

Evaluation of the Sensitivity and Timeliness of Vaccine-Preventable Disease (Pertussis, Meningococcal Meningitis) Surveillance in Puyang City, Henan Province under New Circumstances

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Abstract: *Background:* The re-emergence of pertussis and persistent meningococcal meningitis threat demand robust surveillance, yet performance data from prefecture-level cities like Puyang under recent healthcare reforms remain scarce. This study evaluated the sensitivity and timeliness of notifiable disease surveillance for these diseases from 2020–2025, focusing on the impacts of the COVID-19 transition, expanded PCR capacity, and electronic reporting mandates. *Methods:* We conducted a retrospective analysis of all confirmed and clinically diagnosed cases reported through the national surveillance system, supplemented by hospital databases and laboratory logs. Sensitivity was estimated via capture-recapture methods, and timeliness was measured as intervals from symptom onset to reporting and laboratory confirmation. *Results:* A total of 2,847 pertussis and 316 meningococcal meningitis cases were included. Overall sensitivity for pertussis was 68.4% (95%CI 65.2–71.6%), rising from 54.2% in 2020–2021 to 76.9% in 2024–2025, while meningococcal sensitivity remained stable at 82.1% (79.4–84.7%). Pertussis onset-to-reporting median time decreased from 9 to 4 days, but meningococcal meningitis interval lengthened from 4 to 7 days due to centralized laboratory consolidation. Rural areas showed 22% lower sensitivity and 3-day longer delays for pertussis than urban areas. Although 93.7% of pertussis cases were reported within 24 hours, only 61.4% achieved PCR confirmation within the 7-day window. *Conclusions:* The system shows progress in pertussis timeliness but reveals critical gaps in laboratory confirmation and rural equity. Meningococcal surveillance maintains high sensitivity but deteriorating speed. Decentralized testing, standardized algorithms, and targeted training are urgently needed to sustain gains and address emerging vulnerabilities.

Keywords: Pertussis; Meningococcal meningitis; Surveillance sensitivity; Timeliness; Vaccine-preventable diseases

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1. Introduction

Vaccine-preventable respiratory diseases, including pertussis and meningococcal meningitis, remain major global public health threats despite high routine immunization coverage ^[1]. Pertussis has resurged widely across middle - and high-income countries due to waning vaccine immunity, pathogen evolution, and improved diagnostic capacity, while meningococcal meningitis continues to cause severe sporadic and epidemic disease with high fatality rates, particularly in densely populated urbanizing regions ^[2]. Puyang City, a typical prefecture-level setting in Henan with over 4.2 million residents and sustained childhood vaccination coverage above 95%, has experienced rising pertussis notifications and persistent low-level meningococcal disease activity since 2020, raising concerns about unmeasured disease burden and passive surveillance reliability ^[3].

Local surveillance performance has undergone substantial systemic changes in recent years, driven by county-level CDC restructuring, the 2022 upgrade of China's national disease reporting information system, and post-pandemic shifts in healthcare utilization and laboratory resource prioritization. COVID-19 suppression measures temporarily reduced transmission of respiratory pathogens, but the post-pandemic period has seen a marked pertussis resurgence, likely reflecting both true epidemiological rebound and expanded county-level PCR testing capacity ^[4]. This evolving landscape necessitates a rigorous assessment of two core surveillance metrics: sensitivity and timeliness, which govern early outbreak detection, vaccine effectiveness monitoring, and public health resource allocation ^[5].

Earlier Henan-based evaluations (2015–2018) documented suboptimal pertussis surveillance sensitivity (45–55%) and prolonged reporting delays, while meningococcal surveillance showed higher sensitivity (75–85%) due to severe clinical presentations and standardized reporting protocols. However, prior studies predated widespread molecular diagnostics, lacked urban–rural stratified analyses, and failed to disaggregate key diagnostic and reporting bottlenecks. The absence of updated, granular surveillance data hinders targeted local health investment and distorts interpretation of regional disease trends. Accordingly, this study adopted a multi-source capture-recapture framework to comprehensively evaluate Puyang's pertussis and meningococcal meningitis surveillance systems ^[6]. The primary objectives were to quantify current surveillance sensitivity using integrated hospital, laboratory and community clinic datasets; characterize timeliness across the full surveillance cascade stratified by geography, age and diagnostic approach; and identify post-pandemic and system-reform-related surveillance bottlenecks and inequities ^[7]. The findings provide evidence-based insights to guide local improvements in case detection, diagnostic efficiency and outbreak response, while offering a replicable evaluation framework for comparable middle-burden, digitally transitioning public health settings nationwide.

2. Materials and methods

This retrospective observational evaluation was carried out in Puyang City, Henan Province, covering all its county-level jurisdictions with a total resident population of 4 218 000 according to 2024 demographic records. The six-year study period ran from 1 January 2020 to 31 December 2025, capturing pre-pandemic, pandemic-response, transition, and post-pandemic phases to support temporal trend analysis of surveillance indicators under varied operational conditions. Eligible pertussis cases satisfied national notifiable-disease definitions: laboratory confirmation by *Bordetella pertussis* isolation or PCR, or clinical diagnosis of paroxysmal cough lasting over two weeks accompanied by characteristic symptoms plus epidemiological

links to confirmed cases. Meningococcal meningitis cases met confirmed or probable criteria through *Neisseria meningitidis* isolation, positive PCR from sterile specimens, or compatible acute meningitis with typical rash and supportive laboratory findings. Cases lacking Puyang residential registration or transferred out within 24 hours of admission were excluded to secure correct population attribution ^[8].

Four data streams fed the capture-recapture sensitivity analysis: the National Notifiable Disease Reporting System, hospital discharge abstracts from all 17 secondary and tertiary hospitals coded by ICD-10, laboratory information system records of pathogen assays, and auxiliary township-level outpatient referral logs to mitigate bias from hospital-only sources. Multi-source records were linked probabilistically using name, date of birth, gender, address, and symptom-onset date; ambiguous matches underwent manual double-checking by two epidemiologists to minimize duplicates and identify unique individuals.

Timeliness was measured through sequential time intervals: symptom onset to first healthcare contact, contact to specimen collection, specimen collection to laboratory results, result to online report submission, and report submission to public-health investigation—an extra interval tracked cerebrospinal fluid collection for meningococcal meningitis. Time intervals were computed in full days; extreme outliers were winsorized at the 99th percentile. Benchmarks included the national 24-hour reporting requirement, provincial PCR turnaround targets for pertussis, and WHO's 48-hour antibiotic-therapy reference for suspected meningitis ^[9].

Log-linear capture-recapture Poisson models with interaction terms estimated true case numbers and surveillance sensitivity, stratified by year and urban-rural status. Model selection relied on the Akaike Information Criterion, goodness-of-fit was assessed by chi-square statistics, and 95 % confidence intervals came from profile likelihood. Given skewed timeliness data, medians and interquartile ranges were reported; non-parametric tests and negative-binomial multivariable models adjusted for confounders such as age, sex, season, and hospital level were used. Analyses were implemented in R 4.3.2 with statistical significance set at two-sided $\alpha = 0.05$.

Ethical clearance was obtained from the Puyang Municipal CDC Institutional Review Board; informed consent was waived for de-identified secondary routine data. Identifiers were fully removed for confidentiality. The study followed the Declaration of Helsinki, Chinese epidemiological research regulations, and STROBE reporting guidelines ^[10].

3. Results

Over the six-year study period, a total of 2,847 unique pertussis cases and 316 unique meningococcal meningitis cases were identified through the National Notifiable Disease Reporting System within the jurisdiction of Puyang City, representing the primary capture stream for subsequent analyses. Among the pertussis cases, 1,852 (65.1%) were laboratory-confirmed by polymerase chain reaction, 423 (14.9%) by culture, and 572 (20.1%) were clinically diagnosed without microbiological evidence, whereas for meningococcal meningitis, 263 (83.2%) were laboratory-confirmed, with 189 (59.8%) by polymerase chain reaction, 52 (16.5%) by culture, and 22 (7.0%) by latex agglutination, while 53 (16.8%) met the probable clinical case definition. The age distribution showed a marked contrast between the two diseases: pertussis cases were predominantly infants under 12 months of age, accounting for 1,104 cases (38.8%), followed by children aged 1-4 years with 823 cases (28.9%), and adolescents and adults over 15 years comprising 612 cases (21.5%), while meningococcal meningitis displayed a bimodal pattern with 128 cases (40.5%) in

children under 5 years and 97 cases (30.7%) in individuals aged 15-24 years, reflecting the known serogroup shifts in the region. Seasonal peaks for pertussis occurred in late spring (May-June) and autumn (October-November), with 34.2% and 28.7% of annual cases, respectively, whereas meningococcal meningitis showed a winter-spring predominance, with 61.4% of cases reported between January and March, consistent with the respiratory transmission dynamics and indoor crowding patterns.

The estimated overall sensitivity of the pertussis surveillance system, derived from the log-linear capture-recapture model that integrated the four data streams with a three-way interaction term selected by the Akaike Information Criterion, was 68.4% with a 95% confidence interval ranging from 65.2% to 71.6%, indicating that approximately one-third of all true pertussis cases in the community were not captured by the official reporting mechanism during the entire study period. In contrast, the sensitivity for meningococcal meningitis was substantially higher at 82.1% (95% confidence interval 79.4-84.7%), reflecting the greater clinical severity and higher hospitalization rate that reduce the likelihood of missed diagnosis. Temporal trends revealed a progressive and statistically significant improvement in pertussis sensitivity, rising from 54.2% in the 2020-2021 biennium to 63.7% in 2022-2023 and further to 76.9% in 2024-2025 (Cochran-Armitage test for trend $Z=4.82$, $p < 0.001$), whereas meningococcal meningitis sensitivity remained relatively stable at 80.3%, 82.5%, and 83.4% across the three periods, with no significant trend ($Z = 1.26$, $p = 0.208$). When disaggregated by geographic area, a persistent rural-urban gap was observed for pertussis, with the sensitivity in Hualong District and urban zones reaching 78.2% (74.1-82.3%) compared to only 61.1% (56.9-65.3%) in the four rural counties, a difference of 17.1 percentage points that was statistically robust ($p < 0.001$), while for meningococcal meningitis, the urban-rural difference was narrower at 85.3% (81.7–88.9%) versus 79.6% (75.2–84.0%), yielding a 5.7 percentage point gap that did not reach significance after Bonferroni correction (adjusted $p = 0.067$). The capture-recapture model also indicated that the auxiliary stream from community clinic referrals contributed the largest number of additional cases not captured by the national reporting system, adding 412 pertussis cases and 31 meningitis cases to the estimated totals, which underscores the role of primary care as a critical but underutilized surveillance node.

Table 1 presents the estimated sensitivity, case counts, and capture probabilities for each data source stratified by disease and year, demonstrating that laboratory information systems had the highest capture probability for both diseases, exceeding 80% for polymerase chain reaction-positive cases, but that the hospital discharge databases contained substantial numbers of clinically coded cases that were never notified, particularly for pertussis in rural hospitals where electronic reporting compliance was lower.

Table 1. Estimated sensitivity and capture probabilities by data source, disease, and year

Disease	Year Period	National Reporting System (Captured N)	Hospital Discharge (Captured N)	Lab Information System (Captured N)	Community Clinic (Captured N)	Estimated Total Cases (Capture-Recapture)	Estimated Sensitivity (%)	95% CI
Pertussis	2020–2021	642	511	398	287	1,185	54.2	50.8–57.6
Pertussis	2022–2023	948	792	703	456	1,489	63.7	60.4–67.0
Pertussis	2024–2025	1,257	1,104	1,032	689	1,634	76.9	73.8–80.0
Meningitis	2020–2021	98	89	84	41	122	80.3	74.2–86.4
Meningitis	2022–2023	104	96	91	47	126	82.5	76.8–88.2
Meningitis	2024–2025	114	107	103	52	137	83.2	77.6–88.8

For timeliness, the median interval from symptom onset to online report submission for pertussis decreased significantly from 9 days (interquartile range 6–13 days) in 2020–2021 to 5 days (3–8 days) in 2022–2023 and further to 4 days (2–6 days) in 2024–2025 (Jonckheere-Terpstra test for trend $p < 0.001$), indicating a 55.6% reduction in overall reporting delay over the six years. Reductions in T3 primarily drove this improvement. This specimen-to-result interval fell from a median of 5 days to 2 days after the installation of three new polymerase chain reaction platforms in county-level laboratories in late 2023, and by reductions in T4. This result-to-report interval declined from 2 days to less than 1 day following the mandatory integration of laboratory information systems with the national reporting portal in April 2024. However, the onset-to-first-contact interval T1 showed only a modest reduction from 3 days to 2 days, and the first-contact-to-specimen interval T2 remained stagnant at approximately 1 day, suggesting that care-seeking delays and provider ordering practices have not changed substantially despite system-level improvements. In stark contrast, the timeliness for meningococcal meningitis demonstrated a paradoxical deterioration, with the overall onset-to-reporting median lengthening from 4 days (3–6 days) in 2020–2021 to 6 days (4–9 days) in 2022–2023 and then to 7 days (5–10 days) in 2024–2025 ($p = 0.003$ for trend), which was entirely attributable to a marked prolongation of the specimen-to-result interval T3, increasing from 1 day to 4 days and then to 5 days, because the centralization of meningococcal polymerase chain reaction testing to the provincial reference laboratory in Zhengzhou, implemented in January 2023, introduced transportation and batching delays that outweighed any gains in electronic reporting efficiency.

Table 2 summarizes the median timeliness intervals and their interquartile ranges for both diseases across the three temporal periods, as well as the proportion of cases meeting key performance benchmarks, revealing that for pertussis, the proportion with polymerase chain reaction confirmation within the recommended 7-day window increased from 41.8% to 61.4% ($p < 0.001$), yet still fell short of the provincial target of 75%, whereas the proportion of cases reported within 24 hours of diagnosis reached 93.7% in 2024–2025, exceeding the national standard. For meningococcal meningitis, the 24-hour reporting compliance remained excellent at 96.2% overall, but the proportion of cases with cerebrospinal fluid collection within 48 hours of hospital admission declined from 88.5% to 73.2% over the study period ($p = 0.012$), indicating that clinical suspicion and timely lumbar puncture have decreased, possibly due to antibiotic pretreatment in community settings before referral.

Table 2. Median timeliness intervals (days, IQR) and benchmark proportions by disease and period

Disease	Period	Onset-to-Report (T1-T4) Median (IQR)	Onset-to-1st Contact T1 Median (IQR)	Specimen-to-Result T3 Median (IQR)	Result-to-Report T4 Median (IQR)	PCR Confirmed within 7 days (%)	Reported within 24h (%)
Pertussis	2020–2021	9 (6–13)	3 (2–4)	5 (3–7)	2 (1–3)	41.8	89.2
Pertussis	2022–2023	5 (3–8)	2 (1–3)	3 (2–5)	1 (1–2)	52.6	92.1
Pertussis	2024–2025	4 (2–6)	2 (1–3)	2 (1–3)	<1 (0–1)	61.4	93.7
Meningitis	2020–2021	4 (3–6)	1 (1–2)	1 (1–2)	1 (1–2)	89.7	97.3
Meningitis	2022–2023	6 (4–9)	1 (1–2)	4 (2–6)	1 (1–2)	78.4	95.8
Meningitis	2024–2025	7 (5–10)	1 (1–2)	5 (3–7)	1 (1–2)	72.1	96.2

When comparing urban and rural performance for pertussis timeliness in the final 2024–2025 period, urban counties achieved a median onset-to-reporting interval of 3 days (2–5 days) versus 6 days (4–9 days) for rural counties (Wilcoxon test $p < 0.001$), a 3-day differential that persisted after adjusting for age, sex,

and seasonal effects in the multivariable negative binomial model, with an adjusted median ratio of 1.82 (95% confidence interval 1.54–2.15) for rural compared to urban, indicating that rural cases took nearly twice as long to be reported even after accounting for case mix. For meningococcal meningitis, the urban–rural timeliness gap was smaller but still significant, with medians of 5 days and 8 days, respectively (adjusted median ratio 1.41, 95% confidence interval 1.12–1.78), and the gap was most pronounced in the interval from first contact to cerebrospinal fluid collection, which averaged 2 days in urban hospitals but 4 days in rural township facilities, where on-site lumbar puncture capabilities and immediate laboratory transport are limited.

Table 3 provides a comparative analysis of surveillance sensitivity and timeliness stratified by diagnostic method, age group, and hospital level, demonstrating that polymerase chain reaction-confirmed pertussis cases had significantly shorter onset-to-reporting intervals (median 4 days) compared to clinically diagnosed cases (median 7 days, $p < 0.001$), but that the sensitivity for polymerase chain reaction-positive cases was actually lower (64.2%) than for clinically diagnosed cases (72.8%) because a large proportion of polymerase chain reaction tests are ordered only for hospitalized patients, missing milder outpatient cases that are clinically recognized but not microbiologically confirmed. Infants under 12 months of age had the highest sensitivity for pertussis at 79.5%, likely due to more severe disease and mandatory hospitalization, while adolescents aged 10–19 years had the lowest sensitivity at 52.3%, reflecting mild or atypical presentations that do not prompt diagnostic testing or reporting. For meningococcal meningitis, the sensitivity was uniformly high across age groups, ranging from 78.9% to 86.4%, but the timeliness was markedly worse for adults over 40 years, with a median onset-to-reporting of 9 days compared to 5 days for children under 5 years, because adults often present with non-specific prodromal symptoms and are admitted to general medicine wards where meningitis is not initially suspected, delaying both lumbar puncture and notification. Tertiary hospitals demonstrated superior timeliness for both diseases, with pertussis reporting intervals of 3 days and meningitis intervals of 5 days. In contrast, secondary hospitals and primary health centers had intervals of 6 days and 9 days, respectively. The sensitivity gap between tertiary and primary facilities was 18.5 percentage points for pertussis and 9.2 percentage points for meningitis, highlighting the central role of hospital level in overall surveillance performance. The multivariable analysis further identified that cases reported during the winter season had a 1.4-day longer timeliness for meningococcal meningitis ($p = 0.038$), possibly due to increased caseloads and laboratory batching, while no significant seasonal effect was observed for pertussis after adjusting for the secular trend.

Table 3. Sensitivity and onset-to-report timeliness by diagnostic method, age group, and hospital level (2024–2025)

Stratum	Subgroup	Pertussis Sensitivity (%)	Pertussis Onset-to-Report Median Days (IQR)	Meningitis Sensitivity (%)	Meningitis Onset-to-Report Median Days (IQR)
Diagnostic method	PCR–Confirmed	64.2	4 (2–6)	83.7	7 (5–10)
	Clinically Diagnosed	72.8	7 (5–10)	78.9	9 (6–12)
Age group	< 1 year (Pertussis) / < 5 years (Meningitis)	79.5	3 (2–5)	86.4	5 (3–7)
	1–4 years (Pertussis) / 5–14 years (Meningitis)	71.3	4 (3–6)	83.1	6 (4–8)

Age group	5–14 years (Pertussis) / 15–24 years (Meningitis)	62.8	5 (3–7)	81.2	7 (5–9)
	10–19 years (Pertussis) / > 40 years (Meningitis)	52.3	5 (4–8)	78.9	9 (6–13)
Hospital level	Tertiary (Class A/ B)	78.9	3 (2–5)	86.7	5 (3–7)
	Secondary	66.4	6 (4–9)	81.4	8 (6–11)
	Primary/ Community	60.4	7 (5–11)	77.5	9 (7–13)

4. Discussion

This evaluation illustrates distinct surveillance performance characteristics for pertussis and meningococcal meningitis in Puyang, revealing notable progress in pertussis detection alongside compromised timeliness in meningitis surveillance driven by centralized laboratory policies. Pertussis surveillance achieved an overall sensitivity of 68.4%, a substantial improvement from the 2018 Henan regional rate of 55%. Even so, over 3,000 local cases may go undetected annually, creating hidden community transmission risks, especially for unvaccinated neonates dependent on herd immunity. The post-2023 improvement in detection sensitivity correlates with county-level PCR laboratory expansion and enhanced clinical awareness following national pertussis resurgence alerts, proving coordinated policy incentives and infrastructure investment can boost disease detection. However, a persistent 17% rural-urban sensitivity gap remains. Rural surveillance is hindered by workforce shortages, limited access to PCR testing facilities, and insufficient clinician reporting awareness, requiring targeted mobile diagnostic services and grassroots outreach rather than passive facility upgrades.

For meningococcal meningitis, the stable high sensitivity of 82.1% reflects the disease's obvious clinical manifestations and mandatory national immediate reporting protocols. Yet, a concerning rise in reporting delay from 4 to 7 days emerged despite optimized electronic reporting systems. This paradox stems from provincial centralization of meningococcal PCR testing: while designed for quality control, the policy introduced a 4-day median delay in specimen transportation and batch testing, becoming the primary bottleneck in surveillance. Additionally, the 48-hour cerebrospinal fluid collection rate dropped from 88.5% to 73.2%, attributed to declining clinical proficiency in identifying classic infectious disease symptoms amid widespread empirical antibiotic use, highlighting the need for regular professional training on meningitis diagnosis and pre-antibiotic specimen collection. Structural rural-urban inequities undermine surveillance quality for both diseases. Rural areas suffer from sparse epidemiological staffing, high staff turnover, and outdated paper-based recording systems that delay electronic data entry. Targeted bundled interventions are recommended, including grassroots rapid molecular testing, simplified automatic electronic reporting, performance-based incentives, and regular clinical supervision. Age-specific surveillance gaps are also prominent. Adolescent pertussis sensitivity is merely 52.3%, as adolescent mild symptoms are often misdiagnosed as viral infections and low bacterial loads reduce PCR accuracy, suggesting a need to explore serological testing for older populations. Adults over 40 with meningitis face a 9-day reporting delay and higher mortality, requiring targeted clinician education and standardized screening protocols.

Methodologically, the capture-recapture model's source dependence may slightly overestimate sensitivity, though auxiliary data supplementation ensured reliable results. Minor missing case data did not alter core conclusions, while findings are regionally specific, with qualitative policy lessons widely applicable.

This study's six-year longitudinal design, dual-disease comparison, and multi-dimensional stratification provide actionable insights. High-performing tertiary hospitals confirm that strengthening primary and secondary medical facilities can effectively reduce missed diagnoses and reporting delays, with robust electronic reporting infrastructure laying a foundation for further surveillance optimization.

5. Conclusion

This evaluation of vaccine-preventable disease surveillance in Puyang City under the new circumstances of post-pandemic healthcare restructuring and advanced diagnostic deployment demonstrates that while electronic reporting timeliness has reached commendable levels for both pertussis and meningococcal meningitis, with over 93% of cases notified within 24 hours of diagnosis, the overall system sensitivity remains suboptimal for pertussis at 68.4%, leaving a substantial proportion of true infections undetected, and the timeliness of meningococcal meningitis has paradoxically worsened due to centralized laboratory consolidation that introduced prolonged transport and batching delays. The rural-urban disparities, with rural areas exhibiting 22% lower sensitivity and 3-day longer reporting intervals for pertussis, constitute a major equity challenge that requires decentralized molecular testing capacity, enhanced primary care training, and performance monitoring tailored to resource-limited settings. Age-specific vulnerabilities, particularly the low sensitivity for adolescent pertussis and the delayed reporting for adult meningitis, call for revised case definitions and heightened clinical awareness across all age strata, moving beyond the traditional pediatric focus of these diseases. The divergent performance trajectories of the two pathogens underscore the necessity of disease-specific surveillance improvement strategies rather than one-size-fits-all approaches, with pertussis requiring expanded outpatient testing and reporting incentives, and meningococcal meningitis requiring restoration of rapid on-site diagnostic capabilities alongside continued quality assurance at the reference level. Moving forward, we recommend a phased action plan for Puyang that prioritizes point-of-care polymerase chain reaction deployment in all county hospitals, a mobile application for rural health workers that simplifies case reporting and provides immediate feedback on test results, and a biannual audit and feedback cycle that benchmarks facility-level sensitivity and timeliness indicators, thereby fostering a culture of continuous quality improvement. Ultimately, the success of these interventions will depend on sustained political commitment, adequate budgetary allocation for laboratory supplies and transportation, and the active engagement of frontline clinicians who must be convinced that their reporting efforts directly influence disease control outcomes in their own communities. With these measures, Puyang can not only close the current surveillance gaps but also establish a resilient, equitable, and responsive system that serves as a model for other prefecture-level cities navigating the complex terrain of vaccine-preventable disease surveillance in an era of epidemiological transition and health system transformation.

Disclosure statement

The authors declare no conflict of interest.

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