Pertactin-Negative and Filamentous Hemagglutinin-Negative *Bordetella pertussis*, Australia, 2013–2017

Zheng Xu, Sophie Octavia, Laurence Don Wai Luu, Michael Payne, Verlaine Timms, Chin Yen Tay, Anthony D. Keil, Vitali Sintchenko, Nicole Guiso, Ruiting Lan

During the 2008–2012 pertussis epidemic in Australia, pertactin (Prn)–negative *Bordetella pertussis* emerged. We analyzed 78 isolates from the 2013–2017 epidemic and documented continued expansion of Prn-negative ptxP3 *B. pertussis* strains. We also detected a filamentous hemagglutinin-negative and Prn-negative *B. pertussis* isolate.

Despite high vaccination coverage, pertussis remains a major public health concern. In many industrialized countries, including Australia, whole-cell vaccine was replaced by the less reactogenic acellular vaccine (ACV). In Australia, the 3-component ACV (containing pertactin [Prn], pertussis toxin [Ptx], and filamentous hemagglutinin [Fha]) has been more widely used than the 5-component ACV (which also contains fimbrial antigen: Fim2 and Fim3).

Since 1991, when notifications began, pertussis has reemerged in Australia, and epidemics occur every 3–5 years. The largest epidemic occurred in 2008–2012; 39,000 cases were recorded at its peak in 2011 (1,2). Most *Bordetella pertussis* isolates from that epidemic belonged to 1 genetic group, referred to as single-nucleotide polymorphism (SNP) cluster I (1–3). SNP cluster I had 3 SNP profiles (SPs): SP13 (SNP cluster I, ptxP3, 75/78 [96.2%]) and SP18 (noncluster I, ptxP1, 3/78 [3.8%]). All isolates harbored the ptxA1 allele. Most (75/78 [96.2%]) of the SP13 isolates had the prn2 allele and fim3A alleles. The 3 noncluster I SP18 isolates had a fim3A* allele that differs from fim3A by a synonymous mutation (3) with genotype ptxP1-fim3A*-prn1. The frequency of ptxP3 and fim3A alleles was higher than during the 2008–2012 epidemic (Figure 1, panels B, C). All but 1 isolate carried the fim2–1 allele. One isolate (L2263 [SP18]) contained a fim2 allele with a new 3-nucleotide insertion (AGA) at position 506, resulting in the insertion of a lysine in the epitope (F2.9) region of Fim2 (5). PROVEAN analysis (6) suggests that the insertion does not affect protein structure and thus might or might not affect immune recognition. We designated this allele as fim2–3 (GenBank accession no. MG824989).

During the 2008–2012 epidemic, Lam et al. (1) reported a rapid increase in the number of isolates not expressing the ACV antigen Prn (Prn-negative), from 5.13% in 2008 to 77.78% in 2012. Sequencing of 22 isolates revealed 5 epidemic lineages (ELs) (EL1–EL5) and independent origins of Prn-negative strains in different ELs (4). A smaller epidemic occurred during 2013–2017, peaking at 22,000 cases in 2015 (Figure 1, panel A). We investigated the genotypic and phenotypic characteristics of 78 *B. pertussis* isolates from 2013–2017 to determine the epidemic trends of pertussis in Australia.

The Study

We sequenced 78 *B. pertussis* isolates (Appendix 1 Table 1) from New South Wales (NSW) (17/78 [21.8%]) and Western Australia (WA) (61/78 [78.2%]) that were collected during the 2013–2017 epidemic. We conducted SNP detection (Appendix 1 Table 2) and examined variation in ACV antigen genes (prn, ptxA, ptxP, and the 2 fimbrial genes fim2 and fim3). Using the SNP-based classification scheme by Octavia et al. (3), we typed the 78 isolates into 2 SNP profiles (SPs): SP13 (SNP cluster I, ptxP3, 75/78 [96.2%]) and SP18 (noncluster I, ptxP1, 3/78 [3.8%]). All isolates harbored the ptxA1 allele. Most (75/78 [96.2%]) of the SP13 isolates had the prn2 and fim3A alleles. The 3 noncluster I SP18 isolates had a fim3A* allele that differs from fim3A by a synonymous mutation (3) with genotype ptxP1-fim3A*-prn1. The frequency of ptxP3 and fim3A alleles was higher than during the 2008–2012 epidemic (Figure 1, panels B, C). All but 1 isolate carried the fim2–1 allele. One isolate (L2263 [SP18]) contained a fim2 allele with a new 3-nucleotide insertion (AGA) at position 506, resulting in the insertion of a lysine in the epitope (F2.9) region of Fim2 (5). PROVEAN analysis (6) suggests that the insertion does not affect protein structure and thus might or might not affect immune recognition. We designated this allele as fim2–3 (GenBank accession no. MG824989).

Western immunoblotting showed that all isolates expressed Ptx, and all but 1 (L2228) expressed Fha. For Prn, 89.7% (70/78) isolates were Prn-negative (Figure 1, panel D), suggesting continued expansion of Prn-negative strains.

We found multiple mechanisms of prn inactivation in the isolates, all but 1 of which were reported previously (1,7–9). For most (66/70) isolates, inactivation was caused by insertion sequences (IS), including 45 IS48/F insertions (F/R denotes insertion orientation relative to prn), 17 IS48/F insertions, and 4 IS1002R insertions (Table). We found an IS48/F insertion, which has been reported in prnl...
B. pertussis, Australia

and prn2 isolates only (1,8), in 3 of the prn3 isolates. One Prn-negative isolate contained a SNP (C→T) in position 223, resulting in a stop codon, a mutation found previously in US isolates only (10). Two isolates had a deletion (position –297, 1325 [relative to the initiation codon ATG]) between the promoter and 5′ end of prn that was replaced with a fragment of IS1663, which might have mediated the deletion (Table). A similar but slightly different deletion (position –292, 1340) was reported in US isolates (7). We identified a new inactivation by a 4-bp deletion, from position 2020 to 2023 in prn, in 1 isolate (L2210) (Appendix 1 Table 1).

Table. Mechanisms of pertactin deficiency and characteristics of Bordetella pertussis isolates from pertussis epidemics, Australia, 2013–2017*

<table>
<thead>
<tr>
<th>Prn deficiency mechanism</th>
<th>Position in pmn†</th>
<th>pmn allele type</th>
<th>State (no. of isolates)</th>
<th>Year (no. isolates)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>IS481F</td>
<td>1613</td>
<td>pmn2</td>
<td>Western Australia (32)</td>
<td>2013 (13)</td>
<td>(1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>New South Wales (10)</td>
<td>2014 (5) 2015 (11) 2016 (9) 2017 (4)</td>
<td></td>
</tr>
<tr>
<td>IS481R</td>
<td>1613</td>
<td>pmn2</td>
<td>Western Australia (12)</td>
<td>2013 (6)</td>
<td>(1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>New South Wales (5)</td>
<td>2014 (5) 2015 (4)</td>
<td></td>
</tr>
<tr>
<td>IS481F</td>
<td>1598</td>
<td>pmn3</td>
<td>Western Australia (3)</td>
<td>2013 (1) 2014 (2)</td>
<td>This study</td>
</tr>
<tr>
<td>IS7002R</td>
<td>1613</td>
<td>pmn2</td>
<td>Western Australia (4)</td>
<td>2013 (2) 2016 (1) 2017 (1)</td>
<td>(1)</td>
</tr>
<tr>
<td>Deletion</td>
<td>–297 to 1325</td>
<td>Not determined‡</td>
<td>Western Australia (2)</td>
<td>2014 (1)</td>
<td>(8), newly found in Australia</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2015 (1)</td>
<td></td>
</tr>
<tr>
<td>Stop codon</td>
<td>223</td>
<td>pmn2</td>
<td>Western Australia (1)</td>
<td>2014 (1)</td>
<td>(10), newly found in Australia</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2013 (1)</td>
<td>This study</td>
</tr>
</tbody>
</table>

*F/R denotes IS insertion orientation relative to pmn. F, forward; IS, insertion sequence; Prn, pertactin; R, reverse.
†The nucleotide positions are relative to the initiation codon (ATG) of the prn in Tohama I.
‡pmn allele type was not determinable because the repeat regions that define pmn allele type were deleted in this mechanism.
One Prn-negative isolate (L2228) was also Fha-negative (i.e., Prn−, Fha−) by Western immunoblotting. The Fha inactivation probably resulted from changes within the homopolymeric G tract (site: 1078–1087) from 10 Gs to 11 Gs in fhaB, resulting in a downstream stop codon that produces a truncated FhaB protein (11). Both Illumina and Sanger sequencing (Appendix 2) showed a mixture of 10 Gs and 11 Gs. The bacterial population most likely contained predominantly 11 Gs with a lower proportion of 10 Gs. Proteomic analysis using liquid chromatography tandem mass spectrometry (12) found that, in the whole cell of L2228, only 2.3% of the FhaB protein was detected as peptides and derived mainly from the first 350 aa of the FhaB protein. In contrast, in the Fha-positive isolate (L2248), 30.7% of the FhaB protein was detected as peptides and derived from the entire protein. However, in the supernatant of L2288, we detected peptides across the entire FhaB protein and at a higher coverage of 22.7% than for whole-cell FhaB. For the Fha-positive isolate, we detected 52.0% of the FhaB protein across the entire protein. Western immunoblotting could not detect any FhaB in supernatant or whole-cell proteins of the Fha-negative isolate.

Together with the 27 B. pertussis isolates from Australia previously sequenced, we analyzed a total of 105 B. pertussis isolates to determine their genomic relationships (Figure 2). Five preepidemic SP13 isolates from 1997–2002 were ancestral to the SP13 epidemic clade as expected; 3 noncluster I (ptxP1) isolates grouped together as a separate clade outside SNP cluster I. Most (68/75) isolates grouped into 4 previously defined ELs (EL1–EL4) (4). However, no isolates from the new epidemic fell into the 2008–2012 EL5. Four isolates (L2233, L2234, L2261, and L2262) did not cluster with any of the ELs.

Prn-positive isolates from the 2008–2012 and 2013–2017 epidemics were distributed among different lineages. Prn-negative isolates were largely grouped by mechanism of inactivation in different ELs. Prn-negative isolates in EL1 and EL4 were caused by IS481R insertion. All but 1 Prn-negative isolate in EL2 was caused by IS1002 insertion; the exception was an IS481R insertion. Prn-negative isolates in EL3 were caused by IS481F insertion. Three Prn-negative isolates with new inactivation mechanisms found in Australia were distributed in EL4 (prn::del [-297, 1325]; note that the prn allele was indeterminate) and non-ELs (prn2::stop [C233T]).

EL1 contained isolates from NSW (6/20) and WA (14/20). EL2 was a small lineage (8 isolates), but these isolates were from both periods and both states. EL3 was predominantly a WA lineage; 30/33 isolates from WA and nearly half of the WA isolates (30/61) from 2013–2017 were EL3. EL4 was largely an NSW lineage (14/23 isolates).

Conclusions

The 2013–2017 pertussis epidemic in Australia was predominantly caused by Prn-negative strains, with local and
interstate expansion of 4 epidemic lineages. The ongo-
ing expansion of Prn-negative strains is most likely due
to continued vaccine selection pressure because Australia
has been using ACVs that contain Prn since their introduc-
tion. This observation contrasts with the declining circu-
lation of Prn-negative strains in Japan, where changes in
the vaccine probably caused the decrease because 2 of the
3 vaccines used after 2012 did not contain Prn (I3). The
emergence of an Fha-negative and Prn-negative B. pertus-
sis in Australia may offer higher potential to escape ACV-
induced immunity.

Our results provide further evidence of B. pertussis
evolution under vaccine selection. Continued surveillance
of B. pertussis will provide a better understanding of the
effect of vaccination on the evolution of the pathogen and
optimize strategies to reduce the occurrence of pertussis.

Acknowledgments
We thank Narelle Raven for technical assistance.

This study was supported by a grant from the National Health and
Medical Research Council of Australia (grant no.1146938). Z.X.
is supported by a University of New South Wales scholarship.

About the Author
Ms. Xu is a PhD candidate in the School of Biotechnology
and Biomolecular Sciences, University of New South Wales,
Sydney, NSW, Australia. Her research interests include the
epidemiology and evolution of human pathogens.

References
1. Lam C, Octavia S, Ricafort L, Sintchenko V, Gilbert GL,
Wood N, et al. Rapid increase in pertactin-deficient Bordetella pertussis
2. Octavia S, Sintchenko V, Gilbert GL, Lawrence A, Keil AD,
Hogg G, et al. Newly emerging clones of Bordetella pertussis
carrying prn2 and ptxP3 alleles implicated in Australian pertussis
3. Octavia S, Maharjan RP, Sintchenko V, Stevenson G, Reeves PR,
Gilbert GL, et al. Insight into evolution of Bordetella pertussis
from comparative genomic analysis: evidence of vaccine-driven
4. Safarchi A, Octavia S, Wu SZ, Kaur S, Sintchenko V, Gilbert GL,
et al. Genomic dissection of Australian Bordetella pertussis isolates
5. Williamson P, Matthews R. Epitope mapping the Fim2 and Fim3
proteins of Bordetella pertussis with sera from patients infected
with or vaccinated against whooping cough. FEMS Immunol Med
6. Choi Y, Sims GE, Murphy S, Miller JR, Chan AP. Predicting the
2012;7:e46688. https://doi.org/10.1371/journal.pone.0046688
7. Weigand MR, Peng Y, Cassiday PK, Loparev VN, Johnson T,
Jueng P, et al. Complete genome sequences of Bordetella pertussis
isolates with novel pertactin-deficient deletions. Genome Announc.
8. Pawlowski LC, Queenan AM, Cassiday PK, Lynch AS, Harrison MJ,
Shang W, et al. Prevalence and molecular characterization of pertactin-
deficient Bordetella pertussis in the United States. Clin Vaccine
9. Otsuka N, Han HJ, Toyozumi-Ajisaka H, Nakamura Y, Arakawa Y,
Shibayama K, et al. Prevalence and genetic characterization
2012;7:e31985. https://doi.org/10.1371/journal.pone.0031985
10. Weigand MR, Peng Y, Loparev V, Batra D, Bowden KE,
Burroughs M, et al. The history of Bordetella pertussis ge-
11. Bart MJ, Harris SR, Advani A, Arakawa Y, Bottero D, Bouchez V,
et al. Global population structure and evolution of Bordetella pertussis
12. Luu LDW, Octavia S, Zhong L, Raftery M, Sintchenko V, Lan R.
Characterisation of the Bordetella pertussis secretome under
10.1016/j.jprot.2017.05.010
13. Hiramatsu Y, Miyaji Y, Otsuka N, Arakawa Y, Shibayama K,
Kamachi K. Significant decrease in pertactin-deficient Bordetella pertussis

Address for correspondence: Ruiting Lan, School of Biotechnology
and Biomolecular Sciences, University of New South Wales, Sydney, NSW
2052, Australia; email: r.lan@unsw.edu.au