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Original article

Development and validation of selection algorithms for a non-ventilator hospital-acquired pneumonia semi-automated surveillance system

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ABSTRACT

Objectives: Semi-automated surveillance systems save time compared with traditional manual methods, particularly for non-ventilator hospital-acquired pneumonia (nvHAP), a nosocomial infection which can affect all non-intubated patients. In semi-automated surveillance, a computerized algorithm selects patients with high probability (i.e. "at risk") for subsequent manual confirmation. This study aimed to evaluate the performance of several single indicators and algorithms to preselect patients at risk for nvHAP.

Methods: Single nvHAP indicators, identified based on literature, expert opinion and data availability, were combined to simple and complex algorithms. Both single indicators and algorithms were applied on a patient cohort of 157 902 patients, including 947 patients with nvHAP according to our reference standard, i.e. validated semi-automated nvHAP surveillance system plus the manual surveillance of patients with hospital-acquired pneumonia discharge diagnostic codes. Performance characteristics like sensitivity, workload reduction, and number of patients needed to be screened to detect one case of nvHAP were assessed.

Results: Compared with the reference standard, single indicators had a sensitivity ranging from 35.1% (332/947) (oxygen desaturation) to 99.7% (944/947) (radiologic procedure). The workload reduction varied from 57.3% (90 505/157 902) (length of hospital stay >5 days) to 98.4% (155 453/157 902) (ICD-10 discharge diagnostic code). The highest workload reduction was found in complex algorithms, e.g. the combination "radiologic procedure including full text AND temporally related abnormal white blood count or fever AND antimicrobials AND C-reactive protein AND decreased oxygenation AND hospital stay ≥5 days AND no intubation" which reduced the number of patients who have to undergo manual review by 96.2% (151 867/157 902), while maintaining a sensitivity of 92% (871/947). The number needed to screen applying this algorithm was 6.4 patients.

Discussion: Several single indicators and algorithms showed a high workload reduction and a sensitivity above the defined threshold of 90%. Our results could assist hospitals or stakeholders of surveillance initiatives in developing algorithms customized to their local conditions. **Anna Mueller, Clin Microbiol Infect 2025;31:582**

Introduction

Hospital-acquired pneumonia (HAP) is one of the most common healthcare-associated infections, accounting for 18–26% of all healthcare-associated infections [1–4]. Approximately two-thirds of HAP are not associated with the presence of an invasive respiratory device [2], and are considered non-ventilator hospital-acquired pneumonia (nvHAP). Most surveillance and prevention programmes focus on ventilator-associated pneumonia, even though nvHAP is more frequent, and costs and mortality are comparable with ventilator-associated pneumonia [5,6]. The potential benefits of preventing nvHAP are numerous and include shortened

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length of hospital stay, lower antibiotic use, reduced costs, and improved functional outcomes of patients [7,8]. Outcome-oriented prevention strategies depend on reliable surveillance data, to identify high-prevalence areas, and to evaluate prevention effectiveness [7,9].

Incidence surveillance of nvHAP is particularly challenging, as all patients without respiratory devices may develop nvHAP and risk factors for nvHAP are numerous [10]. Manual chart review is costly and time-consuming [11]. In view of the increasing availability of electronic data, fully or semi-automated surveillance are alternatives [12]. The University Hospital of Zurich (USZ) implemented a semi-automated surveillance system for nvHAP in 2017, applying the European Centre for Disease Prevention and Control (ECDC) HAP definitions [13]. The algorithm preselected patients at risk for nvHAP with high sensitivity and relevant reduction of workload of manual chart review [13].

Sensitivity represents the most important performance characteristic in semi-automated surveillance [9]. The "Providing a Roadmap for Automated Infection Surveillance in Europe" network defined a sensitivity threshold of 90% for semi-automated surveillance [14]. With the overarching aim to optimize the algorithm of our semi-automated nvHAP surveillance system and to provide algorithm options for hospitals interested to set up a semi-automated surveillance system, we tested sensitivity, specificity and workload reduction (WLR) of routine care data, either alone or combined, regarding their ability to reduce the number of patients for manual chart review while maintaining acceptable sensitivity for semi-automated nvHAP surveillance.

Methods

Study setting

The study was performed at USZ, a tertiary care University-affiliated hospital with 900 beds and approximately 40 000 admissions per year. The hospital covers all specialties except orthopaedics and paediatrics. We included all hospitalized patients >16 years with discharge in the years 2017–2019 and 2021.

The study was considered a quality improvement project and the necessity for formal ethical evaluation was waived by the Zurich Cantonal Ethics Commission (Req-2022-00573).

Patient collective with nvHAP

The reference standard was the semi-automated surveillance system of the USZ (a computerized classification algorithm mirroring ECDC criteria to select 'patients at risk', followed by a manual evaluation of these patients) [13], which was supplemented by a manual surveillance of all patients with an International Classification of Diseases, Tenth Revision (ICD-10) discharge diagnostic code for HAP. The computerized classification algorithm of the semi-automated surveillance system was shown to have a sensitivity of 97.5% (CI, 93.7–99.3%) compared with full manual surveillance [13].

The ECDC definition criteria were applied to define nvHAP [15], which require a suggestive radiological image of pneumonia, fever >38°C or an abnormal white blood cell count (WBC), and the presence of clinical criteria (e.g. cough, change in character of sputum, suggestive auscultation, and worsening gas exchange). Microbiologic proof of infection is not required. First symptoms must occur >48 hours after admission or within 48 hours after discharge, and no invasive respiratory device must be present in the 48 hours preceding the onset of symptoms, except for surgical procedures. Only nvHAP acquired during a stay in the USZ was considered, including patients readmitted to the USZ because of nvHAP. The manual chart reviews were carried out by a trained and experienced nurse (M.F.H.). All cases with nvHAP, all cases with ICD-10 discharge diagnostic code for HAP, and all indeterminate cases were re-evaluated by infectious diseases specialists (A.W., I.A., S.B., and V.S.).

Identification of nvHAP indicators

Indicators to build algorithms were selected based on review of the scientific literature, opinion of experts in the field of nvHAP, and their electronic availability. Radiologic procedures of the chest were considered (a) irrespective of results, and (b) by selecting radiographic reports not excluding pneumonia. For (b), full text of radiologic reports was searched for the terms "no" and "infiltrate" within one sentence, without the presence of a "contradictory or restricting term" (see Table S1). Other indicators were e.g. vital signs, blood test results, medication data, bacteriologic, and virologic sampling (see Table S2). The indicators must have been present >48 hours after admission or anytime in patients who were readmitted within 10 days.

Routine data derived from a Data Warehouse. For the intensive care unit, data on oxygen saturation, fever and medication were only available after November 2017, January 2018 and October 2018, respectively. Oxygen administration data from the intensive care unit were not available at all.

Development of candidate algorithms

First, single indicators were tested individually regarding their performance to select patients at risk for nvHAP. Second, simple algorithms were built, combining indicators with a sensitivity of >90% regardless of temporal relationship. Third, complex algorithms were built, combining indicators in a temporal relationship, defined by the presence of indicators 3 days before to 1 day after radiology. To identify the highest WLR while maintaining a sensitivity of >90%, we combined all indicators with a sensitivity >90%, and removed indicators in a stepwise manner up to the threshold of 90%.

Assessing performance of candidate algorithms

All single indicators and algorithms were assessed against the reference standard regarding five performance characteristics: (a) sensitivity for identifying patients with nvHAP, (b) specificity for identifying patients with nvHAP, (c) WLR, i.e. per cent patients who were not selected by the algorithm and therefore do not have to undergo manual surveillance [16] (d) overall performance (i.e. sensitivity × specificity), [16], and (e) number needed to screen, i.e. the mean number of "patients at risk" who have to undergo manual surveillance to detect one patient with nvHAP [17].

We calculated the performance characteristics for each single indicator and for all the algorithms according to standard epidemiological methods.

Results

A dataset of total 157 902 patient discharges with 947 reference nvHAP was used. Table 1 summarizes performance characteristics for single indicators (numbers [no.] 1–12), simple algorithms (no. 13–19), and complex algorithms (no. 20–30). Fig. 1 shows a visual representation of the overall performance of the single indicators and algorithms.

Table 1
Performance characteristics for single indicators, simple, and complex classification algorithms

Indicator / Algorithm Number (No.)	Radiologic procedure of the chest [a]	Radiologic procedure of the chest with full text [b]	Fever >38°C	Abnormal WBC <4000/µl or ≥12 000/µl	Antimicrobials [c]	Bacteriology [d]	Virology [e]	CRP ≥20mg/l	Length of hospital stay >5d	ICD-10 diagnostic code for HAP [f]	Decreased oxygenation [g]	Oxygen desaturation [h]	No intubation [i]	Sensitivity	Specificity	Workload reduction	Overall performance (sensitivity x specificity)	Number needed to screen
1	x													99.7%	83.2%	82.8%	0.83	28.8
2		x												99.3%	90.8%	90.3%	0.90	16.2
3			x											70.1%	91.7%	91.3%	0.64	14.5
4				x										93.3%	79.3%	78.8%	0.74	35.3
5					x									97.4%	66.6%	66.2%	0.65	56.3
6						x								90.6%	90.0%	89.5%	0.82	17.5
7							x							45.1%	94.7%	94.4%	0.43	9.3
8								x						99.4%	69.3%	68.9%	0.69	51.8
9									x					98.7%	57.7%	57.3%	0.57	71.2
10										x				53.7%	98.8%	98.4%	0.53	2.6
11											x			96.4%	72.5%	72.1%	0.70	46.5
12												x		35.1%	92.8%	92.6%	0.33	12.3
13			x or x											99.8%	76.4%	75.9%	0.76	40.1
14	x		x or x											99.6%	89.9%	89.4%	0.90	17.8
15	x		x or x		x									96.9%	92.1%	91.5%	0.89	14.1
16	x		x or x			x								90.4%	93.9%	93.4%	0.85	11.0
17	x		x or x					x						99.0%	90.7%	90.2%	0.90	16.4
18	x		x or x						x					98.4%	90.6%	90.0%	0.89	16.7
19	x		x or x								x			96.1%	91.8%	91.3%	0.88	14.5
20	x		x or x*											99.3%	91.7%	91.1%	0.91	14.8
21		x	x or x*											98.5%	95.2%	94.6%	0.94	9.0
22		x	x or x*										x	98.4%	95.5%	94.9%	0.94	8.5
23		x	x or x*		x								x	96.0%	96.1%	95.5%	0.92	7.4
24		x	x or x*			x							x	91.5%	96.6%	96.1%	0.88	6.6
25		x	x or x*					x					x	97.9%	95.6%	95.1%	0.94	8.2
26		x	x or x*						x				x	97.3%	95.6%	95.1%	0.93	8.2
27		x	x or x*								x		x	94.9%	96.0%	95.4%	0.91	7.6
28		x	x or x*			x			x				x	90.6%	96.7%	96.2%	0.88	6.4
29		x	x or x*		x			x	x		x		x	92.0%	96.7%	96.2%	0.89	6.4
30		x	x or x*		x	x		x	x		x		x	84.7%	97.5%	97.0%	0.83	5.0

CRP, C-reactive protein; ICD-10, International classification of Diseases, Tenth Edition; HAP, hospital-acquired pneumonia; WBC, white blood cell.
No. 1–12, single indicators; no. 13–19, simple algorithms; no. 20–30, complex algorithms which include a temporal relationship between fever or WBC and radiologic procedure (indicated by "*").
[a] Chest X-ray or Computer tomography-scan.
[b] Radiographic reports not excluding pneumonia: full text of radiologic reports was searched for the terms "kein" (English: no) and "Infiltrat" (English: infiltrate) within one sentence, without the presence of a contradictory or restricting term.
[c] Anatomical Therapeutic Chemical (ATC) codes for antibiotics for systemic use (J01 including subcodes), plus ATC codes for remdesivir and oseltamivir, and ATC codes for systemic use of amphotericin B, isavuconazol, posaconazol, and voriconazol.
[d] Bacteriological sampling of blood cultures or respiratory specimen (irrespective of results).
[e] Virological sampling of respiratory tract (irrespective of results).
[f] U69.00 including subcodes.
[g] Oxygen saturation of <95% or provision of supplemental oxygen, during 2 consecutive days.
[h] Stable oxygenation for at least 2 days (defined as oxygen saturation of 95% or more and no provision of supplemental oxygen), followed by oxygen saturation of <95% or provision of supplemental oxygen, during 2 consecutive days.
[i] Absence of an invasive respiratory device during the full 48 hours before chest imaging, except for surgical procedure.

Performance of single indicators

Sensitivity of the single indicators varied between 35.1% (332/947) (oxygen desaturation) and 99.7% (944/947) (radiologic procedure). Although bacteriology (defined as sampling of blood cultures or respiratory specimen) was relatively sensitive ((90.6% [858/947]), with 50.2% (475/947) for respiratory specimen only, and 89% (843/947) for blood culture only), virology was not (45.1% [427/947]). With antimicrobials and decreased oxygenation, only 2.6% (25/947) and 3.6% (34/947) of patients with nvHAP were missed, respectively. On the other hand, ICD-10 discharge diagnostic codes and "oxygen desaturation" were non-sensitive (53.7% [509/947] and 35.1% [332/947]).

WLR varied between 57.3% (90 505/157 902) (length of stay >5 days) and 98.4% (155 453/157 902) (ICD-10 discharge diagnostic codes). The WLR of radiologic procedure of the chest without full-text criteria was 82.8% (130 621/157 902) and increased to 90.3% (142 534/157 902) by including full-text criteria of radiologic reports.

Performance of simple algorithms

Algorithms with a sensitivity of >90% are listed in Table 1. The algorithm "radiologic procedure AND abnormal WBC or fever" with indicators mirroring the ECDC definition criteria for HAP had a high sensitivity (99.6% [943/947]), and these indicators were included in the following algorithms. Adding C-reactive protein (CRP), decreased oxygenation, antimicrobials, or length of hospital stay reduced sensitivity (99.6% [943/947] vs. 96.1% [910/947]–99.0% [938/947]) but slightly improved WLR (89.4% [141 091/157 902] vs. 90.0% [142 133/157 902]–91.5% [144 542/157 902]). Including bacteriology decreased sensitivity to 90.4% (856/947) but improved WLR to 93.4% (147 506/157 902).

Performance of complex algorithms

The complex algorithms had sensitivities between 84.7% (802/947) and 99.3% (940/947), and WLRs between 91.1% (143 877/157 902) and 97.0% (153 213/157 902). The highest sensitivity (99.3%) was seen with the combination of "radiologic procedure AND temporally related abnormal WBC or fever" (no. 20). This algorithm had a WLR of 91.1%. In complex algorithms maintaining a sensitivity of >90%, the highest WLR was 96.2%, achieved by two algorithms: (a) no. 28, "radiologic procedure including full text AND temporally related abnormal WBC or fever AND bacteriology AND stay ≥5 days AND no intubation," and (b) no. 29, "radiologic procedure including full text AND temporally related abnormal WBC or

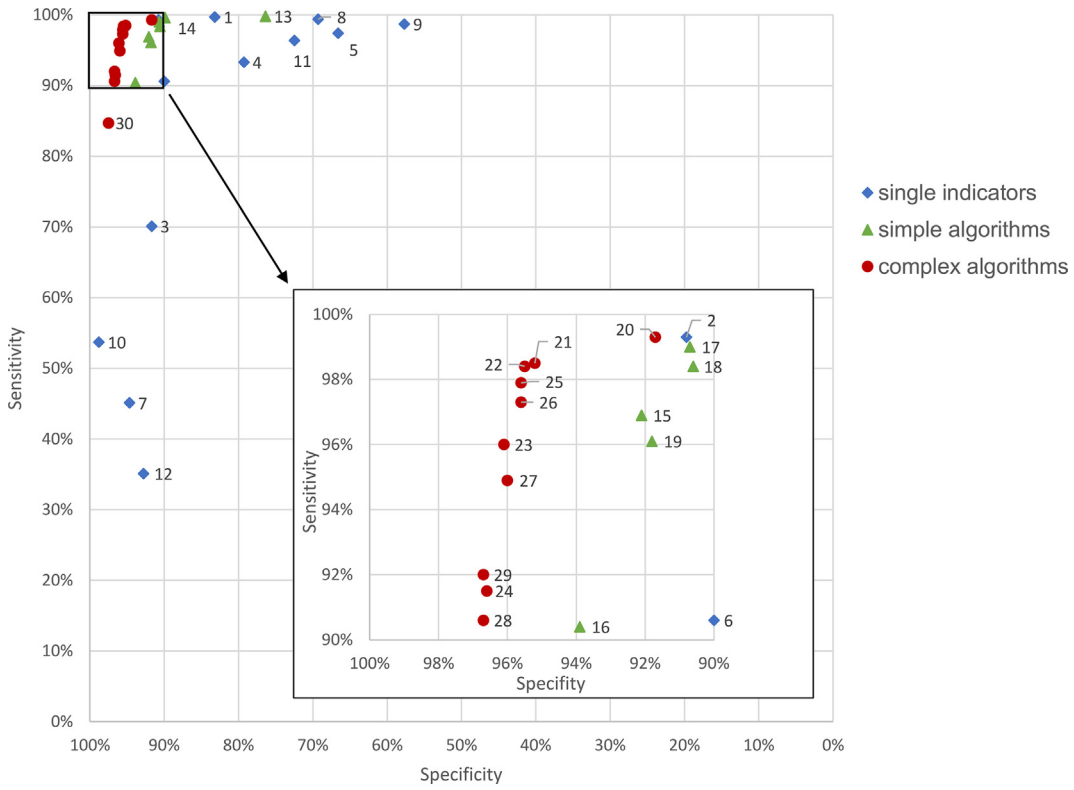

Fig. 1. Overall performance of the single indicators (rectangles, Numbers (No.) 1-12), simple (triangles, No. 13-19) algorithms combining single indicators; and complex (circles, No. 20-30) algorithms combining single indicators while considering temporal relationship of fever and WBC to the radiologic procedure (see **table 1** for more details).

fever AND antimicrobials AND CRP AND decreased oxygenation AND stay ≥5 days AND no intubation." Algorithm no. 24, combining "radiologic procedure including full text AND temporally related abnormal WBC or fever AND bacteriology AND no intubation"—and thus, closest to the ECDC definition—had a sensitivity of 91.5% (867/947) and a WLR of 96.1% (151 697/157 902).

Performance characteristics of most indicators and algorithms were similar when excluding months with reduced data availability, or comparing years pre- and post-COVID-19 (Tables S3 and S4).

Discussion

In this study, we compared the performance of various indicators, individually or combined, to reduce the number of patients for manual chart review while maintaining acceptable sensitivity for semi-automated nvHAP surveillance. Most of the selected single indicators showed high sensitivity to identify patients with nvHAP, with some exceptions: ICD-10 discharge diagnostic codes for HAP had a sensitivity of only 53.7%, which was already described in previous reports [18]; similarly, virology testing had a sensitivity below 50%, which was expected, given that testing presumably is carried out mostly in winter times or in immunosuppressed patients. Some indicators (i.e. length of hospital stay, the use of antimicrobials, CRP, and decreased oxygenation) with high sensitivity had low WLR but led to an increase in WLR when being integrated in an algorithm. Indicators with low sensitivity are generally less relevant for a preselection classification algorithm, but they might still be interesting for an alternative approach: using weighted regression to estimate the risk of infection, a more sophisticated method (outside of the scope of this manuscript) usually achieves higher specificity with similar sensitivity [17].

High sensitivity is the most important performance characteristic in semi-automated surveillance, as missing true-positive cases should be avoided, whereas false-positive cases can be properly classified through manual chart review [9]. For semi-automated surveillance, a 90% sensitivity threshold was defined by the Providing a Roadmap for Automated Infection Surveillance in Europe network [14]. We found that with this threshold, a WLR of 90–93% can be achieved by combining routine care indicators, and a WLR of up to 96.2% can be achieved when also considering the full text of radiologic procedure and the temporal relationship of indicators. WLR correlates with time saved to perform manual chart review, which is key to make nvHAP surveillance feasible. Still, there is a trade-off between sensitivity and specificity/WLR and the acceptable level of performance regarding these characteristics depends on the user's expectations [14].

Some of our algorithms with a WLR of around 95% had a sensitivity of >98%, whereas the algorithms with the highest WLR of 96.2% had a sensitivity of 90.6% and 92.0%, respectively. In numbers, assuming a hospital with 40 000 admissions and 250 nvHAP per year, increasing WLR from 95% to 96.2% (and decreasing sensitivity from 98% to 92.0%) would lead to a decrease of patients for manual chart review from 2000 to 1520, but identifying 230 instead of 245 patients with nvHAP. Whether a hospital decides to compromise sensitivity in favour of WLR might depend on existing resources and the goal of the surveillance. To evaluate the effectiveness of a prevention intervention by comparing incidence rates over time, a 90% sensitivity might be more than sufficient. Importantly, the hospital should stick to the once-established surveillance system by, of course, evaluating changes in underlying data sources regularly.

Manual chart review leaves room for subjective interpretation (e.g. radiologic procedure, respiratory symptoms), and Stern et al. [19] showed high inter-observer variability in manual chart review for nvHAP. In the past 4 years, several authors published fully automated nvHAP surveillance systems with the aim of evaluating

more objective, consistent, and efficient surveillance [19–22]. Alternative definitions for nvHAP had to be established using objective clinical and electronically available data, but the performance of fully automated surveillance remains moderate [23]. In recently published articles on fully automated surveillance, the algorithms included worsening oxygenation in combination with other indicators, e.g. new antibiotics, fever, abnormal WBC, chest imaging obtained, or respiratory culture obtained [19–22]. These were similar to the indicators evaluated in this manuscript. Batlle et al. [21] found moderate agreement of the fully automated surveillance against the reference standard "true pneumonia" (assigned by one reviewing physician), with a sensitivity of 71% (95% CI, 51–87%) and positive predictive valud (PPV) of 48% (95% CI, 37–58%). The authors argue that agreement is similar between CDC criteria and "true pneumonia" (61% [95% CI, 41–79%] and 59% [95% CI, 44–72%]) [21]. However, although manual chart review clearly suffers from the non-objective interpretation of results, automated surveillance—with low PPV—might assign patients suffer from nvHAP because of non-pulmonary sepsis or pulmonary oedema. Thus, as van Mourik et al. [9] stated in 2018, semi-automated surveillance may still have more favourable clinician buy-in than fully automated surveillance.

In our dataset, the algorithm with the highest WLR (by maintaining a sensitivity of >90%) still identified 3.8% of patients to be at risk for nvHAP, whereas only 0.6% suffered from nvHAP according to the reference standard. One possible way to ultimately reach the goal of a sensitive and specific fully automated nvHAP surveillance may be the use of more sophisticated full-text analysis methods for radiographic or healthcare workers' progress reports, or the use of digital analyses of chest radiographic images. Even though we focused on structured data as indicators for nvHAP, we added a simple algorithm of radiologic full-text reports by combining the most common term of describing the absence of a pneumonic infiltrate with a negation. Using "text snippets" to identify radiologic reports clearly rejecting pneumonia halved the number of patients who had to undergo manual chart review while maintaining high sensitivity. Such an approach might also be applicable to clinical signs and symptoms (i.e. cough and auscultation), a step that until now is part of the manual surveillance.

Our study has limitations. First, routine data from a single tertiary care centre in a high-resource setting limits generalizability. Likely, in hospitals with lower resources or fewer patients with immunosuppression, fewer diagnostic tests are performed, which directly affects the performance of certain algorithms. Some tests, like CRP, might reflect local practices in Switzerland and might not be available or used in other countries. In addition, the full-text analysis of radiologic reports must be very carefully validated in case of adoption in other hospitals, especially in other languages. Second, some data were not readily available (e.g. oxygen flow rate), which interfered with the assessment of increased oxygen administration and more direct comparison to the fully automated surveillance systems mentioned above [19–22]. Third, because of feasibility reasons, we used the described reference standard, instead of full manual surveillance of the total patient population. Still, as 97.8% of patients with nvHAP with a ICD-10 discharge diagnostic code for HAP were identified by our established system, we assume that a negligible number of patients with nvHAP was missed by our reference standard. Fourth, we developed and evaluated the algorithms on the same data set, which introduced the problem of overfitting.

In conclusion, we identified sensitive indicators combined in algorithms, allowing accurate pre-selection of patients for manual chart review in our semi-automated nvHAP surveillance. Our findings must be externally validated in other hospital settings with different electronic medical records systems, diagnostic routines, and in different language regions. We believe that our results can guide hospitals aiming to establish semi-automated surveillance of nvHAP, enabling prevention efforts based on reliable incidence surveillance data.

Author contributions

A.M., M.P., and A.W. developed different algorithms, performed descriptive analysis and interpreted the data. M.P. programmed algorithms and provided the data. A.M. and A.W. drafted the manuscript. M.P., M.F.H., and W.Z. edited and reviewed the manuscript.

Transparency declaration

Potential conflict of interest

The authors declare that they have no conflicts of interest.

Financial report

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cmi.2024.11.032.

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