Retrospective cohort study investigating extent of pertussis transmission during a boarding school outbreak, England, December 2017 to June 2018

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On 1 May 2018, a pertussis outbreak was declared at a female secondary boarding school in southern England. We conducted a retrospective cohort study to determine the extent of pertussis transmission and identify risk factors in this semi-closed population. Of 504 students and staff assessed before post-exposure vaccination, 48% (n = 240) had evidence of pertussis. A sub-analysis of 409 students found that both residential dormitory (p = 0.05) and school year (p = 0.03) were associated with pertussis, with odds decreasing by 11% for each increase in school year (95% confidence interval: 0.7–20.2). Odds of pertussis were 1.7 times higher in those assumed to have received acellular vaccines for their primary course compared with those assumed to have received whole-cell vaccines (based on date of birth), although this difference was not significant (p = 0.12). Our findings support the need for timely, widespread vaccination following identification of cases among adolescents in a semi-closed United Kingdom (UK) setting and to review the evidence for the introduction of an adolescent pertussis booster to the UK routine vaccination programme.

Background
Pertussis is a cyclical disease with peaks occurring every 3–4 years [1]. Completion of the accelerated three-dose primary course (at age 2, 3 and 4 months) and preschool booster dose 3 years after the last primary dose (at 3 years and 4 months) in the United Kingdom (UK) was 85.6% in 2017/18 and has been above 80% for the past decade [2]. Despite the high uptake of routine immunisation in England, there was a substantial resurgence of pertussis in 2012, and the incidence of cases observed since then has been considerably higher than in previous years. The most recent epidemic peak occurred in 2016. Similar resurgences have been observed in other countries with longstanding vaccine programmes [3].

After infants under 3 months of age, the next highest incidence of laboratory-confirmed pertussis in the UK is among adolescents aged 10–14 years [1]. There is growing evidence that the shorter duration of protection and lower effectiveness over time against infection conferred by acellular pertussis (aP) vaccines compared with whole-cell pertussis (wP) vaccines have been important contributory factors [4–7]. This is of considerable interest in Europe where a high proportion of countries have switched from a whole-cell to an acellular primary schedule and few routinely recommend adolescent pertussis boosters. In 2018, 35,627 cases were reported in Europe [8]. In the UK, aP vaccines replaced wP vaccines in the accelerated primary course in 2004, later than in many other high-income countries. The single booster dose of aP vaccine has been routinely offered since 2001. Reported increases in adolescent disease, which are in part due to improved case ascertainment but also reflect waning immunity from the childhood programme, has prompted some countries to introduce adolescent boosters. These increases, however, probably underestimate the true burden of disease in adolescent populations [9,10], with delays in recognition and diagnosis being due to atypical
presentations. While adolescents are far less likely to experience severe disease compared with infants younger than 3 months, the overall impact on quality of life can be considerable [11] and they are important reservoirs for onward transmission [12].

Outbreak detection
On 21 March 2018, a local team of Public Health England (PHE) in South England was notified of a serologically confirmed case of pertussis in a 14-year-old student attending an all-female boarding school (school years 7–13, ages 11–18 years). On 1 May, a second confirmed case who resided outside the local team’s jurisdiction was reported, prompting the declaration of an outbreak and initiating a wider investigation. Investigation with the school identified a further two confirmed and one suspected case. The cases were in school years 9 to 13 (ages 14–18 years) and reported onset dates between 25 February and 16 April 2018. As per national guidelines [13], as part of the initial outbreak response, a single dose of pertussis vaccine (Repevax, Sanofi Pasteur, Lyon, France) was considered by the incident management team (IMT) and recommended for students in all affected year groups [9-13] who were residing in boarding houses separate from the younger school years, and to selected staff members. A questionnaire and swabs were taken from individuals attending for vaccination. Clinical evidence of extensive transmission beyond school years 9–13 became immediately apparent and following confirmation by rapid testing, vaccination was extended to all year groups.

This paper summarises the findings of an investigation of a large outbreak of pertussis in a boarding school of 11–18-year-old students. Our objectives were to assess the extent of pertussis transmission within the school setting before post-exposure vaccination by calculating attack rates (AR) of symptomatic and asymptomatic pertussis among students and staff, and to identify risk factors for pertussis.

Methods
A total of 540 residential and 20 day students attended the school. The residential students lived in 10 dormitories (houses); three accommodating students from years 7 and 8 combined, five with students from years 9 to 11, one for year 12 students and one for year 13 students. In addition to the students, the school had ca 600 staff including teachers, boarding staff, housekeepers and grounds staff.

We conducted a retrospective cohort study of all students and ‘high-risk’ staff. The latter were defined based on their level of exposure and included healthcare staff, boarding staff with regular student contact and staff who were themselves in, or lived with someone in, a priority group according to national guidelines [13].

Active case finding for staff and all year groups was undertaken between 11 and 15 May at the time of the vaccination sessions using a combination of clinical questionnaires, determination of anti-pertussis toxin (anti-PT) IgG titres in oral fluid specimens (OF) and determination of *Bordetella* DNA from throat swabs by PCR. Information on clinical symptoms for each individual was collected using questionnaires at a single point in time. However, active surveillance was implemented at the school for 42 days after symptom onset in the last identified case with a low threshold for testing individuals presenting with cough illness regardless of duration. The local PHE team was also notified of cases linked to the school through routine reporting mechanisms.
Clinical questionnaire
The questionnaires were administered by boarding school staff. Individuals were asked to provide details on symptoms experienced since January 2018, demographics, accommodation, pre-existing medical conditions and pertussis vaccination history. Based on reported symptoms, individuals were classified into categories of clinical suspicion for pertussis.

Definitions for ‘high’ and ‘low’ clinical suspicion were developed by the IMT, based on (but more sensitive than) case definitions in the national pertussis guidelines [13]:

High clinical suspicion: Cough for 2 weeks or more OR a cough of shorter duration and either vomiting or sore ribs,

Low clinical suspicion: Onset date within 1 week of completing the questionnaire, and either a cough for less than 2 weeks or two of the following three symptoms: fever, sore throat or tiredness.

For individuals reporting no symptoms, or symptoms not meeting the above criteria, we considered that there was no clinical suspicion for pertussis.

Microbiological testing
Apart from a small number of serology samples collected before outbreak detection, all samples for microbiological testing were collected by staff at the school health centre. All throat swabs were sent to Southampton Public Health Laboratory for primary PCR testing and all OF and serology specimens were sent to the National Reference Laboratory at PHE Colindale.

Oral fluid specimens and serology testing
The standard in-house serum anti-PT IgG ELISA reports titres in international units (IU)/mL using a threshold of 70 IU/mL, above which titres are considered indicative of recent infection for samples taken ≥ 2 weeks after onset of cough symptoms [9,14]. The OF assay acts as a surrogate for the serum antibody assay and detects anti-PT IgG but is a capture ELISA and reports in assay arbitrary units (aU), with an equivalent diagnostic threshold of 70 aU [14].

Although the routine diagnostic OF cut-off is >70 aU for samples taken ≥ 2 weeks after cough onset, in this outbreak, given the uncertainty around sample timing in relation to exposure, the IMT agreed to use a lower threshold of >60 aU to increase sensitivity. Seronegative samples (≤ 60 aU) known to have been taken 2 weeks or more since symptoms onset were classified as having reliable timing, with all others classified as having unreliable timing.

| Data                          | Outcome                  | School year (student age in years) | Staff | Total |
|-------------------------------|--------------------------|------------------------------------|-------|-------|
|                               |                          | 7 (11–12)                          | n %   | n %   |
|                               |                          | 8 (12–13)                          | n %   | n %   |
|                               |                          | 9 (13–14)                          | n %   | n %   |
|                               |                          | 10 (14–15)                         | n %   | n %   |
|                               |                          | 11 (15–16)                         | n %   | n %   |
|                               |                          | 12 (16–17)                         | n %   | n %   |
|                               |                          | 13 (17–18)                         | n %   | n %   |
| Clinical suspicion            | High                     | 4 11 4 16 8 14 10 14 7 11 12 20 8 12 12 16 65 14 |
|                               | Low                      | 10 28 7 28 23 40 22 30 15 24 24 40 15 23 9 12 125 28 |
|                               | None                     | 22 61 14 56 27 47 42 57 40 65 24 40 42 65 52 71 263 58 |
|                               | Total                    | 36 100 25 100 58 100 74 100 62 100 60 100 65 100 73 100 453 100 |
|                               | Unknown                  | 3 39 31 32 23 26 26 22 5 8 202 |
| OF anti-PT IgG test result     | Positive                 | 12 32 3 12 15 25 18 24 25 40 10 16 11 15 6 6 100 21 |
|                               | Reliable negative        | 0 0 2 8 10 17 10 14 7 11 14 22 14 20 11 12 68 14 |
|                               | Unreliable negative      | 26 68 20 80 34 58 46 62 30 48 40 63 46 65 76 82 318 65 |
|                               | Total                    | 38 100 25 100 59 100 74 100 62 100 64 100 71 100 93 100 486 100 |
|                               | No test                  | 1 39 30 32 32 23 22 20 2 2 169 |
| PCR test result               | Positive                 | 7 18 3 12 8 13 13 17 3 5 4 6 8 11 19 20 65 13 |
|                               | Reliable negative        | 2 5 6 24 12 19 19 25 2 3 17 27 6 8 14 15 78 16 |
|                               | Unreliable negative      | 29 76 16 64 43 68 45 58 61 92 43 67 58 81 60 65 355 71 |
|                               | Total                    | 38 100 25 100 63 100 77 100 66 100 64 100 72 100 93 100 498 100 |
|                               | No test                  | 1 39 26 29 19 22 19 2 2 157 |

Anti-PT: anti-pertussis toxin; OF: oral fluid specimen.

* Total number of high-risk staff not known, figures represent identified staff with missing data.
PCR testing

PCR detection targeting two *Bordetella pertussis* genomic regions, (i) the pertussis toxin S1 promoter (*ptxP*) and (ii) the insertion element *IS481*, also known to be present in *B. holmesii* and some *B. bronchiseptica* [15], was conducted on throat swabs (in viral transport medium or dry). We used a TaqMan (Applied Biosystems, Waltham, United States (US)) assay based on Fry et al. [16]. For the purposes of this investigation, a quantification cycle of ≤ 45 for both targets or for the *IS481* target only were both considered as consistent with the detection of *B. pertussis*.

For outbreak management, the following results were considered consistent with *B. pertussis* infection and/or carriage: (i) positive for *IS481* only and (ii) positive for both *IS481* and *ptxP*. Negative samples known to have been taken within 3 weeks of symptom onset were classified as having reliable timing, with all others classified as having unreliable timing.

Case definitions

Based on test results and clinical suspicion categories, to support the outbreak investigation we created case definitions and calculated AR for asymptomatic and symptomatic individuals. Symptomatic cases were divided into those identified by active case finding vs those identified through routine reporting and further divided into confirmed, probable and possible cases (Table 1).

Vaccination status

Questionnaire responses relating to existing medical conditions and vaccination histories were poorly recorded and not considered suitable for inclusion in the analysis. The extraction of vaccine histories directly from individual medical records was considered but was not logistically feasible, as readily available data were limited and did not include details of type of vaccine given.

In November 2004, national procurement of vaccines in the childhood programme changed from wP to aP. In the absence of individual vaccination histories, we used date of birth for students born in the UK to infer whether a student would have received aP or wP vaccine for their primary schedule. Allowing an 8-week period from birth to first vaccine, students born on or before 7 September 2004 were inferred to have received wP, with those born later inferred to have received aP. Students born outside the UK were assigned an unknown vaccination status.

For 37 students where school year was not provided, this was calculated based on their date of birth. Date of onset was estimated for 12 confirmed cases based on approximate descriptions (e.g. mid-point of the month used when only month stated).

Statistical methods

Data were collated and validated in MS Access and analysed using R v1.1.456. Univariate AR (risk ratios) were calculated for each type of case, both overall and by year group. As teachers predominantly lived off-site and as adults would all have been immunised using wP, we used a subset of data including students only. Logistic regression was used to calculate univariate odds ratios for a combined AR incorporating all case definitions, which were calculated for country of birth, year group, house and vaccine type. Sex was not included as all students were female. Multivariable logistic regressions were then conducted, with all variables included a priori because an association was very plausible, to identify the model that best explained the data.

To assess whether participants with high clinical suspicion had statistically different PCR results to those with low or no clinical suspicion, we conducted chi-squared analyses. This was done for individuals where data on symptoms and PCR test with reliable timing were available.

To investigate the impact that the timing of symptom onset in relation to sample collection may have had on differences in allocation of case definitions between younger and older age groups, students with a date of onset and symptoms were dichotomised into Years 7 and 8 and Years 9 to 13 and by whether symptom onset occurred within 21 days of sample collection, and then a two-sided Fisher’s exact test conducted.

Ethical statement

Informed consent was obtained when taking samples for diagnostic purposes. Public Health England has legal permission, provided by Regulation 3 of The Health Service (Control of Patient Information) Regulations 2002, to process patient confidential information for national surveillance of communicable diseases. As such, individual patient consent was not required for the use of patient data for this outbreak investigation.

Results

**Demographics**

In total, 504 individuals (409 students and 95 staff) were categorised using the response from the clinical

| Clinical suspicion | PCR test result | Total |
|--------------------|-----------------|-------|
|                    | Positive | Negative (reliable) |       |
| High               | 12      | 55 | 10 | 45 | 22 |
| Low                | 17      | 27 | 45 | 73 | 62 |
| Sub-clinical / none| 30      | 57 | 23 | 43 | 53 |
| Total              | 59      | 43 | 78 | 57 | 137 |

Table 3

Cross-tabulation of clinical suspicion category against PCR test result, pertussis outbreak in a school, England, December 2017–June 2018 (n =137)
questionnaire and/or microbiological investigations and were included in the analysis. As 560 students were known to attend the school, the student response rate was therefore 73%. A list of all staff considered high-risk was not available, and so it was not possible to calculate a response rate for this group.

All students were female, as were most staff (n = 79; 83%). Most students (n = 295; 72%) and almost all staff (n = 87; 92%) were born in the UK, with over half of non-UK students born in mainland China (n = 23; 20%), Hong Kong (n = 21; 18%) or the US (n = 20; 18%).

**Questionnaire completion**

Questionnaires were completed by 453 individuals, 380 of whom were students. Based on reported symptoms, clinical suspicion of pertussis was high for 65 (14%) and low for 125 (28%) of respondents (Table 2). The proportion of respondents with either high or low clinical suspicion varied by school year, with the highest proportion being in Year 12 (36/60) and the lowest in Year 13 (23/65). There was clinical suspicion for 21 of 73 staff completing a questionnaire.

**Laboratory testing**

Of 486 individuals tested for anti-PT IgG in OF, 100 (21%) had evidence of recent infection (>60 aU titre), 68 (14%) a negative result with reliable timing, and 318 (65%) a negative result with unreliable timing. Among students assessed by OF test (70%; 393/560), the highest proportion with recent infection was in Year 7 (45/62) and the lowest in Year 8 (21/45). There was no clear trend between year groups. Of 93 staff assessed by PCR test, 20 (20%) were PCR-positive.

**Association between PCR test result and symptoms**

Data on symptoms and a PCR test with reliable timing was available for 137 participants. The proportion of positive test results was higher among participants who had high clinical suspicion of pertussis compared with those for whom there was low (chi-squared p = 0.02) and no (chi-squared p < 0.01) clinical suspicion (Table 3).

**Attack rates**

Of the 504 individuals assessed, a total of 72 were confirmed (AR: 14%), 19 probable (AR: 4%) and 59 possible (AR: 12%) symptomatic cases. Of the confirmed and probable cases, only eight of 72 and two of 19, respectively, were identified by routine reporting.

In addition, there were 90 asymptomatic individuals (AR: 18%). Questionnaires were unavailable for 15 individuals classified as asymptomatic. These could potentially have been categorised as asymptomatic cases, had questionnaires been available.

The combined AR (symptomatic and asymptomatic) was 48% (n=240) (Table 4). For students, the highest combined AR was for Year 7, with the lowest in Year 13. The overall AR in staff was lower than all student year groups (n = 33; 35%). Overall AR for UK-born (n = 183; 48%) and non-UK-born individuals (n = 57; 47%) were similar. The median ages were similar (Wilcoxon rank sum, p = 0.05) for combined student cases (15 years) and student non-cases (16 years).
Pertussis cases by case definition and week of disease onset, school outbreak, England, December 2017–June 2018 (n = 90)

![Graph showing pertussis cases by case definition and week of disease onset.]

**Outbreak progression**

Date of onset was available for 90 of 150 (60%) cases meeting possible, probable and confirmed case definitions (Figure). Of 90 asymptomatic cases, 50 tested IgG-positive and PCR-negative, indicating that exposure may have been more than 3 weeks before sampling. Based on the PCR sampling date, 43 individuals may have been exposed earlier than 20 April 2018 (Figure). Two cases were identified after vaccination and testing. An additional 43 asymptomatic individuals may have been exposed before 20 April (IgG-positive and PCR-negative).

Risk factors for pertussis

Univariate analysis of school year as a linear variable showed a significant relationship with pertussis (p = 0.03), with the odds of pertussis in students decreasing by 11% for each increase in school year (95% confidence interval: 0.7–20.2). House as a categorical variable was also significantly associated (chi-squared statistic, p = 0.05), with odds ranging from 0.58 to 2.33. Odds of pertussis were 1.7 times higher in those receiving aP vaccines as the primary course compared with those receiving wP vaccines, although the association between vaccine type and pertussis was not significant (chi-squared statistic, p = 0.12). Birth region showed no association with pertussis (chi-squared statistic, p = 0.66) and was excluded from further models. Univariate logistic regression model outputs are shown in Table 5.

Bivariable and multivariable models were built using all combinations of school year, house and vaccine type. There was considerable collinearity between these variables. Years 7 and 8 lived in houses A to C, Years 9 to 11 lived in houses D to H, Year 12 lived in house I and almost all of Year 13 (65/68) lived in house J. Based on date of birth, all students in school Years 7 and 8 were assumed to have received a primary course using aP vaccine, with students in older school years assumed to have received a primary course of wP vaccine. This precluded the use of multivariable models in determining which group of variables best predicted whether a child had pertussis. The univariable models were therefore considered the most reliable for inference for risk factors of pertussis.

**Discussion**

This study evaluates the extent of symptomatic and asymptomatic pertussis transmission in an outbreak setting using questionnaires, PCR and OF anti-PT IgG testing. A strength of this investigation is the collection of demographic and laboratory data from individuals who reported no symptoms. This is different than during most outbreak investigations, when only symptomatic individuals are swabbed. Our findings demonstrate a rate of confirmed symptomatic disease (AR: 14%) similar to those previously reported in other pertussis school outbreaks [17,18]. When including all symptomatic (AR: 30%) and asymptomatic cases (AR: 18%), the rate more than tripled (AR: 48%). Given the low proportion of cases identified through routine reporting, this study provides valuable insight into the potential magnitude of pertussis under-ascertainment. Our findings of higher AR in younger age groups might be unexpected given that immunity wanes following childhood vaccination and the initial reported cases were in the older students. However, in the UK, cohorts born before 2004 were eligible to receive wP vaccines only as part of the primary infant schedule and after 2004, only aP containing vaccines were recommended. Thus, younger cohorts were fully primed and boosted with aP vaccines only. As there is evidence that disease onset tended to be later in Years 7 and 8, it is unlikely that the higher symptomatic AR in younger groups was due to insufficient time for clinical symptoms to develop in older age groups at the time questionnaires were administered.

PCR testing targeting a repetitive sequence in *B. pertussis*, conducted as part of another boarding school outbreak in Sydney, Australia [19], found no association with symptomatic cases. However, a positive PCR result appeared more likely when specimens were
collected close to the date of symptom onset, including some (n = 6) that were positive before onset [19]. In our study, a larger proportion of individuals with a PCR result from a sample taken within 3 weeks of symptom onset tested positive in those with high clinical suspicion, compared with those with low or no clinical suspicion, providing further evidence of this.

Our finding that AR were 1.7 times higher in students assumed to have received aP vaccine than in those assumed to have received wP vaccine based on their date of birth suggests that aP vaccine offers a shorter duration of protection, although our study was not sufficiently powered to demonstrate statistical significance (p = 0.12). Differences in respiratory hygiene and mixing patterns may also have played a role.

Owing to the high degree of collinearity between house and school year, it is not possible to determine which was the most important exposure, although both were significant (p = 0.05 and p = 0.03, respectively. The p value of 0.05 was rounded up, and so this was significant). There is good plausibility for either of these variables to impact odds of pertussis through increased risk of transmission in classroom and/or residential settings.

Consideration of post-exposure vaccination is recommended in the national public health guidelines in England [13]. While there is limited published evidence of effectiveness, the rationale for such an approach is to rapidly boost antibody levels in a susceptible population to reduce ongoing transmission. There is good scientific plausibility for this, and a similar approach has been adopted in the US [20].

While this was not a randomised intervention, which would have enabled a more robust evaluation of the use of vaccination in an outbreak setting, the prompt reduction in cases (only two identified after vaccination) suggests that vaccination is likely to have helped control the outbreak. The generalisability of this study to adolescent populations is restricted by the fact that the study population was almost exclusively female, where behaviour may be different from mixed populations. However, the elevated levels of pertussis transmission demonstrated through this unique investigation highlight the importance of timely post-exposure vaccination where cases are identified in semi-closed settings, and demonstrate the susceptibility in these age groups.

While routine immunisation against pertussis has helped reduce pertussis morbidity in childhood, there is evidence it may not have a notable impact on the incidence of adolescent and adult pertussis, with incidence in these age groups increasing in some countries [21]. The World Health Organization recommends that countries consider the need for additional booster doses taking into account local epidemiology [7] but the age at which boosters are offered requires careful consideration, as an adolescent booster will shift the

| Variable               | Group | Cases | Non-cases | Odds | OR   | p     | 95% CI |
|------------------------|-------|-------|-----------|------|------|-------|--------|
| School year            |       |       |           |      |      |       |        |
| House                  |       |       |           |      |      |       |        |
| (p = 0.05^)            |       |       |           |      |      |       |        |
| House A                | 13    | 14    | 0.93      | Reference |
| House B                | 10    | 10    | 1.00      | Reference |
| House C                | 3     | 2     | 1.50      | Reference |
| House D                | 2     | 2     | 1.00      | Reference |
| House E                | 2     | 2     | 1.00      | Reference |
| House F                | 2     | 2     | 1.00      | Reference |
| House G                | 2     | 2     | 1.00      | Reference |
| House H                | 2     | 2     | 1.00      | Reference |
| House I                | 2     | 2     | 1.00      | Reference |
| House J                | 2     | 2     | 1.00      | Reference |
| Unknown                | 2     | 2     | 1.00      | Reference |
| Birth region           |       |       |           |      |      |       |        |
| (p = 0.66)             |       |       |           |      |      |       |        |
| United Kingdom         | 154   | 141   | 1.00      | Reference |
| Africa                 | 5     | 2     | 2.50      | 0.33  | 0.48–16.16 |
| Asia                   | 30    | 36    | 0.83      | 0.76  | 0.32  | 0.44–1.30 |
| Europe                 | 5     | 8     | 0.62      | 0.57  | 0.34  | 0.17–1.76 |
| North America          | 10    | 12    | 0.83      | 0.76  | 0.54  | 0.31–1.82 |
| Other                  | 3     | 3     | 1.00      | 0.92  | 0.91  | 0.17–5.02 |
| Vaccine type           |       |       |           |      |      |       |        |
| (p = 0.30)             |       |       |           |      |      |       |        |
| Whole cell             | 124   | 123   | 1.00      | Reference |
| Acellular              | 30    | 18    | 1.67      | 1.65  | 0.12  | 0.88–3.17 |
| Unknown                | 53    | 61    | 0.87      | 0.86  | 0.51  | 0.55–1.84 |

CI: confidence interval; NA: not applicable; OR: odds ratio; ^ p value significant but rounded up.
peak incidence of pertussis towards groups of child-bearing age [22]. Our findings suggest there may be an argument for the introduction of an adolescent pertussis booster in the UK programme.

Our study had some limitations. Information on clinical symptoms and samples for testing for each individual were collected at a single point in time as it was not logistically feasible to follow up progression of symptoms (except for the two cases detected by active surveillance). This is likely to have affected allocation of case definitions in the following ways: (i) Any individuals with disease onset within 2 weeks of questionnaire completion may have been categorised as possible instead of probable because they did not have time to meet the 2-week cough criteria; (ii) asymptomatic carriers who were exposed within 2 weeks of being tested may have tested positive for OF anti-PT IgG had the test been conducted after 2 weeks from exposure; this would have resulted in them being counted as asymptomatic cases; (iii) there was a reduced likelihood of a true case testing positive and hence being categorised as confirmed or asymptomatic.

Because of the age of our study population and the lack of individual vaccine histories (including product information), it was not possible to identify whether the aP vaccine effectiveness waned over time, as pupils from only two school years had received the aP pertussis vaccine. The lower AR observed in Year 8 is likely to be due to 20 students from this year group spending January to April overseas on a field trip, and so having a lower level of exposure. Although they only made up a small proportion of the total cohort, it was not possible to determine from the available information whether data were provided for day students and if so, which students these were. The lower exposure risk for these students means they have the potential to confound our results if associated with any of our exposure variables. While the response rate for students was high (73%), as no information was available for students not included in the study, it is not known what effect selection bias may have had on our findings. Another limitation of this study is the inability to discern the direction of transmission, in particular whether asymptomatic individuals transmitted infection to others.

**Conclusion**

Our findings support the need for timely, widespread vaccination following identification of cases among adolescents in a semi-closed (UK) setting, to review the evidence for the introduction of an adolescent pertussis booster to the UK routine vaccination programme and, in the longer term, advocate for better vaccines that have a longer period of protection.

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**Conflict of interest**

None declared.

**Authors’ contributions**

RM and JF coordinated the outbreak investigation; RM, JF, SR, GA, ME, CS, NC, CA, SB, CB and DL drafted the protocol and questionnaires; SR, GP, MM, AC and ME contributed to data collection, case information and data analysis; CB, NF, DL, GU, NA and SF were involved in the laboratory investigations. MM and GP co-ordinated vaccination of pupils and staff; GA and CB provided expert clinical advice in managing the outbreak; ME drafted the manuscript, with GA, CB, CA, SB, NC, CS, RM, AC, and NF involved in revisions. All authors reviewed and approved the final manuscript.

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