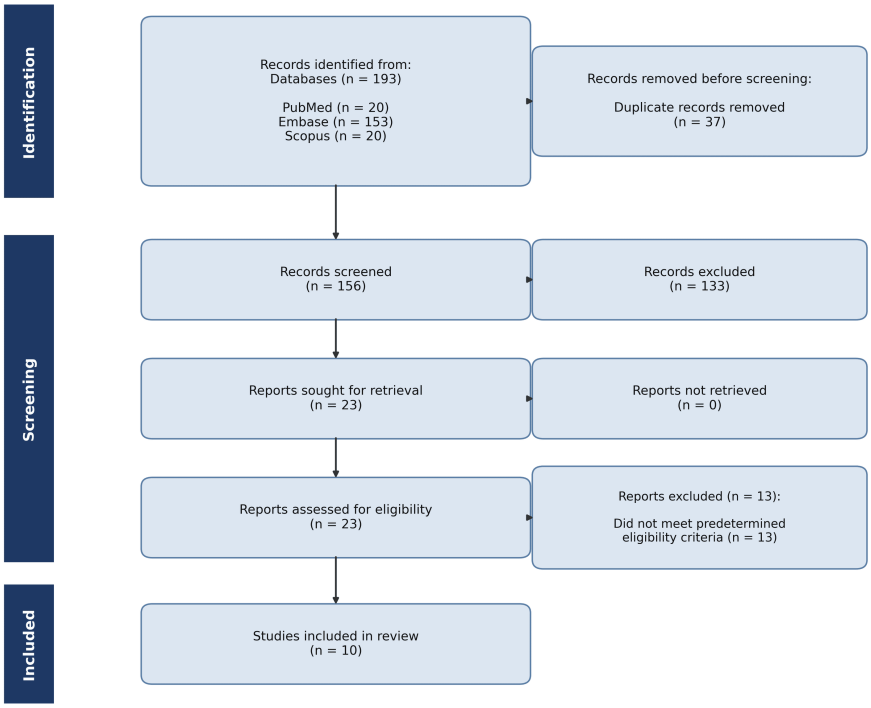


FIGURE 1: PRISMA 2020 flow diagram of the literature search and selection of studies on age-associated outcomes following anterior cervical discectomy and fusion (ACDF)

The flow diagram follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidance and summarizes the identification, screening, and inclusion of studies [13-22].

All 10 studies were retrospective (level of evidence III) and were published between 2016 and 2025 (Table *2*).

Study title	Authors	Year	Journal	Study design	Risk of bias
Age as a predictor of patient-reported outcomes in anterior cervical discectomy and fusion: analysis of the Michigan Spine Surgery Improvement Collaborative	Beladi et al. [20]	2025	Journal of Neurosurgery: Spine	Retrospective cohort study	Moderate
Elderly age as a risk factor for 30-day postoperative outcomes following elective anterior cervical discectomy and fusion	Di Capua et al. [21]	2017	Global Spine Journal	Retrospective cohort study	Moderate
Impact of old age on patient-reported outcomes and cost utility for anterior cervical discectomy and fusion surgery for degenerative spine disease	Chotai et al. [22]	2017	European Spine Journal	Retrospective cohort study	Moderate
Octogenarians are independently associated with extended length of stay and non-routine discharge after elective ACDF for cervical spondylotic myelopathy	Elsamadicy et al. [16]	2022	Global Spine Journal	Retrospective cohort study	Moderate
Age as a risk factor for complications following anterior cervical discectomy and fusion: analysis from the Michigan Spine Surgery Improvement Collaborative	Lawless et al. [14]	2022	Spine (Phila Pa 1976)	Retrospective cohort study	Low
Radiological and clinical outcomes of anterior cervical discectomy and fusion in older patients: a comparative analysis of young-old patients (ages 65–74 years) and middle-old patients (over 75 years)	Lee et al. [15]	2020	Neurospine	Retrospective cohort study	Moderate
The surgical outcome of multilevel anterior cervical discectomy and fusion in myelopathic elderly and younger patients	Luo et al. [18]	2022	Scientific Reports	Retrospective cohort study	Moderate
Complications and mortality following one to two-level anterior cervical fusion for cervical spondylosis in patients above 80 years of age	Puvanesarajah et al. [19]	2017	Spine (Phila Pa 1976)	Retrospective cohort study	Moderate
An 11-year-long analysis of the risks associated with age in patients undergoing anterior cervical discectomy and fusion in a large, urban academic hospital	Tang et al. [17]	2025	Global Spine Journal	Retrospective cohort study	Moderate
Surgical outcomes of cervical spondylotic myelopathy: an analysis of a national, administrative, longitudinal database	Veeravagu et al. [13]	2016	Neurosurgical Focus	Retrospective cohort study	Moderate

TABLE 2: Characteristics of the included studies

The 10 studies included in the systematic review, listed in alphabetical order by first author; all were retrospective comparative cohort studies (level of evidence III). Risk of bias was assessed using the Methodological Index for Non-randomized Studies (MINORS). Refer to the next table for individual scores and the Materials and methods section for the classification thresholds. ACDF: anterior cervical discectomy and fusion.

Across studies, 141,168 patients were identified; eight studies reported sex distribution, totaling 64,454 male subjects (49.0%) and 66,990 female subjects (51.0%). All studies compared distinct age groups; six reported total fused segments, five reported follow-up duration, seven reported length of stay, eight described preoperative risk factors or comorbidities, and nine reported postoperative complications (Table *3*).

Study	Age group	Patients, n	Female, n	Female, %	BMI, mean (kg/m²)	BMI, SD	Length of follow-up	MINORS score
Beladi et al. [20]	≥70 years	845	428	50.7	29.7	5.9	NR	20
Beladi et al. [20]	<70 years	6887	3585	52.1	30.7	7.0	NR	20
Di Capua et al. [21]	≥61 years	5258	2559	48.7	NR	NR	30 days	20
Di Capua et al. [21]	53–60 years	5058	2512	49.7	NR	NR	30 days	20
Di Capua et al. [21]	46–52 years	5049	2757	54.6	NR	NR	30 days	20
Di Capua et al. [21]	≤45 years	5198	2777	53.4	NR	NR	30 days	20
Chotai et al. [22]	≥65 years	33	28	85	30.2	5.9	≥2 years	20
Chotai et al. [22]	<65 years	218	99	45	31.3	6.9	≥2 years	20
Elsamadicy et al. [16]	50–64 years	7910	4010	50.7	NR	NR	NR	18
Elsamadicy et al. [16]	65–79 years	6480	3007	46.4	NR	NR	NR	18
Elsamadicy et al. [16]	≥80 years	475	200	42.1	NR	NR	NR	18
Lawless et al. [14]	≥70 years	1014	NR	NR	NR	NR	NR	21
Lawless et al. [14]	<70 years	8121	NR	NR	NR	NR	NR	21
Lee et al. [15]	65–74 years	30	6	20	24.07	2.47	21.75 months	16
Lee et al. [15]	≥75 years	18	6	33.3	24.90	2.60	17.37 months	16
Luo et al. [18]	≥70 years	18	4	22.2	25.1	7.27	43.8 months	18
Luo et al. [18]	<70 years	45	14	31.1	26.6	5.96	55.5 months	18
Puvanesarajah et al. [19]	≥80 years	5515	2700	49.0	NR	NR	90 days	19
Puvanesarajah et al. [19]	65–79 years	51808	26585	51.3	NR	NR	90 days	19
Tang et al. [17]	60–69 years	409	NR	NR	NR	NR	NR	19
Tang et al. [17]	70–79 years	154	NR	NR	NR	NR	NR	19
Tang et al. [17]	≥80 years	25	NR	NR	NR	NR	NR	19
Veeravagu et al. [13]	≥65 years	3656	NR	NR	NR	NR	30 days	18
Veeravagu et al. [13]	<65 years	26944	NR	NR	NR	NR	30 days	18

TABLE 3: Methodological assessment, study characteristics, and demographic data

Data are presented as reported in each study, with one row per study age group. Length of follow-up is reported as stated in each study (mean duration in months, the minimum duration, or the postoperative outcome-assessment window in days). Di Capua reported obesity prevalence rather than mean body mass index (BMI), and Veeravagu reported sex for the total cohort only (15,713 female subjects (51.35%)); these values are therefore shown as NR.

BMI: body mass index; MINORS: Methodological Index for Non-randomized Studies; NR: not reported; SD: standard deviation.

The mean ± standard deviation (SD) MINORS score across the 10 studies was 18.9 ± 1.4 (observed range: 16-21). One study was classified as low risk of bias and nine as moderate risk; none were classified as high risk. Risk of bias across the 10 studies is summarized: the most frequent limitations were the absence of a

prospective study design and of blinded or independent endpoint assessment, consistent with the retrospective nature of all included studies.

Individual study comparisons are summarized in Tables 3 and 4.

Study	Age group	Readmission, n	Readmission, %	Mortality, n	Mortality, %	Dysphagia, n	Dysphagia, %	Total complications, n	Total complications, %
Beladi et al. [20]	≥70 years	NR	NR	NR	NR	NR	NR	210	26.0
Beladi et al. [20]	<70 years	NR	NR	NR	NR	NR	NR	1236	19.0
Di Capua et al. [21]	≥61 years	51	1.0	18	0.3	NR	NR	672	NR
Di Capua et al. [21]	53–60 years	158	3.1	3	0.1	NR	NR	520	NR
Di Capua et al. [21]	46–52 years	99	2.1	2	0.0	NR	NR	381	NR
Di Capua et al. [21]	≤45 years	81	1.7	0	0.0	NR	NR	296	NR
Chotai et al. [22]	≥65 years	3	9.1	NR	NR	NR	NR	0	NR
Chotai et al. [22]	<65 years	4	1.8	NR	NR	NR	NR	11	5
Elsamadicy et al. [16]	50–64 years	NR	NR	NR	NR	570	7.2	807	10.2
Elsamadicy et al. [16]	65–79 years	NR	NR	NR	NR	616	9.5	816	12.6
Elsamadicy et al. [16]	≥80 years	NR	NR	NR	NR	85	17.9	90	18.9
Lawless et al. [14]	≥70 years	92	9.1	9	0.9	117	11.5	319	31.5
Lawless et al. [14]	<70 years	375	4.6	14	0.2	473	5.8	1947	24.0
Lee et al. [15]	65–74 years	NR	NR	0	NR	0	NR	1	NR
Lee et al. [15]	≥75 years	NR	NR	0	NR	0	NR	3	NR
Luo et al. [18]	≥70 years	NR	NR	2	NR	1	NR	11	NR
Luo et al. [18]	<70 years	NR	NR	0	NR	2	NR	16	NR
Puvanesarajah et al. [19]	≥80 years	NR	NR	162	NR	645	11.7	813	14.7
Puvanesarajah et al. [19]	65–79 years	NR	NR	425	NR	2989	5.8	4979	9.6
Tang et al. [17]	60–69 years	3	NR	NR	NR	0	NR	0	NR
Tang et al. [17]	70–79 years	6	NR	NR	NR	2	NR	2	NR
Tang et al. [17]	≥80 years	2	NR	NR	NR	0	NR	2	NR
Veeravagu et al. [13]	≥65 years	94	NR	NR	NR	NR	NR	814	NR
Veeravagu et al. [13]	<65 years	1025	NR	NR	NR	NR	NR	3951	NR

TABLE 4: Summary of postoperative complications, readmissions, and mortality by study

Data are presented as reported in each study, with one row per study age group. For studies reporting complication subtypes, the overall (“any”) complication count is shown; for Puvanesarajah et al., which did not report a single composite, the 90-day major-medical-complication count (the only composite reported) is used. Beladi et al. additionally reported major (≥70: 99 (12.3%); <70: 429 (6.6%)) and minor (≥70: 146 (18.1%); <70: 954 (14.7%)) complications, and Lawless et al. additionally reported major complications (≥70: 143 (14.1%); <70: 567 (7.0%)). For dysphagia, the total count is shown where reported; Veeravagu et al. did not report dysphagia stratified by age, and Lawless additionally reported nothing-by-mouth (NPO; ≥70: 41 (4.0%); <70: 101 (1.2%)) and feeding-tube–dependent (≥70: 20 (2.0%); <70: 42 (0.5%)) dysphagia. NR: not reported.

Briefly, Veeravagu et al. [13] (⩾65 vs. <65 years) reported higher overall complications (22.26% vs. 14.66%) but lower 30-day readmissions (2.57% vs. 3.80%) in the elderly cohort. Lawless et al. [14] (⩾70 vs. <70 years) found significantly higher rates of 90-day readmission, any and major complications, dysphagia, myocardial infarction, mortality, stroke, and urinary complications in older patients (all $p<0.001$), with independent preoperative ambulation associated with lower odds of complications on multivariable analysis. Lee et al. [15] (65-74 vs. ⩾75 years) found no significant between-group differences in radiographic outcomes, patient-reported outcomes, length of stay, or complications. Elsamadicy et al. [16] (50-64, 65-79, ⩾80 years) reported progressively worse length of stay, non-routine discharge, overall complications, and dysphagia with

advancing age (all p<0.05), with age ⩾80 independently associated with non-routine discharge (OR 2.46, 95% CI 1.44-4.21) and extended length of stay (OR 1.97, 95% CI 1.10-3.55). Tang et al. [17] (60s, 70s, ⩾80 years) reported readmission, complication, and dysphagia rates that varied non-monotonically across age strata, with the oldest cohort having the only recorded intensive care unit (ICU) stays. Luo et al. [18] (<70 vs. ⩾70 years) found a higher Charlson Comorbidity Index and American Society of Anesthesiologists (ASA) class ⩾3 proportion in the elderly cohort, together with a higher short-term complication rate (61.1% vs. 35.6%) and a higher reoperation rate (p=0.02). Puvanesarajah et al. [19] reported higher rates in the ⩾80-year cohort than the 65-79-year cohort for at least one major medical complication (14.74% vs. 9.61%), dysphagia (11.70% vs. 5.77%), and 90-day (1.63% vs. 0.38%) and one-year (2.94% vs. 0.82%) mortality (all p<0.0001). Beladi et al. [20] (<70 vs. >70 years) found higher rates of any, major, and minor complications and longer hospital stay in older patients (all p⩽0.011).

Because the oldest reported stratum in each study was designated the elderly cohort, the lower age boundary of that cohort varied widely across studies. For example, ⩾61 years in Di Capua et al. [21] and ⩾65 years in Veeravagu et al. [13] and Chotai et al. [22], versus ⩾80 years in Elsamadicy et al. [16], Puvanesarajah et al. [19], and Tang et al. [17], so the pooled elderly group does not correspond to a single age threshold. This mismatch between the ⩾65-year eligibility criterion and the study-specific analysis cutoffs is the rationale for the matched-cutoff sensitivity analysis reported below.

Pooled data from all 10 studies [13-22] demonstrated a significantly increased risk of total complications in the elderly cohort (OR 1.64, 95% CI 1.52-1.77; I^2=44.7%), with a 95% prediction interval of 1.36-1.97 (Figure *2*).

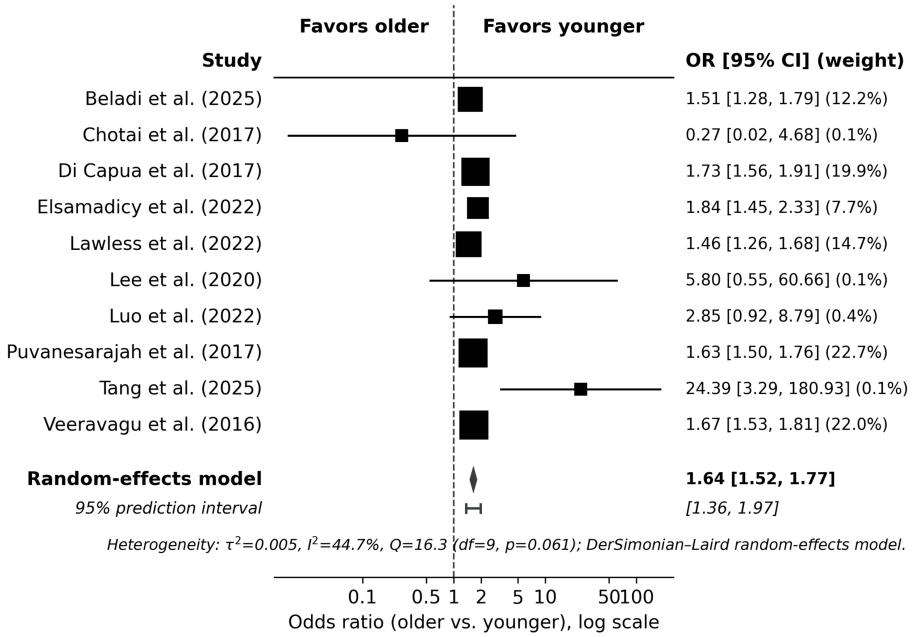


FIGURE 2: Forest plot of total complications in older versus younger patients undergoing ACDF

Forest plot of the pooled odds ratio (older vs. younger cohort) for total complications across all 10 included studies [13-22]. Each row shows the individual study odds ratio with its 95% confidence interval; the diamond is the DerSimonian–Laird random-effects pooled estimate, and the bar below it is the 95% prediction interval. An odds ratio greater than 1 indicates higher odds of complications in older patients. ACDF: Anterior Cervical Discectomy and Fusion; CI: confidence interval; OR: odds ratio.

Pooled data from Di Capua et al. [21], Chotai et al. [22], Lawless et al. [14], Tang et al. [17], and Veeravagu et al. [13] showed no significant difference in total readmissions between age groups (OR 1.35, 95% CI 0.61-2.98; I^2=95.4%) (Figure *3*).

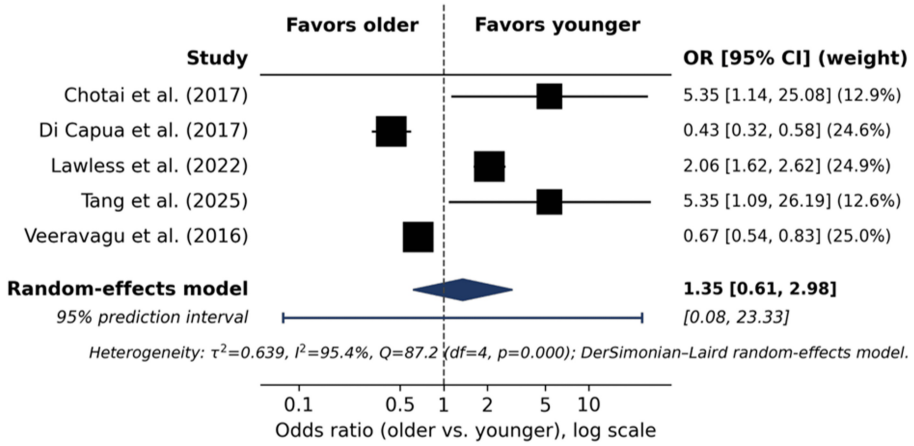


FIGURE 3: Forest plot of hospital readmissions in older versus younger patients undergoing Anterior Cervical Discectomy and Fusion (ACDF)

Forest plot of the pooled odds ratio (older vs. younger cohort) for total hospital readmissions across the five contributing studies [13,14,17,21,22]. Each row shows the individual study odds ratio with its 95% confidence interval; the diamond is the DerSimonian–Laird random-effects pooled estimate, and the bar below it is the 95% prediction interval. An odds ratio greater than 1 indicates higher odds of readmission in older patients. CI: confidence interval; OR: odds ratio.

Pooled data from Di Capua et al. [21], Lawless et al. [14], Lee et al. [15], Luo et al. [18], and Puvanesarajah et al. [19] demonstrated a significantly increased risk of mortality in the elderly cohort (OR 5.06, 95% CI 2.97-8.65; I^2=44.2%) (Figure *4*).

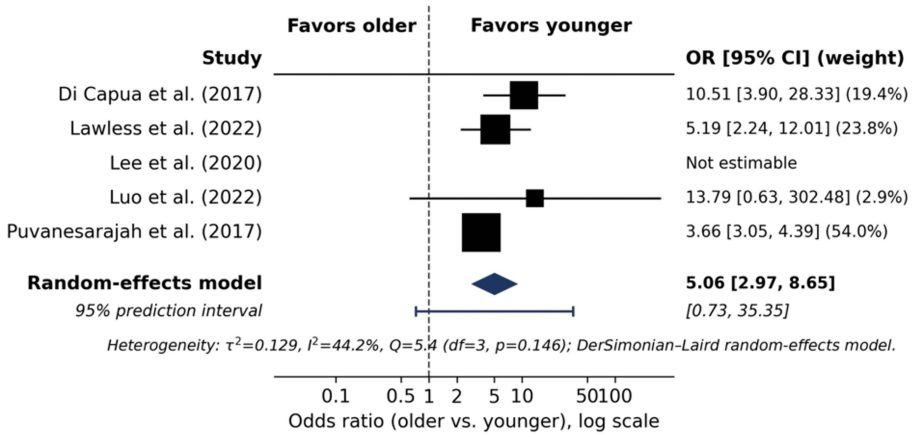


FIGURE 4: Forest plot of mortality in older versus younger patients undergoing ACDF

Forest plot of the pooled odds ratio (older vs. younger cohort) for mortality across the five mortality-reporting studies [14,15,18,19,21]; one study (Lee et al.) recorded no deaths in either group and was therefore not estimable. Each row shows the individual study odds ratio with its 95% confidence interval; the diamond is the DerSimonian–Laird random-effects pooled estimate, and the bar below it is the 95% prediction interval. An odds ratio greater than 1 indicates higher odds of death in older patients. ACDF: Anterior Cervical Discectomy and Fusion; CI: confidence interval; OR: odds ratio.

Pooled data from Elsamadicy et al. [16], Lawless et al. [14], Lee et al. [15], Luo et al. [18], Tang et al. [17], and Puvanesarajah et al. [19] demonstrated a significantly increased risk of dysphagia in the elderly cohort (OR 2.18, 95% CI 2.02-2.36; I^2=0.0%) (Figure *5*).

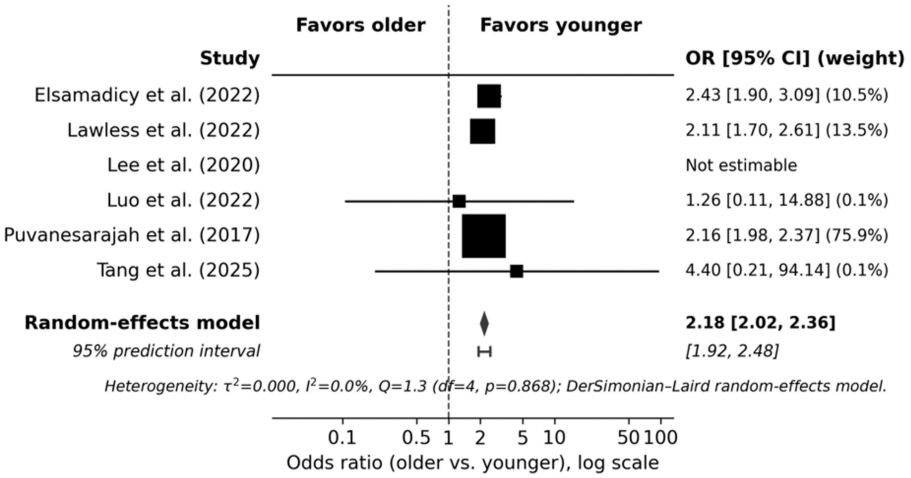


FIGURE 5: Forest plot of dysphagia in older versus younger patients undergoing ACDF

Forest plot of the pooled odds ratio (older vs. younger cohort) for dysphagia across the six dysphagia-reporting studies [14-19]; one study (Lee et al.) recorded no dysphagia events in either group and was therefore not estimable. Each row shows the individual study odds ratio with its 95% confidence interval; the diamond is the DerSimonian–Laird random-effects pooled estimate, and the bar below it is the 95% prediction interval. An odds ratio greater than 1 indicates higher odds of dysphagia in older patients. ACDF: Anterior Cervical Discectomy and Fusion; CI: confidence interval; OR: odds ratio.

Small-study effects were examined with funnel plots and the Egger regression test (Figure 6).

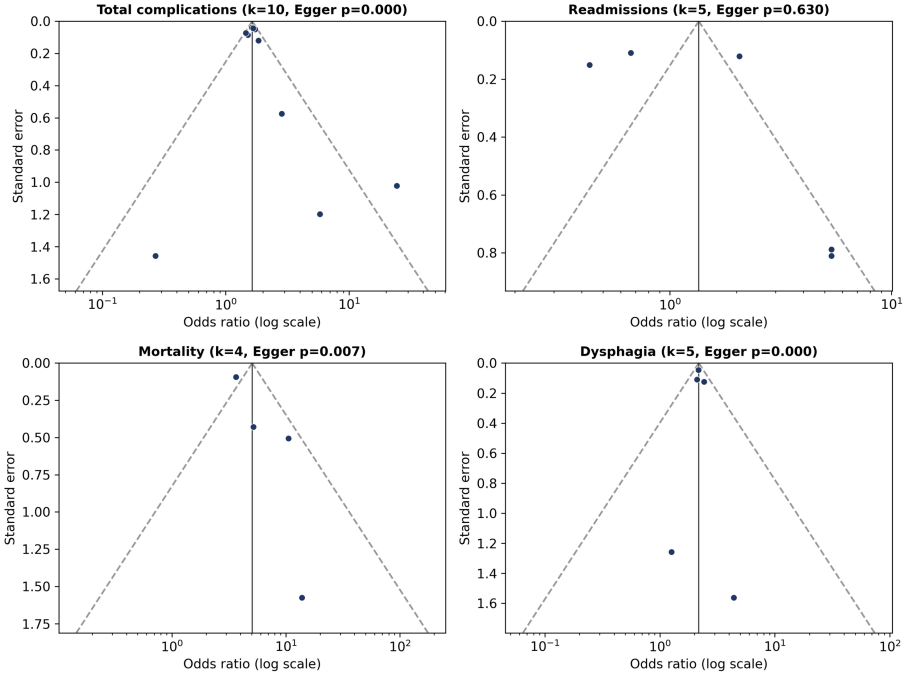


FIGURE 6: Funnel plots for the four pooled outcomes

Funnel plots for the four pooled outcomes, with pseudo-95% confidence limits and the pooled estimate (vertical line). Egger regression test p-values are shown; the test is adequately powered only for total complications (10 studies). OR: odds ratio.

A formal test is adequately powered only for total complications, the only outcome informed by at least 10 studies; for this outcome the funnel plot was asymmetric (Egger p<0.001), an asymmetry attributable chiefly to the small studies with imprecise, extreme estimates [15,17,18,22] rather than to the large cohorts, which

clustered tightly around the pooled effect. For readmissions, mortality, and dysphagia (four to six studies each), the funnel plots are provided for completeness but are underpowered, and their Egger tests - particularly for dysphagia, where a single large study carries most of the weight - should not be interpreted as evidence for or against publication bias.

Risk of bias across the 10 studies is summarized in Figure 7.

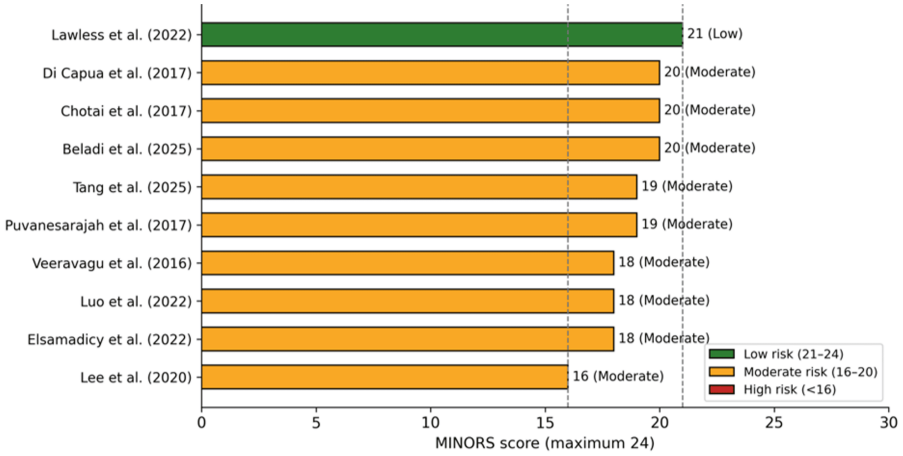


FIGURE 7: Risk-of-bias assessment of the included studies (MINORS)

Risk-of-bias assessment of the 10 included studies using the Methodological Index for Non-randomized Studies (MINORS; maximum 24 points). Dashed lines mark the thresholds for low (21–24), moderate (16–20), and high (<16) risk of bias.

The most frequent limitations were the absence of a prospective study design and of blinded or independent endpoint assessment, consistent with the retrospective nature of all included studies.

To probe the heterogeneity remaining in the primary analyses and the effect of inconsistent age-cutoff definitions, each outcome was re-pooled among the subset of studies defining the elderly cohort using an identical <70/⩾70-year cutoff (Beladi et al. [20], Lawless et al. [14], and Luo et al. [18]). Restricting total complications to these three studies yielded a pooled OR of 1.49 (95% CI 1.34-1.66) with no residual heterogeneity (I^2=0.0%, versus 44.7% in the full 10-study analysis). Restricting mortality to the two contributing matched-cutoff studies (Lawless et al. [14], Luo et al. [18]) gave OR 5.55 (95% CI 2.47-12.48; I^2=0.0%), and restricting dysphagia to the same two studies gave OR 2.10 (95% CI 1.70-2.60; I^2=0.0%). A comparable analysis could not be performed for readmissions, as only Lawless et al. [14] among the matched-cutoff studies reported this outcome. Across all three estimable outcomes the matched-cutoff estimates were concordant in direction and magnitude with the primary analyses and showed no heterogeneity (Table 5), indicating that the primary pooled effects for total complications, mortality, and dysphagia are robust to variation in age-cutoff definition.

Outcome	Contributing studies, k	Pooled OR	95% CI	I^2, matched (%)	I^2, full analysis (%)
Total complications	3	1.49	1.34–1.66	0.0	44.7
Mortality	2	5.55	2.47–12.48	0.0	44.2
Dysphagia	2	2.10	1.70–2.60	0.0	0.0
Total readmissions	1	NA	NA	NA	95.4

TABLE 5: Sensitivity analysis restricted to studies sharing an identical <70/≥70-year age cutoff

The matched-cutoff subset comprised studies defining the elderly cohort using an identical <70/≥70-year cutoff: total complications (Beladi et al. [20], Lawless et al. [14], Luo et al. [18]); mortality and dysphagia (Lawless et al. [14], Luo et al. [18]); and readmissions (Lawless et al. [14] only, for which a pooled estimate was not estimable). CI: confidence interval; I^2: heterogeneity statistic; k: number of contributing studies; NA: not applicable; OR: odds ratio.

The persistent heterogeneity in the readmission analysis (I^2=95.4%) therefore appears to reflect genuine

between-study inconsistency rather than age-cutoff differences alone.

Certainty of evidence for each pooled outcome was assessed with the GRADE framework. As all included studies were retrospective, non-randomized cohorts, each outcome began at low certainty and was downgraded one level for serious risk of bias, reflecting the retrospective designs, the predominantly moderate MINORS scores, and the potential for confounding by indication; no outcome was rated up for magnitude of effect, since rating up is not appropriate when the evidence already carries a serious risk-of-bias limitation. This yielded very low certainty for all four outcomes (Table 6).

Outcome	Studies, n	Participants, n	Risk of bias	Inconsistency	Imprecision	Overall certainty
Total complications	10	141,168	Serious	Not serious	Not serious	Very low
Total readmissions	5	61,137	Serious	Very serious	Very serious	Very low
Mortality	5	87,132	Serious	Not serious	Not serious	Very low
Total dysphagia	6	82,022	Serious	Not serious	Not serious	Very low

TABLE 6: GRADE certainty of evidence for the four primary pooled outcomes

Certainty of evidence was assessed using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) framework. Contributing studies: total complications [13-22]; total readmissions [13,14,17,21,22]; mortality [14,15,18,19,21]; and total dysphagia [14-19]. All outcomes began at low certainty given the retrospective observational design and were downgraded one level for serious risk of bias; no outcome was rated up for magnitude of effect. I^2: heterogeneity statistic; OR: odds ratio.

The downgrade profiles nonetheless differed: total complications (I^2=44.7%) and, in particular, dysphagia (I^2=0.0%) no longer warranted downgrading for inconsistency or imprecision, as their pooled estimates were consistent and precise; mortality (I^2=44.2%) was likewise not downgraded on these domains; and total readmissions was additionally limited by very serious inconsistency (I^2=95.4%) and imprecision (a wide interval crossing the null). The mortality and dysphagia associations are thus the most consistent of the four, although all ratings remain very low and should be interpreted with the retrospective design in mind.

Discussion

ACDF is commonly performed for cervical spine disorders such as cervical spondylosis [2], a condition to which older adults are particularly prone owing to age-related processes including osteoarthritis and disc degeneration [23], and by which they may be disproportionately disabled [24]. As the older population expands, the volume of ACDF performed in this group is projected to rise [25], which makes the contribution of age to outcomes increasingly important to understand. Synthesizing the 10 included studies, this review aims to clarify how age-related factors relate to postoperative outcomes after ACDF and to inform surgical decision-making in elderly patients.

Older patients demonstrated a significantly higher likelihood of total complications, mortality, and dysphagia following ACDF, whereas readmissions did not differ significantly between age groups. Heterogeneity was moderate for total complications and mortality (I^2=44.7% and 44.2%) and absent for dysphagia (I^2=0.0%), indicating broadly consistent effects across studies for these outcomes; the matched-cutoff sensitivity analysis, restricted to studies sharing an identical <70/⩾70-year cutoff, reproduced each of these estimates with no residual heterogeneity (Table 5), confirming that they are robust to variation in how the elderly cohort was defined. The pooled total-complication estimate (OR 1.64, 95% CI 1.52-1.77) is precise, and its 95% prediction interval (1.36-1.97) lies entirely above 1, implying that a higher complication burden in older patients would be expected in essentially any similar future cohort. The significant, homogeneous dysphagia estimate (OR 2.18, 95% CI 2.02-2.36) is consistent with the recognized predisposition of older patients to postoperative swallowing dysfunction after anterior cervical surgery. In contrast, readmissions remained markedly heterogeneous (I^2=95.4%) and non-significant (OR 1.35, 95% CI 0.61-2.98): study-level odds ratios spanned roughly 0.43 to 5.35, with the large administrative-database cohorts (Di Capua et al. [21], Veeravagu et al. [13]) reporting lower readmission odds in older patients and smaller cohorts (Chotai et al. [22], Tang et al. [17]) reporting higher odds, so the wide pooled interval is compatible with both a clinically meaningful increase and a decrease in readmission with older age. This inconsistency most plausibly reflects differences in data source, readmission definition, and follow-up window (ranging from 30 days to more than two years) across studies rather than age-cutoff variation, and indicates that the readmission question remains unresolved.

The pattern of relatively worse outcomes in older patients observed here is consistent with prior literature, which has generally found ACDF to produce favorable functional outcomes across age groups [26] while also linking age-related comorbidities to poorer overall and major complication rates [14], including dysphagia,

thromboembolism, stroke, gait disturbance, and infection [13,15].

Limitations

This review has several limitations. The evidence base comprised only 10 retrospective studies, which limited analysis of outcomes such as length of stay, infection rate, and intraoperative blood loss, for which aggregate data were insufficient. The included studies differed in outcome definitions and in follow-up windows (ranging from 30 days to more than two years), and in the age threshold used to define the elderly cohort; although the matched-cutoff sensitivity analysis indicated that the total-complication, mortality, and dysphagia estimates were robust to age-cutoff variation, the readmission analysis remained markedly heterogeneous and inconclusive. Methodological quality was appraised with MINORS, which, although validated for non-randomized surgical studies, does not quantify confounding by indication - the preferential selection of particular patients for surgery - as thoroughly as instruments such as ROBINS-I, so residual confounding of this kind may be incompletely reflected in the risk-of-bias assessment. Finally, the pooled analyses combine unadjusted, crude event counts across studies, whereas several included studies reported their own multivariable-adjusted associations between age and outcomes (e.g., Lawless et al. [10]) that account for confounders such as comorbidity burden and preoperative functional status not captured by the pooled crude odds ratios; the pooled estimates should therefore be interpreted as associations rather than independent causal effects.

Since age-related factors in ACDF remain understudied relative to the burden of cervical spine pathology in older patients, an important direction for this literature is to examine age-related mechanisms, such as bone quality and degenerative change, using standardized protocols, consistent age cutoffs, and long-term follow-up. The present results underscore the value of incorporating age-related factors, including comorbidity burden, into preoperative assessment and patient selection for ACDF, so as to guide tailored perioperative strategies and improve safety for this growing and vulnerable population.

Conclusions

ACDF is performed with increasing frequency in older adults, yet most of the outcomes literature centers on younger patients, leaving age-related postoperative risk poorly defined; this systematic review and meta-analysis set out to determine whether older age predicts a higher burden of total and individual postoperative complications after ACDF. Older age was significantly associated with worse outcomes - a higher risk of total complications, mortality, and dysphagia - with consistent effects across studies and robustness confirmed in a matched-cutoff sensitivity analysis, marking older age as an important risk factor for poorer recovery. Readmissions, by contrast, did not differ significantly and remained too heterogeneous across studies to support a firm conclusion. Age-related factors and comorbidities therefore warrant careful weighting during patient selection and preoperative planning, and the overall certainty of evidence, limited by the retrospective designs, underscores the need for harmonized age stratification and outcome reporting in future studies. A clearer understanding of how age shapes risk will support more individualized, age-specific perioperative care for elderly patients undergoing ACDF.

Appendices

Section and topic	Item	Checklist item	Location where item is reported
TITLE			
Title	1	Identify the report as a systematic review.	Title
ABSTRACT			
Abstract	2	See the PRISMA 2020 for Abstracts checklist.	Abstract
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	Introduction
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	Introduction (final paragraph); Materials and methods (hypothesis statement)
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	Materials and methods (Search Strategy and Eligibility Criteria)
		Specify all databases, registers, websites, organisations, reference lists and other	Materials and methods

Information sources	6	sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	(Search Strategy and Eligibility Criteria); Table 1
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	Materials and methods; Table 1
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	Materials and methods (Search Strategy and Eligibility Criteria): two reviewers (S.A., G.B.)
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	Materials and methods (Data Extraction and Quality Assessment)
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought, and if not, the methods used to decide which results to collect.	Materials and methods (Statistical Analysis)
Data items	10b	List and define all other variables for which data were sought. Describe any assumptions made about any missing or unclear information.	Materials and methods (Data Extraction and Quality Assessment)
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	Materials and methods (Data Extraction and Quality Assessment): MINORS; Table 3; Figure 7
Effect measures	12	Specify for each outcome the effect measure(s) (e.g., risk ratio, mean difference) used in the synthesis or presentation of results.	Materials and methods (Statistical Analysis): odds ratios
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g., tabulating the study intervention characteristics and comparing against the planned groups for each synthesis).	Materials and methods (Statistical Analysis)
Synthesis methods	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	Materials and methods (Statistical Analysis)
Synthesis methods	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	Results; Tables 2–4; Figures 2–5
Synthesis methods	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	Materials and methods (Statistical Analysis): random-effects model, I^2, Python (NumPy/SciPy)
Synthesis methods	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g., subgroup analysis, meta-regression).	Materials and methods (Statistical Analysis); Results; Table 5
Synthesis methods	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	Materials and methods (Statistical Analysis); Table 5
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	Materials and methods (Statistical Analysis): funnel plots, Egger test; Figure 6
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	Materials and methods (Statistical Analysis): GRADE; Table 6
RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	Results (first paragraph); Figure 1

Study selection	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	Results; Figure 1
Study characteristics	17	Cite each included study and present its characteristics.	Results; Table 2; Table 3
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	Results (MINORS scores); Table 3; Figure 7
Results of individual studies	19	For all outcomes, present, for each study, summary statistics for each group (where appropriate) and an effect estimate and its precision (e.g., confidence/credible interval), ideally using structured tables or plots.	Results (individual study comparisons); Table 4
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.	Results; Tables 2–4 and 6
Results of syntheses	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g., confidence/credible interval) and measures of statistical heterogeneity.	Results; Figures 2–5
Results of syntheses	20c	Present results of all investigations of possible causes of heterogeneity among study results.	Results; Table 5; Discussion
Results of syntheses	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	Results; Table 5
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	Results; Figure 6
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	Results; Table 6
DISCUSSION			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	Discussion
Discussion	23b	Discuss any limitations of the evidence included in the review.	Discussion (Limitations)
Discussion	23c	Discuss any limitations of the review processes used.	Discussion (Limitations)
Discussion	23d	Discuss implications of the results for practice, policy, and future research.	Discussion; Conclusions
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including the register name and registration number, or state that the review was not registered.	Materials and methods: PROSPERO CRD42024561187
Registration and protocol	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	Materials and methods: PROSPERO (CRD42024561187)
Registration and protocol	24c	Describe and explain any amendments to information provided at registration or in the protocol.	Materials and methods: amendments documented in the PROSPERO record
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	Additional information (Disclosures): no financial support received
Competing interests	26	Declare any competing interests of review authors.	Additional information (Disclosures)
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	Additional information: all data derived from the included published studies [13–22]

TABLE 7: Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 checklist

Completed PRISMA 2020 checklist. For each item, the location column indicates the manuscript section, table, or figure where the item is reported. The

checklist follows the PRISMA 2020 statement (Page MJ, et al. BMJ. 2021). GRADE: Grading of Recommendations Assessment, Development and Evaluation; MINORS: Methodological Index for Non-randomized Studies; PROSPERO: International Prospective Register of Systematic Reviews.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Shaheryar Asad, Jean Shanaa, Kevin Tang, Sarah Lateef, Ferhan Asghar

Acquisition, analysis, or interpretation of data: Shaheryar Asad, Guneet S. Bindra, Jean Shanaa, Ferhan Asghar

Drafting of the manuscript: Shaheryar Asad, Guneet S. Bindra, Jean Shanaa, Kevin Tang, Sarah Lateef, Ferhan Asghar

Critical review of the manuscript for important intellectual content: Shaheryar Asad, Guneet S. Bindra, Jean Shanaa, Kevin Tang, Sarah Lateef, Ferhan Asghar

Supervision: Shaheryar Asad, Ferhan Asghar

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