

Does Hospital Volume Still Matter in Contemporary Transcatheter Aortic Valve Replacement? A Systematic Review and Dose–Response Meta-Analysis

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Abstract

Introduction

Higher hospital procedural volume has traditionally been associated with improved outcomes in complex cardiovascular interventions. However, whether this volume–outcome relationship remains clinically relevant in contemporary transcatheter aortic valve replacement (TAVR) practice is uncertain. In addition, potential temporal changes, geographic variation, and quantitative dose–response relationships have not been comprehensively evaluated.

Methods

A systematic review and meta-analysis of observational studies was conducted to evaluate short-term mortality (in-hospital or 30-day) following TAVR according to hospital procedural volume. Pooled odds ratios (ORs) were estimated using random-effects models. Prespecified subgroup analyses were performed according to study era and geographic region. A dose–response meta-analysis was conducted to evaluate the relationship between annual hospital procedural volume and short-term mortality.

Results

Seventeen studies involving 441,393 patients were included. Overall, treatment at high-volume hospitals was associated with a significantly lower risk of short-term mortality than treatment at low-volume hospitals (OR: 0.63; 95% confidence interval [CI]: 0.54–0.76). In subgroup analyses, a significant inverse association was observed during the early TAVR era (2002–2014; OR: 0.50; 95% CI: 0.43–0.58), whereas no significant association was identified in the contemporary era (2015–2020; OR: 0.95; 95% CI: 0.56–1.59). Studies conducted in Western countries consistently demonstrated lower mortality at higher-volume hospitals, whereas findings from Eastern regions were less consistent. Dose–response analysis demonstrated a significant non-linear association, with mortality risk decreasing as annual hospital procedural volume increased and reaching a plateau at approximately 200 procedures per year.

Conclusions

Higher hospital procedural volume is associated with lower short-term mortality following TAVR. However, the volume–outcome relationship appears to have attenuated substantially in contemporary practice, suggesting that hospital procedural volume alone may no longer fully reflect institutional quality. Dose–response analysis further demonstrated a threshold effect, indicating that the incremental benefit associated with increasing procedural volume diminishes beyond approximately 200 procedures per year. These findings suggest that hospital procedural volume remains an important indicator of outcomes but should be interpreted alongside other measures of institutional performance when evaluating TAVR program quality.

INTRODUCTION

Transcatheter aortic valve replacement (TAVR) has fundamentally reshaped the management of severe aortic stenosis over the past two decades, evolving from a therapy initially reserved for inoperable patients to a standard treatment option across the full spectrum of surgical risk [1–9]. This rapid expansion has been accompanied by major advances in valve technology, procedural techniques, imaging guidance, and peri-procedural care, resulting in substantial improvements in procedural safety and short-term outcomes [2–4]. As TAVR becomes increasingly integrated into routine cardiovascular practice worldwide, identifying reliable markers of institutional quality and ensuring equitable access to high-quality care have emerged as critical clinical and health system priorities.

Hospital procedural volume has long been considered a surrogate marker of quality in complex cardiovascular interventions [10–14]. Evidence from cardiac surgery and percutaneous coronary intervention has consistently demonstrated inverse relationships between institutional volume and short-term mortality, forming the basis for regionalization strategies and minimum volume requirements for program accreditation [10, 11, 15, 16]. Early observational studies in TAVR similarly reported lower short-term mortality at high-volume centers, suggesting that institutional experience plays a key role during the early adoption phase of technically demanding procedures [17–19].

However, whether the historical volume–outcome relationship remains clinically meaningful in contemporary TAVR practice is increasingly uncertain [20–23]. Most available evidence was generated during the early diffusion phase of TAVR, when operator learning curves, device limitations, and procedural variability were more pronounced. As TAVR has matured into a highly standardized intervention, the extent to which institutional procedural volume continues to influence mortality outcomes remains unclear. Widespread procedural standardization, the adoption of transfemoral-first strategies, implementation of structured heart-team models, formalized operator training pathways, and continuous improvements in device design may have attenuated traditional learning-curve effects [2–4, 24]. Recent large registry-based studies have reported heterogeneous findings, with some suggesting persistent volume-related advantages and others demonstrating little or no association between institutional volume and short-term mortality [22, 24, 25]. These inconsistencies raise important questions regarding the continued validity of procedural volume as a proxy for quality in modern TAVR programs.

Interpretation of the existing literature is further complicated by substantial methodological heterogeneity. Definitions of hospital procedural volume vary widely across studies, ranging from annual procedural thresholds to cumulative experience or relative categorization by tertiles and quartiles [17–19, 22, 24–27]. Short-term mortality has also been inconsistently defined as either in-hospital or 30-day mortality, and the degree of confounder adjustment differs across datasets and study eras. Moreover, prior analyses often combine data across periods of rapid technological evolution, potentially obscuring temporal changes in the relevance of institutional experience. Importantly, emerging evidence from non-Western healthcare systems suggests that the volume–outcome relationship may differ across

healthcare settings, highlighting potential differences in healthcare system structure, patient selection, and referral patterns [25].

Despite the growing body of evidence, a comprehensive evaluation integrating temporal trends, geographic variation, and dose–response relationships remains lacking. Addressing this gap is essential for clarifying whether institutional procedural volume remains a robust and generalizable indicator of short-term outcomes in contemporary TAVR practice, and for informing evidence-based policy decisions regarding volume-based benchmarks and quality metrics. Therefore, we conducted a systematic review, meta-analysis, and dose–response analysis to (1) quantify the association between hospital TAVR procedural volume and short-term mortality, (2) evaluate whether this relationship has evolved over time, and (3) characterize potential threshold effects and geographic heterogeneity.

METHODS

Study Design and Data Sources

This systematic review and meta-analysis was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 (PRISMA 2020) Statement [28]. The study protocol was prospectively registered in the International Prospective Register of Systematic Reviews (PROSPERO; CRD42024617101).

A comprehensive literature search was performed in PubMed, Embase, Web of Science, the Cochrane Library, and major Chinese databases including China National Knowledge Infrastructure (CNKI), WanFang Data, and VIP from database inception through February 28, 2026. The search strategy combined Medical Subject Headings (MeSH) and free-text terms related to transcatheter aortic valve replacement, hospital procedural volume, and short-term mortality. No language restrictions were applied. In addition, reference lists of relevant reviews and included studies were manually screened to identify potentially eligible articles. The detailed search strategy is provided in Table S1.

Study Selection and Data Extraction

Studies were considered eligible if they met the following criteria: (1) enrolled adult patients undergoing transcatheter aortic valve replacement; (2) reported short-term mortality outcomes (in-hospital or 30-day mortality); (3) stratified outcomes according to hospital procedural volume; and (4) used observational cohort designs, including prospective, retrospective, or registry-based analyses.

Studies were excluded if mortality data were not extractable, hospital volume categories were not clearly defined, duplicate analyses from the same dataset were identified (in which case the most comprehensive or recent study was retained), or if the report was a review, editorial, case report, or conference abstract.

Two investigators independently screened titles and abstracts, followed by full-text review of potentially eligible studies. Discrepancies were resolved through discussion or consultation with a third reviewer. Data extraction was performed independently using a standardized data collection form and included study characteristics, geographic region, study period, sample size, definitions of hospital procedural volume, definitions of mortality outcomes, and reported effect estimates. When both unadjusted and adjusted estimates were available, the most fully adjusted estimates were preferentially extracted. Any disagreements in study selection, data extraction, or risk-of-bias assessment were resolved through consensus.

Risk of Bias Assessment

Risk of bias was evaluated using the Newcastle–Ottawa Scale (NOS), which assesses cohort selection, comparability of study groups, and outcome ascertainment [29, 30]. Studies scoring ≥ 7 points were considered high quality. Detailed assessments are presented in Supplementary Table S2 (Additional file 1).

Statistical Analysis

The primary outcome was short-term mortality following transcatheter aortic valve replacement. The most fully adjusted effect estimates were preferentially extracted whenever available. Because short-term mortality was a relatively infrequent outcome across the included studies, adjusted odds ratios (ORs), hazard ratios (HRs), and risk ratios (RRs) were considered approximately equivalent measures of relative risk under the rare-event assumption and were pooled as ORs for quantitative synthesis.

Given anticipated clinical and methodological heterogeneity related to differences in study populations, healthcare systems, and technological evolution of TAVR, pooled analyses were performed using random-effects models (DerSimonian–Laird method) [31, 32]. Statistical heterogeneity was assessed using Cochran’s Q test and quantified using the I^2 statistic. Values of approximately 25%, 50%, and 75% were considered to represent low, moderate, and high heterogeneity, respectively.

In addition, a dose-response meta-analysis was performed to evaluate the potential quantitative relationship between hospital procedural volume and short-term mortality. For studies reporting outcomes across multiple volume categories, the median or mean value of each category was assigned as the corresponding exposure level. When ranges were reported, midpoints were calculated; for open-ended categories, values were estimated based on adjacent intervals.

A two-stage generalized least squares regression approach was applied to model study-specific dose-response relationships, as described by Greenland and Longnecker[33–35], and further extended by Orsini et al.[33, 36]. Potential non-linear associations were explored using restricted cubic spline models with three knots placed at the 10th, 50th, and 90th percentiles of the exposure distribution. A likelihood

ratio test comparing the non-linear model with a linear model was used to assess departure from linearity.

Subgroup and Sensitivity Analyses

Prespecified subgroup analyses were conducted according to study period (early vs contemporary TAVR era), geographic region (Western vs Eastern countries), study sample size, number of participating centers, degree of confounder adjustment, definitions of hospital procedural volume, and definitions of short-term mortality (in-hospital vs 30-day).

Sensitivity analyses were performed using leave-one-out methods and by excluding studies with lower methodological quality or extreme hospital volume thresholds.

Publication Bias

Publication bias was evaluated through visual inspection of funnel plots and quantitatively assessed using Egger's regression asymmetry test [40–42]. All statistical analyses were performed using R software version 4.4.0 (R Foundation for Statistical Computing, Vienna, Austria). A two-sided P value < 0.05 was considered statistically significant.

RESULTS

Study Selection and Characteristics

The systematic literature search identified 6,214 records across all databases. After removal of duplicates, 3,182 unique records underwent title and abstract screening, of which 214 articles were selected for full-text review. Studies were primarily excluded because they did not stratify outcomes according to hospital procedural volume, did not report short-term mortality outcomes, or represented duplicate analyses of the same registry datasets. Ultimately, 17 studies met the predefined eligibility criteria and were included in the final meta-analysis. The study selection process is presented in Fig. 1.

The included studies comprised 441,393 patients undergoing transcatheter aortic valve replacement across North America, Europe, and Asia. All studies were observational cohort or registry-based investigations reflecting real-world clinical practice. Study periods spanned both the early TAVR adoption era (2002–2014) and the contemporary era (2015–2020).

Definitions of hospital procedural volume varied across studies. Most investigations categorized institutional volume according to annual procedural thresholds, whereas others used relative rankings such as tertiles or quartiles. The characteristics of the included studies are summarized in Table S3.

Primary Analysis

Overall, treatment at high-volume hospitals was associated with a significantly lower risk of short-term mortality following transcatheter aortic valve replacement compared with treatment at low-volume hospitals. In the pooled analysis of 17 studies involving 441,393 patients, the pooled odds ratio was 0.63 (95% confidence interval [CI]: 0.54–0.76; $P < 0.001$) (Fig. 2). Substantial between-study heterogeneity was observed ($I^2 = 90.5\%$). Nevertheless, the direction of the association was generally consistent across studies, with most investigations reporting lower mortality rates among higher-volume centers. The high heterogeneity likely reflects differences in patient populations, healthcare systems, definitions of hospital procedural volume, and study periods.

Dose–Response Analysis

A total of 12 studies were included in the dose–response meta-analysis evaluating the association between annual hospital TAVR procedural volume and short-term mortality. A significant non-linear dose–response relationship was observed (P for non-linearity < 0.001).

As annual hospital procedural volume increased, the risk of short-term mortality progressively decreased. However, the magnitude of risk reduction became less pronounced at higher procedural volumes, with the dose–response curve reaching a plateau at approximately 200 TAVR procedures per year. These findings indicate a potential threshold effect, suggesting that the incremental benefit associated with increasing procedural volume diminishes beyond this level.

The dose–response relationship is shown in Fig. 3, and the distribution of hospital procedural volumes and mortality rates is presented in Supplementary Figure S1.

Subgroup Analyses

Subgroup analyses showed that the association between hospital procedural volume and short-term mortality varied according to study era and geographic region (Fig. 4).

When stratified by study period, the volume–outcome relationship differed across TAVR eras. In studies conducted during the early phase of TAVR adoption (2002–2014), treatment at higher-volume hospitals was associated with significantly lower short-term mortality compared with lower-volume centers (OR: 0.50; 95% CI: 0.43–0.58). In contrast, no significant association was observed in studies conducted during the contemporary TAVR era (2015–2020) (OR: 0.95; 95% CI: 0.56–1.59) (Fig. 4A).

Geographic subgroup analyses also showed regional variation. In studies conducted in Western countries, higher hospital procedural volume was consistently associated with lower short-term mortality (OR: 0.60; 95% CI: 0.50–0.72). In contrast, studies from Eastern regions yielded different effect estimates (OR: 2.37; 95% CI: 1.25–4.50), although these findings should be interpreted with caution because they were based on a limited number of studies (Fig. 4B).

Additional subgroup analyses according to study sample size, number of participating centers, hospital volume definitions, and mortality outcome definitions are presented in Supplementary Figures S2–S6.

Sensitivity Analyses

The inverse association between hospital procedural volume and short-term mortality remained significant in both studies reporting multivariable-adjusted estimates and studies without clearly reported adjustment for confounding variables (Supplementary Figure S2).

Sensitivity analyses further confirmed the stability of the primary findings. Excluding studies without adjustment for confounding factors, studies without reported odds ratios, or studies with sample sizes < 1,000 patients did not materially alter the pooled effect estimates (Fig. 5).

Additional analyses according to study quality yielded consistent results (Supplementary Figures S7 and S8). Leave-one-out analyses demonstrated stable effect estimates across all iterations (Supplementary Figure S9). No evidence of publication bias was observed based on visual inspection of the funnel plot or Egger's regression test (Supplementary Figure S10).

DISCUSSION

Principal Findings

This systematic review and dose–response meta-analysis provides a comprehensive evaluation of the association between hospital procedural volume and short-term mortality following transcatheter aortic valve replacement (TAVR). Four principal findings emerged from this study. First, treatment at high-volume hospitals was associated with a significantly lower risk of short-term mortality than treatment at low-volume hospitals. Second, this association differed substantially across study eras and was no longer statistically significant in contemporary TAVR practice. Third, dose–response analysis demonstrated a significant non-linear relationship, with mortality risk decreasing as annual hospital procedural volume increased and reaching a plateau at approximately 200 procedures per year. Finally, subgroup analyses suggested geographic variation in the volume–outcome relationship across different healthcare settings.

Taken together, these findings indicate that hospital procedural volume remains associated with short-term outcomes after TAVR; however, its value as a standalone indicator of institutional quality appears to have diminished as TAVR technology, procedural techniques, and clinical practice have evolved.

Comparison With Previous Evidence

Previous studies have reported inconsistent findings regarding the association between hospital procedural volume and outcomes following TAVR. Early registry-based studies from the United States, Germany, and other Western healthcare systems generally demonstrated lower mortality rates at higher-volume hospitals, supporting a volume–outcome relationship during the early adoption of TAVR [17, 19,

22, 27, 37]. In contrast, more recent registry studies have reported weaker or inconsistent associations, suggesting that the impact of hospital procedural volume may have changed as TAVR technology, patient selection, and procedural practice have evolved [25, 37, 38].

Compared with the previous meta-analysis by He et al. [20], the present study substantially extends the available evidence. In addition to including a larger number of studies and patients from diverse healthcare systems and study periods, our analysis evaluated temporal changes, geographic variation, and dose–response relationships, providing a more comprehensive assessment of the evolving volume–outcome relationship in TAVR. These findings suggest that although higher hospital procedural volume remains associated with lower short-term mortality overall, this association has become less pronounced in contemporary practice.

Evolution of the Volume–Outcome Relationship

One of the most important findings of the present study is the apparent attenuation of the volume–outcome relationship over time. While treatment at higher-volume hospitals was associated with significantly lower short-term mortality during the early phase of TAVR adoption (2002–2014), this association was no longer statistically significant in the contemporary TAVR era (2015–2020). These findings suggest that the role of hospital procedural volume has evolved as TAVR technology and clinical practice have matured.

Several factors may explain this temporal trend. Advances in valve technology, procedural techniques, imaging guidance, and peri-procedural care have substantially improved procedural safety and clinical outcomes across institutions [39, 40]. In parallel, increasing operator experience, structured heart-team models, standardized procedural pathways, and formalized training programs may have reduced variability in outcomes between lower- and higher-volume centers [39, 40].

Patient selection has also changed considerably since the introduction of TAVR. Early procedures were largely performed in highly specialized centers treating patients at prohibitive or high surgical risk, whereas contemporary TAVR has expanded to include intermediate- and low-risk populations and is now performed across a broader range of institutions [9, 41]. Consequently, hospital procedural volume alone may no longer fully reflect differences in institutional quality or procedural performance.

These findings have important implications for quality assessment. Although minimum procedural volume thresholds may have been appropriate during the early diffusion of TAVR, our results suggest that procedural volume should no longer be considered in isolation when evaluating institutional performance. Future quality assessment frameworks should integrate procedural volume with additional measures, such as risk-adjusted clinical outcomes, procedural quality indicators, and adherence to evidence-based care pathways.

Threshold Effect and Clinical Implications

Beyond the overall volume–outcome association, the dose–response analysis provides additional insight into the relationship between hospital procedural volume and short-term mortality following TAVR. Mortality risk decreased progressively with increasing annual hospital procedural volume; however, the magnitude of risk reduction became less pronounced at higher procedural volumes, with the dose–response curve reaching a plateau at approximately 200 procedures per year. This pattern suggests a threshold effect, whereby the incremental benefit associated with increasing procedural volume diminishes beyond a certain level.

Several factors may contribute to this non-linear relationship. Increasing procedural volume may be associated with improvements in operator proficiency, multidisciplinary team coordination, patient selection, and peri-procedural management, all of which may contribute to better clinical outcomes. Once these processes become well established, however, further increases in procedural volume may provide only limited additional benefit.

The identification of a potential threshold has important implications for healthcare planning and quality assessment. Rather than assuming that progressively higher procedural volumes will continuously translate into better outcomes, our findings suggest that the relationship is not linear across the entire volume spectrum. Procedural volume should therefore be interpreted alongside other measures of institutional performance when evaluating TAVR program quality.

Importantly, the observed threshold should not be interpreted as a definitive cutoff for accreditation, reimbursement, or program designation. Hospitals with similar procedural volumes may still achieve different clinical outcomes because of differences in patient case mix, institutional resources, operator expertise, and quality improvement initiatives. Accordingly, hospital procedural volume should be considered as one component of a comprehensive quality assessment framework rather than a standalone indicator of institutional performance.

Geographic Variation

An additional finding of this study was the potential geographic variation in the volume–outcome relationship. While studies conducted in Western healthcare systems generally demonstrated lower short-term mortality at higher-volume hospitals, findings from Eastern regions were less consistent. However, these observations should be interpreted with caution because only a limited number of studies were available from Eastern healthcare systems, and substantial differences existed in study design, patient populations, healthcare delivery models, and institutional referral patterns.

Several factors may contribute to these regional differences. Healthcare systems vary considerably with respect to referral networks, hospital accreditation standards, procedural centralization, and resource allocation. In addition, differences in patient selection, timing of TAVR adoption, operator training pathways, and access to specialized structural heart programs may influence the relationship between hospital procedural volume and clinical outcomes [22, 37, 38].

Given the limited evidence from Eastern healthcare systems, these findings should be considered hypothesis-generating rather than definitive. Further studies from underrepresented regions are needed to determine whether the volume–outcome relationship differs across healthcare systems and to identify institutional factors beyond procedural volume that may influence patient outcomes.

Strengths and Limitations

This study has several important strengths. It represents the largest and most comprehensive synthesis to date evaluating the association between hospital procedural volume and short-term mortality following TAVR, including more than 440,000 patients from diverse healthcare systems and study periods. In addition to providing an updated pooled estimate, this study incorporated temporal subgroup analyses, geographic comparisons, and dose–response modeling, offering a more comprehensive assessment of the evolving volume–outcome relationship than previous evidence syntheses.

Several limitations should also be acknowledged. First, all included studies were observational, and residual confounding cannot be excluded despite the use of multivariable-adjusted estimates in many studies. Second, substantial between-study heterogeneity was observed, likely reflecting differences in study populations, risk-adjustment strategies, procedural eras, healthcare systems, and definitions of hospital procedural volume. Third, hospital procedural volume was defined inconsistently across studies, and the pooled findings therefore reflect the overall volume–outcome relationship rather than a universally applicable procedural threshold. Fourth, although subgroup analyses suggested attenuation of the volume–outcome relationship in contemporary TAVR practice, relatively few studies were available in some subgroups. Finally, evidence from Eastern healthcare systems remained limited; therefore, the geographic subgroup findings should be considered exploratory and require confirmation in future multinational studies.

CONCLUSIONS

Higher hospital procedural volume is associated with lower short-term mortality following transcatheter aortic valve replacement. However, the volume–outcome relationship appears to have attenuated substantially in contemporary practice, suggesting that hospital procedural volume alone may no longer fully reflect institutional quality. Dose–response analysis demonstrated a significant non-linear association, with mortality risk decreasing as annual procedural volume increased and reaching a plateau at approximately 200 procedures per year. Collectively, these findings suggest that although hospital procedural volume remains an important indicator of outcomes, it should be interpreted alongside other measures of institutional performance when evaluating TAVR program quality. Further studies are warranted to identify complementary quality metrics that more comprehensively reflect institutional performance in contemporary TAVR practice.

Declarations

Author Contributions

Jin Shi, Xueyan Li, and Ying Liu contributed equally to this work. Jin Shi and Xueyan Li designed the study, performed the literature search, extracted the data, and conducted the statistical analyses. Ying Liu contributed to data verification and interpretation of the findings. Zige Wang, Mingxu Shuai, and Xiaoyang Cai assisted with data collection and quality assessment. Jin Shi and Xueyan Li drafted the manuscript. Donghan Zheng and Weina Hu conceived and supervised the study and critically revised the manuscript. Donghan Zheng and Weina Hu contributed equally as corresponding authors. All authors approved the final version of the manuscript.

Ethics Approval and Consent to Participate

Not applicable. This study was a systematic review and meta-analysis of previously published studies and did not involve direct human participant enrollment.

Conflicts of interest disclosure

The authors report no conflicts of interests.

Data availability statement

Datasets generated during and/or analyzed during the current study are available upon reasonable request.

Clinical trial number

Clinical trial number: not applicable.

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Figures

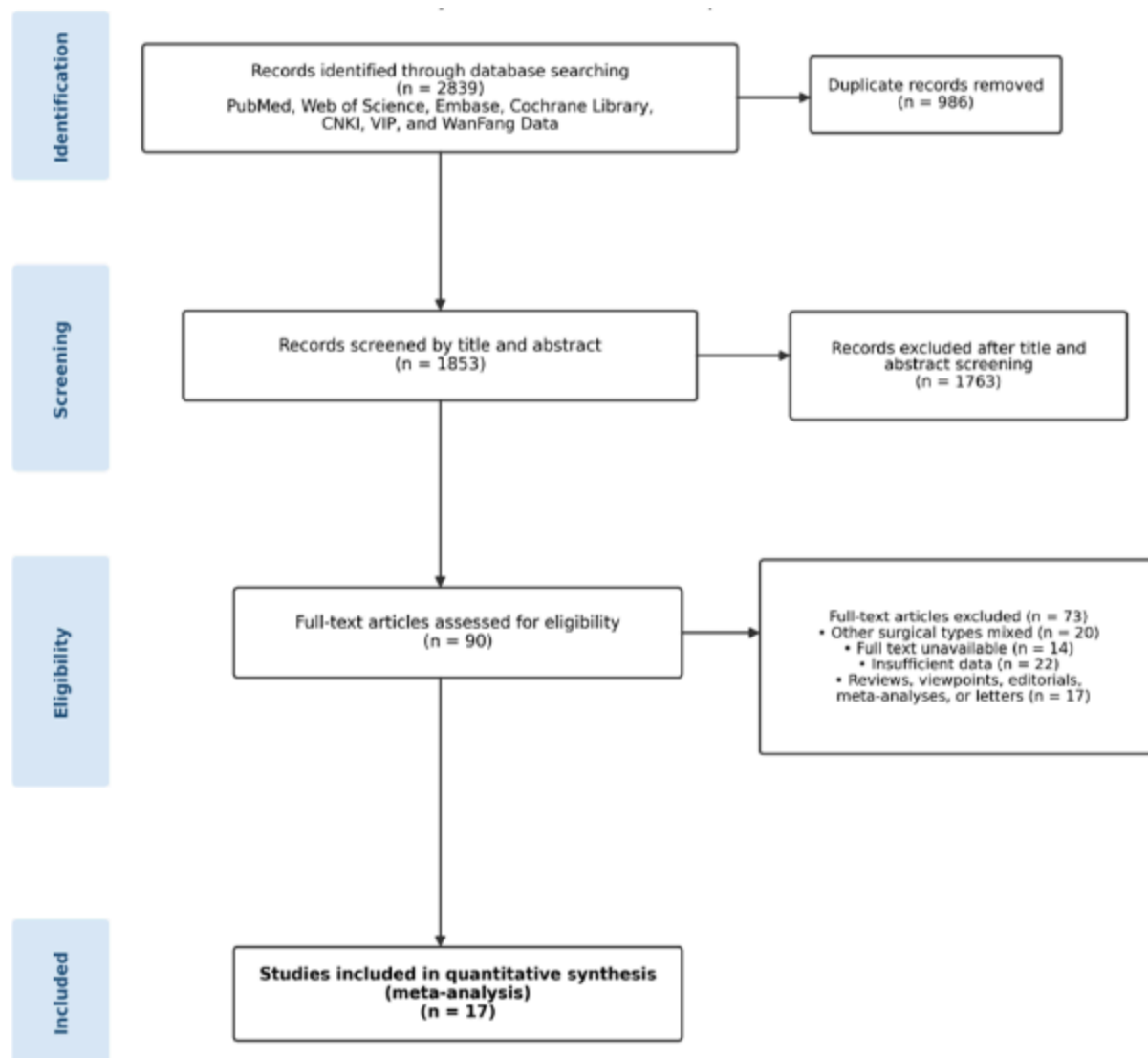


Figure 1

PRISMA Flow Diagram

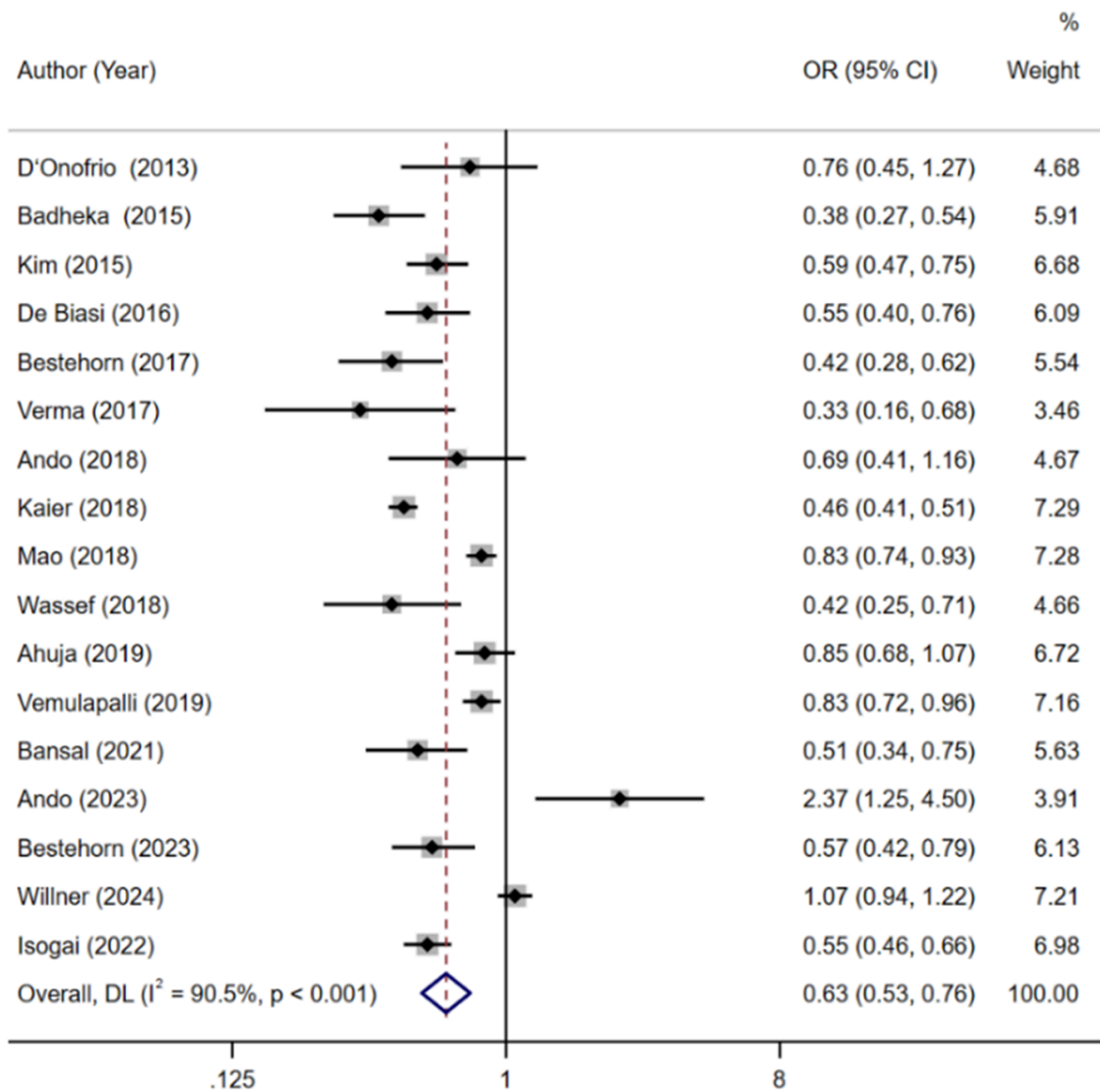


Figure 2

Overall Association Between Hospital Volume and Short-Term Mortality

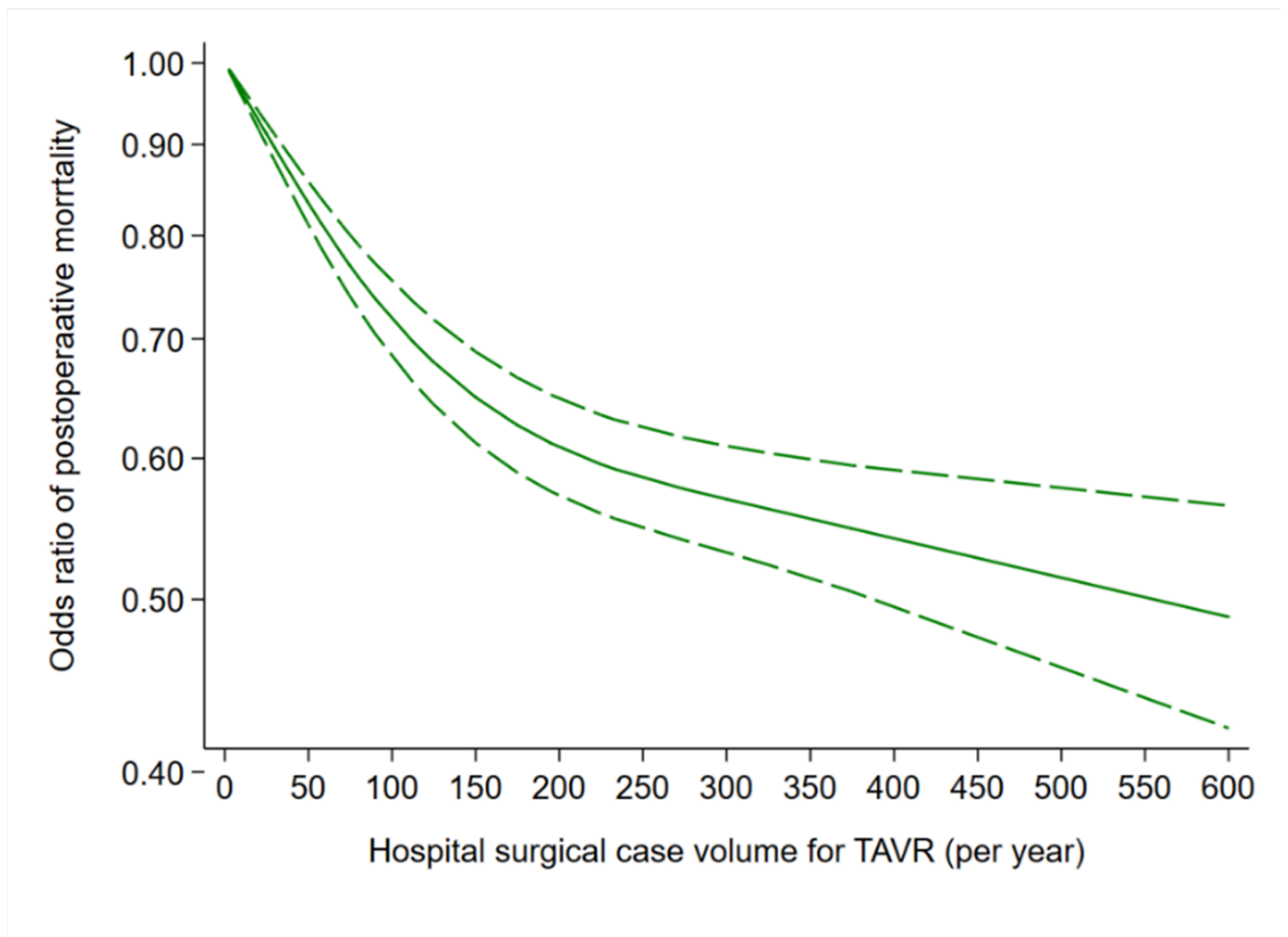


Figure 3

Dose-response association between annual hospital TAVR volume and short-term mortality.

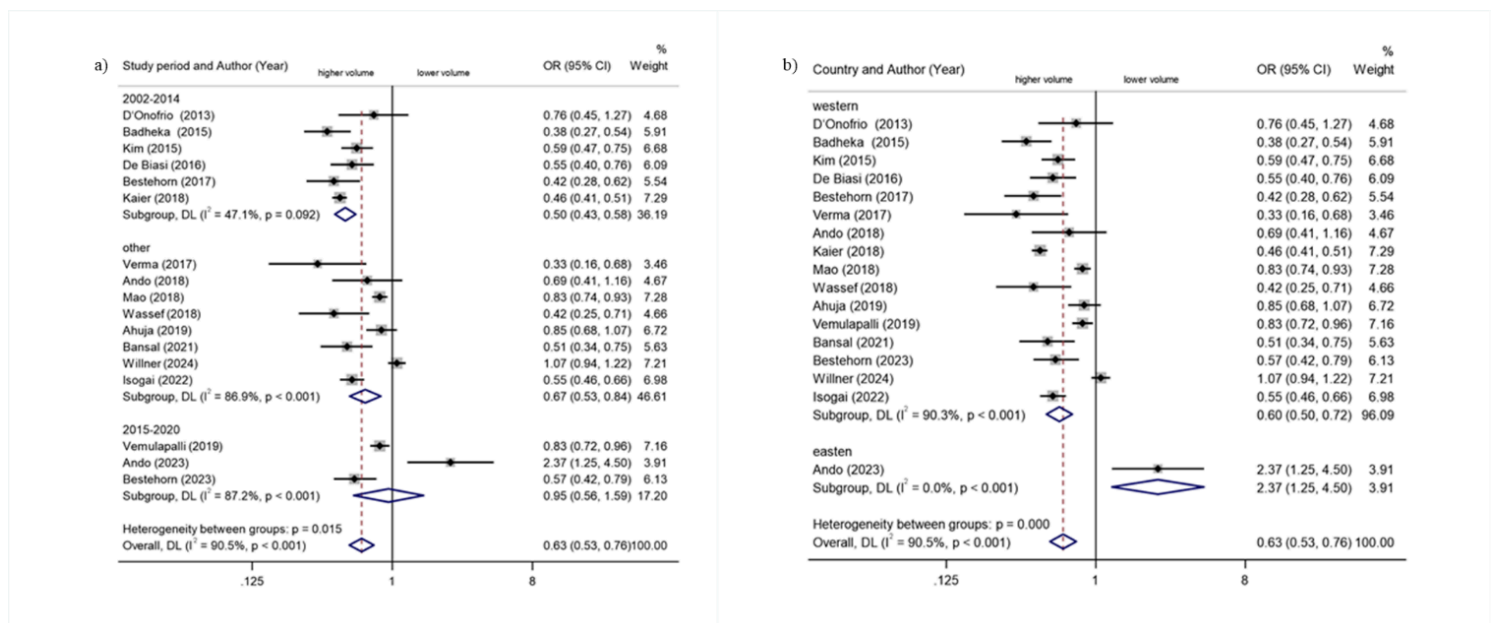


Figure 4

Subgroup Analyses of the Association Between Hospital Procedural Volume and Short-Term Mortality After TAVR (a) Stratified by study period and (b) Stratified by geographic region

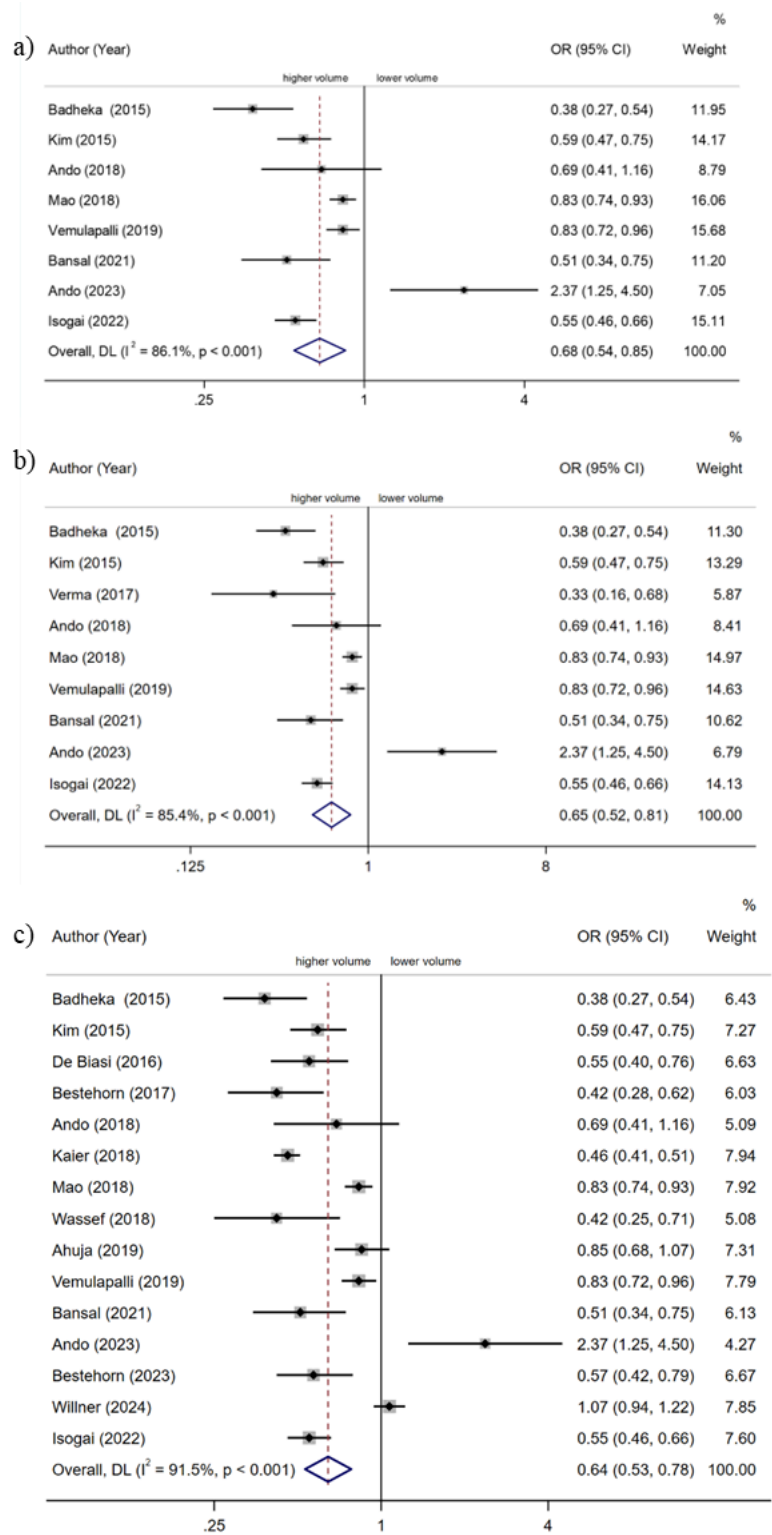


Figure 5

Sensitivity analyses evaluating the robustness of the association between hospital TAVR procedural volume and short-term mortality by excluding studies (A) without adjustment for confounding factors, (B) without reported odds ratios, and (C) with sample sizes <1000.

Supplementary Files

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