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Concomitant infective endocarditis in vertebral osteomyelitis and other spinal infections: a retrospective cohort study

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Abstract. **Introduction:** Concomitant infective endocarditis (IE) occurs in vertebral osteomyelitis and other spinal infections, but routine-care estimates and microbiologic descriptions remain limited. This study aimed to describe the frequency and microbiologic phenotype of concomitant clinically recognized IE among adults hospitalized with spinal infection. **Methods:** This retrospective cohort study used the MIMIC-IV electronic health record (EHR) database to identify adults hospitalized with diagnosis-coded spinal infection. IE was identified from diagnosis codes and therefore represents clinically recognized, coded IE. A prespecified adjusted model excluding septic pulmonary emboli (SPE) was primary; an SPE-inclusive model was secondary. **Results:** Among 1002 patients, 97 (9.68 %) had coded IE. In the primary model, IE was associated with *Enterococcus* spp. (odds ratio (OR) 3.35, 95 % confidence interval (CI) 1.30–8.68), *Streptococcus* spp. (OR 5.25, 95 % CI 2.53–10.90), and repeated same-group positive blood cultures on two or more dates (OR 4.03, 95 % CI 2.17–7.51); the association with *Staphylococcus aureus* was not significant (OR 1.47, 95 % CI 0.77–2.82). SPE also co-occurred strongly with IE in the secondary model (OR 9.47, 95 % CI 3.89–23.07). IE was associated with longer adjusted length of stay (ratio 1.33, 95 % CI 1.14–1.55); adjusted mortality was not significant. **Conclusions:** Concomitant clinically recognized IE was identified in approximately one in 10 patients with spinal infection and clustered with enterococcal and streptococcal bacteremia and repeated same-group positive blood cultures. These EHR-based findings define a clinically recognized IE-associated phenotype in routine care.

1 Introduction

Vertebral osteomyelitis and the broader spectrum of spinal infection, encompassing intervertebral disc infection, discitis, spondylodiscitis, and other infective spondylopathies, constitute an important and increasingly encountered category of bone-and-joint infection. These overlapping entities share clinical, radiological, and microbiologic features, and the historical absence of a standardized definition has complicated their recognition and comparison across studies (Petri et al., 2024). Diagnosis generally rests on the integration of clinical presentation, inflammatory biomarkers, cross-sectional imaging (most often magnetic resonance imaging), and microbiologic confirmation from blood cultures or image-guided biopsy (Berbari et al., 2015). The incidence of native vertebral osteomyelitis has been reported to be rising in US administrative data, in the context of an aging population (Issa et al., 2018; Kremers et al., 2015). Spinal infection carries substantial morbidity, including prolonged hospitalization (Issa et al., 2018), the potential for neurologic compromise, and a risk of relapse (McHenry et al., 2002).

Infective endocarditis (IE) is an important endovascular condition that can share this hematogenous route. Concomitant IE has been described in patients with vertebral osteomyelitis, and the two conditions can plausibly seed one another through sustained bacteremia, so that recognizing coexisting IE may carry implications for the duration of therapy, the search for embolic complications, and consideration of surgery. Reported associations are not uniform, however, and estimates of how often the two co-occur vary widely with

the population studied, the case definition used, and how systematically endocarditis is sought (von der Höh et al., 2025; Pigrau et al., 2005).

A recent systematic review and meta-analysis of 16 studies comprising 641 patients with concomitant NVO and IE highlighted the predominantly retrospective and heterogeneous nature of the available evidence (Borgonovo et al., 2025). Large, real-world estimates of how frequently IE is recognized among patients hospitalized with spinal infection, and of the accompanying microbiologic features, remain limited. Using a large electronic health record cohort drawn from routine care, this study aimed to describe the frequency of concomitant clinically recognized IE among adults hospitalized with vertebral osteomyelitis and other spinal infections, and to characterize the associated microbiologic phenotype. In this cohort, clinically recognized IE was identified from diagnosis codes rather than standardized adjudication.

2 Methods

2.1 Data source and study design

A retrospective cohort study was conducted using the Medical Information Mart for Intensive Care IV (MIMIC-IV) version 3.1, a publicly available, de-identified electronic health record (EHR) database derived from routine care at the Beth Israel Deaconess Medical Center (BIDMC), Boston, Massachusetts (Johnson et al., 2023, 2024). The cohort was assembled from the hospital-wide Hosp module using inpatient ICD diagnosis codes and was not restricted to intensive care unit (ICU) admissions. The study was reported in accordance with the RECORD extension of the STROBE statement for observational routinely collected health data (Benchimol et al., 2015; von Elm et al., 2007); a completed checklist is provided in the Supplement. The establishment of MIMIC-IV was approved by the BIDMC Institutional Review Board with a waiver of informed consent; because the data are de-identified, no additional review or consent was required for this analysis, which was conducted by a credentialed user under the PhysioNet Credentialed Health Data Use Agreement (Goldberger et al., 2000).

2.2 Cohort definition

The primary (expanded spinal infection) cohort comprised adults hospitalized with vertebral osteomyelitis or other spinal infections, identified from inpatient ICD diagnosis codes (ICD-9-CM 730.28 and ICD-10-CM M46.2x–M46.5x, corresponding to vertebral osteomyelitis, pyogenic intervertebral disc infection, discitis, and other infective spondylopathies). Adults were defined by a MIMIC-IV anchor age of at least 18 years, with no upper age limit. For patients with more than one qualifying hospitalization, the earliest was selected as the index admission, so that each patient contributed one hospitalization and served as the unit of analysis. No further exclusions were applied; patients were not excluded on the basis of ICU admission or the availability of blood cultures, echocardiography, or microbiology results. A stricter vertebral osteomyelitis cohort (ICD-9-CM 730.28 and ICD-10-CM M46.2x only) was evaluated as a sensitivity analysis. Complete code lists for all definitions are provided in the Supplement.

2.3 Outcome and phenotype variables

The primary outcome was concomitant infective endocarditis (IE), identified from ICD diagnosis codes recorded during the index hospitalization; it therefore represents clinically recognized, coded IE and was not adjudicated using the modified Duke or 2023 Duke-ISCVID criteria (Li et al., 2000; Fowler et al., 2023), nor was it confirmed by chart review or echocardiographic findings. The prespecified strict definition comprised explicitly infective codes (ICD-9-CM 421.0; ICD-10-CM I33.0, B37.6); a broader definition including less-specific endocarditis codes was assessed for sensitivity.

Blood culture organisms were identified by case-insensitive text matching of reported organism names from 48 h before admission through discharge, as *Staphylococcus aureus*, *Enterococcus* spp., and *Streptococcus* spp. (the latter including viridans streptococci and pneumococci); these indicators were not mutually exclusive. Repeated same-group positive blood cultures were defined as isolation of the same mapped organism group on two or more distinct culture dates; as a mapped-group rather than species-level indicator, it does not by itself establish persistent bacteremia. A stricter persistent proxy additionally requiring at least 48 h between the earliest and latest positive cultures was used in sensitivity analyses, along with blood-culture subgroups. An echocardiography procedure proxy was derived from ICD procedure codes for echocardiography or cardiac ultrasonography; it reflects only procedure-code evidence of echocardiography-related evaluation, contains no findings, and was not treated as IE confirmation. Septic pulmonary emboli were identified from septic pulmonary embolism-specific ICD diagnosis codes and interpreted as a co-occurring embolic and endovascular marker. Operational definitions, text-matching rules, and complete code lists are provided in Sect. S1 of the Supplement.

2.4 Secondary outcomes

Secondary outcomes were length of stay and mortality for the index hospitalization. Length of stay was the integer-day difference between discharge and admission, with prolonged stay evaluated at thresholds of 14 or more and 21 or more days. In-hospital mortality was defined by a recorded in-hospital death; 30 d, 90 d, and 1-year mortality were defined, using the MIMIC-IV date-of-death field, as death within 30, 90, or 365 d of the index admission date.

2.5 Statistical analysis

Categorical variables were summarized as counts and percentages, and continuous variables as means and medians. Associations with clinically recognized IE were examined using multivariable logistic regression fit by maximum likelihood, with odds ratios and 95 % confidence intervals obtained by exponentiating the regression coefficients and their confidence limits. The prespecified primary model was a parsimonious multivariable microbiologic model adjusting for age (per 10 years), female sex, ICD-10 coding era, transfer-in admission, cardiac or other implanted-device diagnosis, the organism group indicators, and repeated same-group positive blood cultures; a comprehensive comorbidity index was not included (residual confounding is addressed in the Discussion). Septic pulmonary emboli were excluded from this model and added in a secondary phenotype model. For secondary outcomes, binary endpoints used logistic regression and length of stay used linear regression of log(length of stay + 1) with HC3 robust standard errors. Further sensitivity analyses used a broader IE definition, the strict vertebral osteomyelitis cohort, an ICD-10-only cohort, the persistent $\geq$ 48 h proxy, and the blood-culture subgroups. Two post hoc sensitivity analyses used alternative specifications of the primary model. One analysis omitted repeated same-group positive blood cultures while retaining all other covariates to assess organism-specific estimates without this adjustment (Table S3, Panel C in the Supplement). The other added a single continuous Charlson comorbidity score computed from ICD codes and entered without its age component to avoid adjusting for age twice (Table S8). Analyses were performed in Python using statsmodels; software versions are listed in the Supplement. Two-sided p values below 0.05 were considered significant.

3 Results

ICD code-defined vertebral osteomyelitis or other spinal infection was identified in 1002 unique adult patients across 1388 qualifying hospitalizations. No patients were excluded for age below 18 years. After selecting the first qualifying hospitalization per patient and excluding 386 subsequent qualifying hospitalizations, the final analytic cohort comprised 1002 adults, each contributing one index hospitalization (Fig. 1).

In this primary cohort, the proportion of patients with concomitant clinically recognized IE defined by the strict ICD code set was 9.68 % (97 of 1002). Using a broader IE definition, the proportion was 10.38 % (104 of 1002). Alternative cohort definitions yielded estimates in the same range: 8.83 % (81 of 917) in the strict vertebral osteomyelitis cohort and 10.59 % (70 of 661) in the ICD-10-only cohort. Across these definitions, the proportion of patients with clinically recognized IE was near one in 10 (Table 1).

Selected characteristics by IE status are shown in Table 2. Patients with and without IE were of similar age (mean 60.3 versus 59.2 years), and women comprised 34.0 % versus 40.9 %. Cardiac or other implanted-device diagnoses were more frequent among patients with IE (13.4 % versus 7.2 %). Blood cultures were obtained in nearly all patients, regardless of IE status (100.0 % versus 94.1 %), so culture-positivity differences are less likely to reflect differential sampling alone. A positive blood culture was recorded in 74.2 % of patients with IE versus 30.1 % of those without. Typical IE organisms were more common in the IE group, including *Staphylococcus aureus* (37.1 % versus 16.2 %), *Streptococcus* spp. (15.5 % versus 3.6 %), and *Enterococcus* spp. (9.3 % versus 1.9 %). Repeated same-group positive blood cultures (49.5 % versus 14.6 %) and the persistent $\geq$ 48 h proxy (30.9 % versus 8.5 %) were also more frequent, as were septic pulmonary emboli (16.5 % versus 1.4 %). These are unadjusted comparisons; adjusted associations are presented below.

In the prespecified adjusted microbiologic model excluding septic pulmonary emboli (Table 3), clinically recognized IE was associated with *Enterococcus* spp. (adjusted OR 3.35, 95 % CI 1.30–8.68), *Streptococcus* spp. (OR 5.25, 95 % CI 2.53–10.90), and repeated same-group positive blood cultures (OR 4.03, 95 % CI 2.17–7.51). The association with *Staphylococcus aureus* was not significant (OR 1.47, 95 % CI 0.77–2.82). None of the demographic, coding-era, admission, or implanted-device covariates was significantly associated with IE. A microbiology-only model yielded similar associations for *Enterococcus* spp., *Streptococcus* spp., and repeated same-group positive blood cultures (Table S3).

In a secondary phenotype model where septic pulmonary emboli were added (Table 4), these showed the strongest association with clinically recognized IE (adjusted OR 9.47, 95 % CI 3.89–23.07). Associations with *Enterococcus* spp. (OR 3.43, 95 % CI 1.30–9.04), *Streptococcus* spp. (OR 4.80, 95 % CI 2.26–10.20), and repeated same-group positive blood cultures (OR 3.67, 95 % CI 1.93–6.96) remained similar to the primary model, and *Staphylococcus aureus* remained non-significant (OR 1.25, 95 % CI 0.63–2.45). Because septic pulmonary emboli may represent manifestations or complications of endovascular infection, this association was interpreted as reflecting co-occurring embolic and endovascular disease without implying causality.

All six prespecified sensitivity analyses generally supported the primary findings (Table S5). The associations of *Streptococcus* spp. and the repeated or persistent culture-positivity measures were preserved across all six analyses. *Enterococcus* spp. remained directionally consistent but was estimated less precisely in the ICD-10-only and positive-culture-only analyses, with confidence intervals crossing the null. Estimates were generally attenuated in the smaller positive-culture-only subgroup. When repeated same-group positive blood cultures were replaced by the persistent $\geq$ 48 h proxy, associations for *Enterococcus* spp., *Streptococcus*

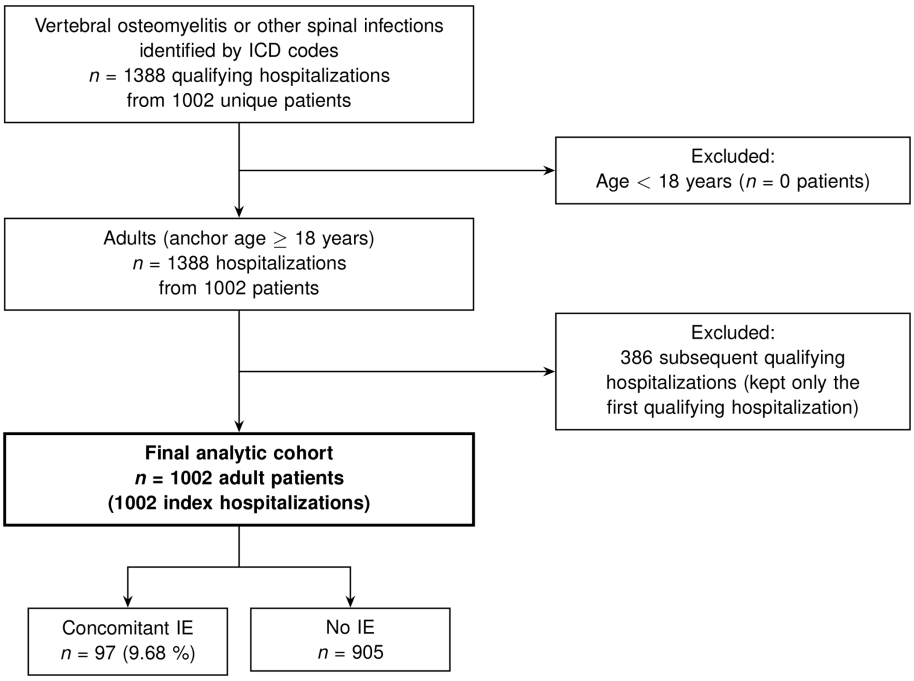

Figure 1. Cohort flow.

Table 1. Proportion of clinically recognized IE across case and cohort definitions.

Definition	IE/N	Proportion
Primary (expanded spinal infection cohort, strict IE codes)	97/1002	9.68 %
Broader IE definition	104/1002	10.38 %
Strict vertebral osteomyelitis cohort	81/917	8.83 %
ICD-10-only cohort	70/661	10.59 %

Proportion of clinically recognized, coded IE under alternative case and cohort definitions. Estimates remained near one in 10 across definitions.

spp., and the persistent proxy remained, and *Staphylococcus aureus* was significant in this specification (adjusted OR 2.51, 95 % CI 1.45–4.35). When repeated same-group positive blood cultures were omitted from the primary model, the adjusted ORs were 3.68 (95 % CI 2.26–5.97) for *Staphylococcus aureus*, 5.48 (95 % CI 2.21–13.58) for *Enterococcus* spp., and 6.46 (95 % CI 3.18–13.12) for *Streptococcus* spp. (Table S3, Panel C). Adding an age-free Charlson comorbidity score to the primary model left the microbiologic associations essentially unchanged, and the score was not itself associated with coded IE (Table S8).

Patients with clinically recognized IE had longer hospitalizations. Crude mean length of stay was 21.5 versus 14.5 d and median 15 versus 9 d, and prolonged hospitalization was more common in the IE group, including length of stay of 14 d or more (53.6 % versus 32.3 %) and 21 d or more (38.1 % versus 16.8 %). After adjustment, IE remained associated with longer length of stay (adjusted length-of-stay ratio 1.33, 95 % CI 1.14–1.55), length of stay of 14 d or more (OR 1.81, 95 % CI 1.16–2.82), and 21 d or more (OR 2.18, 95 % CI 1.36–3.50). Crude mortality was numerically higher in the IE group at each time point, but associations with in-hospital, 30 d, 90 d, and 1-year mortality were not significant after adjustment. One-year mortality reflects database-ascertained mortality within 365 d of index admission. Full crude and adjusted estimates are provided in Table S6.

4 Discussion

In this large, real-world electronic health record cohort of adults hospitalized with vertebral osteomyelitis or other spinal infections, concomitant clinically recognized IE was present in approximately one in 10 patients, with similar proportions across alternative case and cohort definitions. After adjustment, IE was associated with *Enterococcus* spp., *Streptococcus* spp., and repeated same-group positive blood cultures, whereas the *Staphylococcus aureus* association was attenuated and non-significant. Septic pulmonary emboli co-occurred strongly with IE. IE was also associated with longer

Table 2. Selected cohort characteristics by clinically recognized IE status.

Characteristic	IE ($n = 97$)	No IE ($n = 905$)
Age, years, mean (median)	60.3 (64)	59.2 (60)
Female	33 (34.0 %)	370 (40.9 %)
ICD-10 era	70 (72.2 %)	591 (65.3 %)
Transfer-in admission	40 (41.2 %)	315 (34.8 %)
Strict vertebral osteomyelitis code	81 (83.5 %)	836 (92.4 %)
Cardiac or other implanted-device diagnosis	13 (13.4 %)	65 (7.2 %)
Blood culture obtained	97 (100.0 %)	852 (94.1 %)
Any positive blood culture	72 (74.2 %)	272 (30.1 %)
Staphylococcus aureus	36 (37.1 %)	147 (16.2 %)
Streptococcus spp.	15 (15.5 %)	33 (3.6 %)
Enterococcus spp.	9 (9.3 %)	17 (1.9 %)
Repeated same-group positive blood cultures	48 (49.5 %)	132 (14.6 %)
Persistent $\geq$ 48 h proxy	30 (30.9 %)	77 (8.5 %)
Septic pulmonary emboli	16 (16.5 %)	13 (1.4 %)

Data are *n* (%) unless otherwise stated. Comparisons are unadjusted; no hypothesis testing was performed for this table. Blood culture "obtained" reflects any recorded blood-culture event; organism indicators are at the patient level and not mutually exclusive.

Table 3. Prespecified adjusted microbiologic model for clinically recognized IE (primary model, excluding septic pulmonary emboli).

Variable	Adjusted OR (95 % CI)
Microbiologic phenotype variables	
Staphylococcus aureus	1.47 (0.77–2.82)
Enterococcus spp.	3.35 (1.30–8.68)
Streptococcus spp.	5.25 (2.53–10.90)
Repeated same-group positive blood cultures	4.03 (2.17–7.51)
Adjustment covariates	
Age, per 10 years	1.02 (0.88–1.19)
Female sex	0.98 (0.61–1.56)
ICD-10 era	0.93 (0.55–1.59)
Transfer-in admission	1.44 (0.89–2.32)
Cardiac or other implanted-device diagnosis	1.54 (0.76–3.11)

The model was prespecified and adjusted for all variables shown; septic pulmonary emboli were excluded and evaluated in a secondary model (Table 4). A microbiology-only supportive model gave similar associations (Table S3). *p* values for the primary model are provided in Table S3, Panel A.

hospitalization, whereas adjusted mortality associations were not significant.

Prior estimates of the overlap between spinal infection and IE vary substantially, reflecting differences in denominator definitions, referral patterns, and echocardiographic ascertainment. A recent systematic review and meta-analysis of 16 studies summarized this heterogeneous literature (Borgonovo et al., 2025). A contemporary spondylodiscitis cohort reported concomitant IE in approximately 9.9 % of patients (von der Höh et al., 2025), whereas a tertiary-referral pyogenic vertebral osteomyelitis cohort in which IE was specifically sought reported approximately 30.8 % (Pigrau et al., 2005), illustrating the influence of case selection and ascertainment. In the present study, the proportion of patients with clinically recognized, coded IE was approximately one in 10.

The streptococcal and enterococcal associations are consistent with the recognized role of these organisms in IE (Baddour et al., 2015). Streptococci, *Staphylococcus aureus*, and enterococci were the three most frequently reported pathogen groups in the recent systematic review and meta-analysis (Borgonovo et al., 2025). Repeated-culture measures were among the most consistent correlates of clinically recognized IE across the prespecified sensitivity analyses, although these EHR-derived measures do not establish adjudicated persistent bacteremia. *Staphylococcus aureus* warrants particular caution. Although it was numerically more common among patients with IE and is a leading cause of IE generally (Selton-Suty et al., 2012; Baddour et al., 2015), its adjusted association was attenuated and non-significant. Its common occurrence in vertebral osteomyelitis (Berbari et al., 2015) and overlap with repeated-culture positivity may

Table 4. Secondary phenotype model including septic pulmonary emboli (SPE).

Variable	Adjusted OR (95 % CI)
Microbiologic and embolic phenotype variables	
Septic pulmonary emboli	9.47 (3.89–23.07)
Staphylococcus aureus	1.25 (0.63–2.45)
Enterococcus spp.	3.43 (1.30–9.04)
Streptococcus spp.	4.80 (2.26–10.20)
Repeated same-group positive blood cultures	3.67 (1.93–6.96)
Adjustment covariates	
Age, per 10 years	1.12 (0.95–1.32)
Female sex	0.97 (0.60–1.57)
ICD-10 era	0.89 (0.52–1.53)
Transfer-in admission	1.28 (0.78–2.11)
Cardiac or other implanted-device diagnosis	1.52 (0.74–3.13)

The secondary phenotype model included the same variables as the primary adjusted model (Table 3), with the addition of septic pulmonary emboli. SPE were interpreted as a co-occurring embolic and endovascular marker. *p* values are provided in Table S4.

have contributed to this attenuation, and differential diagnostic evaluation, organism-driven echocardiography, and selection effects may also have influenced the estimate. Consistent with this potential overlap, the *S. aureus* estimate was stronger both under the persistent ≥ 48 h proxy specification and in the post hoc model omitting repeated same-group positive blood cultures (OR 3.68, 95 % CI 2.26–5.97), indicating sensitivity to how repeated-culture information was handled.

Septic pulmonary emboli co-occurred strongly with clinically recognized IE, consistent with a concurrent embolic and endovascular phenotype. Although septic pulmonary emboli are a recognized manifestation of right-sided IE (Baddour et al., 2015), MIMIC-IV lacks valve-level echocardiographic findings, and left-sided involvement predominated in a contemporary spondylodiscitis-IE cohort (von der Höh et al., 2025). Because septic pulmonary emboli are commonly recognized on chest CT (Kuhlman et al., 1990), their presence in patients with spinal infection may prompt endocarditis evaluation and subsequent IE coding, particularly alongside streptococcal or enterococcal bacteremia or repeated same-group positive blood cultures. The observed association may therefore reflect both underlying biology and differential diagnostic evaluation.

Clinically recognized IE was associated with longer hospitalization, including higher adjusted odds of length of stay of 14 and 21 d or more. Length of stay should be interpreted cautiously because in-hospital death is a competing event that can make stays appear shorter among more severely ill patients. Strengths include a relatively large, hospital-wide cohort not restricted to ICU admissions, selection of the first qualifying hospitalization per patient, transparent ICD- and microbiology-based definitions, and multiple sensitivity analyses. Limitations include the single-center design and reliance on diagnosis codes for both cohort and IE definitions. IE was not adjudicated using Duke or ISCVID criteria or chart review, and coded outcomes may be misclassified, with uncertain direction because diagnostic evaluation may differ by microbiology and embolic findings. Echocardiographic findings and valve-level localization were unavailable, limiting interpretation of septic pulmonary emboli and diagnostic workup. The *Streptococcus* spp. category was heterogeneous, including viridans streptococci and pneumococci, which differ in IE propensity; the pooled association may therefore not apply uniformly across streptococcal subgroups. Species-level ascertainment was also limited. Residual confounding remains possible; the primary model was intentionally parsimonious, although the post hoc Charlson-adjusted sensitivity analysis left the microbiologic associations essentially unchanged (Table S8). Spinal infection codes, particularly ICD-9-CM 730.28, may mix phenotypes and incompletely distinguish postoperative or hardware-associated cases. The cardiac or other implanted-device covariate was broadly defined and may not correspond precisely to prosthetic heart valves. Finally, mortality analyses relied on database-ascertained death dates, so longer-term mortality estimates warrant caution.

5 Conclusions

In this large, real-world EHR cohort of adults hospitalized with vertebral osteomyelitis or other spinal infections, concomitant clinically recognized IE was identified in approximately one in 10 patients, with similar proportions across alternative case and cohort definitions. Coded IE clustered with streptococcal and enterococcal bacteremia, repeated same-group positive blood cultures, and septic pulmonary emboli, consistent with an endovascular and disseminated infection phenotype. These findings define an IE-associated phenotype in routine care and warrant confirmation in cohorts with systematic echocardiographic and microbiologic adjudication.

Code and data availability. Individual-level MIMIC-IV data cannot be redistributed under the PhysioNet Credentialed Health Data Use Agreement. The extraction queries, analysis code, and aggregate outputs are archived on Zenodo (https://doi.org/10.5281/zenodo.21232560; Liu et al., 2026); credentialed users can regenerate the datasets from MIMIC-IV v3.1 using the provided queries.

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Author contributions. JL: conceptualization, data curation, formal analysis, methodology, software, visualization, and writing (original draft, and review and editing). WG: conceptualization, methodology, validation, visualization, and writing (original draft, and review and editing). RAS: conceptualization, supervision, and writing (review and editing), including radiological input on septic pulmonary emboli. All authors reviewed and approved the final article.

Competing interests. The contact author has declared that none of the authors has any competing interests.

Ethical statement. This study used MIMIC-IV version 3.1, a publicly available, restricted-access, de-identified electronic health record database derived from Beth Israel Deaconess Medical Center (Boston, MA, USA). The collection of patient information and creation of the MIMIC-IV research resource were reviewed by the Institutional Review Board of Beth Israel Deaconess Medical Center, which approved the data-sharing initiative and granted a waiver of informed consent. This secondary analysis used only de-identified data and involved no direct interaction with patients or access to identifiable information; therefore, no additional patient consent was required. Jinghao Liu completed the required CITI Program training and accessed MIMIC-IV version 3.1 as a credentialed PhysioNet user under the PhysioNet Credentialed Health Data Use Agreement. Access to record-level MIMIC-IV data was limited to Jinghao Liu; co-authors contributed to study design, interpretation, supervision, and paper revision without accessing record-level data.

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