Antibodies Mediate Formation of Neutrophil Extracellular Traps in the Middle Ear and Facilitate Secondary Pneumococcal Otitis Media

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Otitis media (OM) (a middle ear infection) is a common childhood illness that can leave some children with permanent hearing loss. OM can arise following infection with a variety of different pathogens, including a coinfection with influenza A virus (IAV) and Streptococcus pneumoniae (the pneumococcus). We and others have demonstrated that coinfection with IAV facilitates the replication of pneumococci in the middle ear. Specifically, we used a mouse model of OM to show that IAV facilitates the outgrowth of S. pneumoniae in the middle ear by inducing middle ear inflammation. Here, we seek to understand how the host inflammatory response facilitates bacterial outgrowth in the middle ear. Using B cell–deficient infant mice, we show that antibodies play a crucial role in facilitating pneumococcal replication. We subsequently show that this is due to antibody-dependent neutrophil extracellular trap (NET) formation in the middle ear, which, instead of clearing the infection, allows the bacteria to replicate. We further demonstrate the importance of these NETs as a potential therapeutic target through the transtympanic administration of a DNase, which effectively reduces the bacterial load in the middle ear. Taken together, these data provide novel insight into how pneumococci are able to replicate in the middle ear cavity and induce disease.

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Development of secondary bacterial OM by inducing NETs in the middle ear. These NETs, instead of clearing the pneumococci, may then provide scaffolding for bacterial outgrowth. Accordingly, DNase treatment reduced pneumococcal OM. These data provide new mechanistic insight into pneumococcal-IAV coinfections and identify NETs as an important target for treating and preventing pneumococcal OM.

MATERIALS AND METHODS

Viral and bacterial strains. The bioluminescent S. pneumoniae strain EF3030lux (type 19F) (23) was used in all experiments. Influenza virus strain A/Udorn/307/72 (H3N2) was used to model infection with IAV. Virus stocks were prepared in embryonated eggs and quantitated as described previously (24).

Mice. Animal experiments were approved by the Animal Ethics Committee of the University of Melbourne and were conducted in accordance with the relevant Australian legislation. C57BL/6, B6.µMT−/−, and B6.pIgR+/− mice were bred and housed under specific-pathogen-free (SPF) conditions at the Department of Microbiology and Immunology, the University of Melbourne. B6.µMT−/− mice lack B lymphocytes and antibodies (although these mice can selectively produce some antibodies) (22, 25, 26). In contrast, B6.pIgR+/− mice are deficient in the polymeric Ig receptor (plgR) (27, 28). Accordingly, these mice are unable to secrete polymeric antibodies, and the sera of the mice contain significantly more IgA and IgG than sera from C57BL/6 (B6) mice (27, 28).

Infection of mice. Five-day-old B6 and B6.µMT−/− mice were colonized intranasally (i.n.) with 2 × 10^4 CFU of S. pneumoniae EF3030lux or phosphate-buffered saline (PBS) in 3 microliters. At 14 days of age, the mice were infected intranasally with 10^7 PFU of egg-grown IAV in 3 microliters. Six days post-IAV infection, the mice were euthanized, and organs were collected for analysis.

Enumeration of bacterial and viral loads. Tissues used to quantify bacterial and viral loads were collected and processed as described previously (3, 23). The viral load was determined using plaque assays on MDCK cells, as described elsewhere (24).

Histology and immunofluorescence. Middle ears were collected and processed for histological analysis as described previously (3). Antigen retrieval was performed by heating slides in citrate buffer (anti-gen retrieval solution; Dako) in a microwave. The slides were treated with Image-IT FX Signal Enhancer (Invitrogen), as recommended by the manufacturer, and stained with rabbit anti-CRAMP, a marker for mouse NETs (7.75 μg/ml; provided by Richard Gallo, UCSD, San Diego, CA [29]) or the respective isotype controls (rabbit IgG whole molecule; Jackson ImmunoResearch). The slides were subsequently stained with an Alexa 647-conjugated goat anti-rabbit antibody (Invitrogen) and mounted using Prolong Gold with 4',6'-diamidino-2-phenylindole (DAPI) (Invitrogen). For each sample (individual ear), a minimum of three randomly selected images were acquired (Leica DMI6000CS confocal microscope) and used for quantification of NET-producing cells. The data were expressed as percentages of NET-forming cells in relation to the total number of cells. The mean value derived from random images per sample was used for statistical analysis.

Antibody transfer. One hundred microliters of sera was transferred to B6.µMT−/− mice (14 to 19 days old) daily via intraperitoneal (i.p.) injection. Sera used for transfer experiments were collected from naive B6.pIgR+/− mice (male and female) that were ≥6 weeks of age and pooled.

Trans tympanic injection. IgA was enriched from naive B6.pIgR+/− sera using ammonium sulfate immunoprecipitation. IgG was then depleted with protein G (Genscript, USA), and IgA was further purified using mouse IgA purification resin (Affiland SA, Belgium) according to the manufacturer’s instructions. IgA purity was confirmed by SDS-PAGE, Western immunoblotting, and enzyme-linked immunosorbent assay (ELISA) (data not shown). Purified IgA (2 μg) or PBS was then injected trans tympanically into the middle ears of S. pneumoniae EF3030lux-colo-
not result in hearing loss (3). The difference in bacterial outgrowth between B6 and B6,μMT−/− mice was not due to impaired replication of IAV in B6,μMT−/− mice or a reduced inflammatory infiltrate in the ears of B6,μMT−/− mice (see Fig. S1 in the supplemental material). Importantly, the observed decrease in pneumococcal replication was restricted to the middle ear, as no differences in pneumococcal titers were observed between B6 and B6,μMT−/− mice in the nasopharynx (Fig. 1B).

Antibodies facilitate pneumococcal outgrowth in the middle ear. B6,μMT−/− mice lack B lymphocytes and therefore, for the most part, do not produce antibodies (22). However, these mice can produce at least some level of IgA in response to Salmonella (25), as well as IgE/IgG in the lung in response to Aspergillus fumigatus (26). Therefore, to determine if antibodies could restore pneumococcal growth, we adoptively transferred serum into B6,μMT−/− recipient mice from naive B6,pIgR−/− mice (Fig. 2A). B6,pIgR−/− mice were used instead of wild-type B6 mice, as they have higher levels of serum IgG and IgA than wild-type mice (27, 28), thereby reducing the number of intraperitoneal injections required. Sera were derived from naive mice, rather than from mice with specific anti-pneumococcal antibodies, as we found that 20-day-old coinfected mice have not yet developed significant levels of specific anti-pneumococcal antibodies in the middle ear (see Fig. S2 in the supplemental material). Therefore, any putative role of antibodies in pneumococcal OM is not likely to be driven by specific anti-pneumococcal antibodies. The transfer of naive serum to coinfected B6,μMT−/− mice significantly increased bacterial titers in the middle ear relative to mice treated with PBS (Fig. 2A). Serum transfer also resulted in middle ear antibody titers that were equivalent to those of coinfected B6 mice (Fig. 2B to D). To confirm that antibodies facilitated pneumococcal outgrowth in the middle ear, we injected IgA purified from naive sera directly into the middle ears of coinfected B6,μMT−/− mice. Although we were unable to use a large number of mice for these experiments, due to the difficulties associated with administering transtympanic injections to infant mice, the administration of IgA resulted in higher bacterial and IgA titers than the injection of PBS (Fig. 2E and F). No reactivity was observed between the IgA used for these transtympanic injections and pneumococcal or IAV antigens (see Fig. S3A and B in the supplemental material), suggesting that OM can occur in the absence of specific anti-pneumococcal/IAV antibodies.

NETs facilitate pneumococcal outgrowth in the ears of coinfected B6 mice. We had previously demonstrated that infection
with IAV induces an influx of neutrophils into the middle ear cavities of infant mice (3). Moreover, pneumococci in the ear colocalize with this influx of neutrophils (3), and neutrophils are thought to interact with antibodies in the middle ear (19). In light of the suggested role of NETs in OM (14, 15), we reasoned that antibodies in the middle ear may facilitate bacterial outgrowth by inducing NETs. To test this hypothesis, B6 and B6.μMT−/− mice were coinfect ed with S. pneumoniae, and IAV and NET formation in the middle ear was assessed. Immunofluorescence showed that B6.μMT−/− mice formed significantly fewer NETs in the middle ear than coinfected wild-type B6 mice (Fig. 3A and B). We confirmed with immunofluorescence assays that pneumococci localized to the neutrophilic infiltrate in the middle ears of NET-positive B6 mice (see Fig. S4 in the supplemental material). The production of NETs in the middle ear was independent of S. pneumoniae, as NETs were also detected in the middle ears of B6 mice infected with IAV alone (Fig. 3A and B).

To confirm that reduced NET formation in B6.μMT−/− mice was due to the absence of antibodies in the mice, NET formation was assessed in coinfect ed B6.μMT−/− mice following transtympanic injection of IgA or PBS. The administration of IgA resulted in a significant increase in NET production in the middle ear compared to injections with PBS (Fig. 3C). PBS-treated B6.μMT−/− mice displayed reduced NET formation compared to B6.μMT−/− mice that were not treated transtympanically (Fig. 3B and C), suggesting that the transtympanic injection itself may limit the detection of NETs by immunofluorescence. Nevertheless, the significant increase in NETs observed between B6 and B6.μMT−/− mice following injection with IgA or PBS. For each sample, a minimum of three randomly selected images were acquired and used to quantify NET-producing cells. The data are expressed as percentages of NET-forming cells in relation to the total number of cells. The mean value derived from random images per sample (individual ear) was used for statistical analysis. Statistical significance was determined using a Mann-Whitney U test and is denoted by one asterisk (P < 0.05) or two asterisks (P < 0.01). The data represent means and SEM. (C) Quantification of NETs in the middle ears of 20-day-old B6 or B6.μMT−/− mice. For each sample, a minimum of three randomly selected images were acquired and used to quantify NET-producing cells. The data are expressed as percentages of NET-forming cells in relation to the total number of cells. The mean value derived from random images per sample (individual ear) was used for statistical analysis. Statistical significance was determined using a Mann-Whitney U test and is denoted by one asterisk (P < 0.05) or two asterisks (P < 0.01). The data represent means and SEM. (D) Titers of S. pneumoniae EF3030lux in the middle ears of B6 mice 6 days after i.n. infection with IAV. Mice were transtympanically injected with IgA or PBS at 18 and 19 days of age. Each data point represents an individual ear from one mouse. Statistical significance was determined using a Mann-Whitney U test and is denoted by one asterisk (P < 0.05) or two asterisks (P < 0.01). The data are representative of two independent experiments.

**DISCUSSION**

OM represents a major health care burden worldwide and can arise from coinfection with IAV and S. pneumoniae. We have previously shown that IAV facilitates pneumococcal outgrowth in the middle ear by triggering middle ear inflammation (3, 8). The present study suggests that the ability of antibodies to trigger NET production in the middle ear may be a key component of the host inflammatory response that facilitates the development of bacterial middle ear disease.

It has previously been suggested that NETs may be an important mechanism by which pneumococci persist in the middle ear (14, 16), as they are able to reside in NETs and resist NET-mediated killing (18, 30). Consistent with this notion, bacterial biofilms entangled with DNA strands from NETs can be found in the in the middle ear effusions of children with recurrent acute OM (16).

Accordingly, it has been suggested that DNases may be a useful adjunct treatment in children with recurrent or chronic otitis media (16). However, the therapeutic benefit of DNase treatment in an animal model of OM has yet to be demonstrated. Here, we show that not only do coinfect ed mice develop NETs in the middle ear, but the transtympanic administration of a DNase reduces
pneumococcal outgrowth in the middle ears of IAV-infected mice. DNases have previously been used very successfully to treat patients with cystic fibrosis (31–33). Similarly, a study from the early 1960s showed that a DNase derived from beef pancreas had a therapeutic effect on patients with OM (34). Our data thus may suggest that DNase treatment could be an efficacious treatment option for children with OM. Indeed, the ability of a DNase (dornase alpha) to resolve OM in children is currently the subject of a clinical trial in Australia, where dornase alpha is administered to the middle ears of children undergoing surgery for grommet insertion (35). In the present study, the transtympanic administration of DNase to the middle ear was designed to mimic this surgical administration DNase. Of course, an animal model can never fully recapitulate the complexity of human disease, and it remains possible that DNase treatment would not reduce bacterial titers in children or that this would not result in a subsequent improvement in hearing. Nevertheless, our data suggest that the therapeutic benefits of DNase treatment in OM is an interesting area for further study.

Surprisingly, we identified antibodies as an important trigger for NET production in the middle ear. Previous studies have suggested that B6.µMT−/− mice can at least produce IgG and IgA upon challenge with a fungal pathogen (26). However, the potential production of IgE/IgG in these mice following microbial challenge (26) does not detract from our findings that antibodies mediate NET formation and pneumococcal OM. We showed that the transfer of purified IgA to B6.µMT−/− mice induced NET production in the middle ear, which clearly indicates that antibodies contribute to disease development. One possible explanation to reconcile our findings with the suggestion that B6.µMT−/− mice still produce some antibodies upon infection (26) may be that a certain threshold level of antibodies is required for the development of secondary pneumococcal OM. Alternatively, it is possible that the CD19+ CD9+ IgD+ B-1 cells found by Ghosh et al. (26) in the lungs of µMT−/− mice are not present in the middle ear.

A variety of different stimuli have been identified as triggering NET formation either in vivo or in vitro (36). They include interleukin 8 (IL-8), components of the complement cascade, and select bacterial and fungal pathogens (36). It is therefore interesting to consider the ways in which antibodies may trigger NET formation in the middle ear. Antibodies could induce NET formation in an indirect manner by activating the complement cascade (36, 37). The chemotactic complement-derived peptide complement factor 5α (C5a) can then induce NET formation by neutrophils that have been primed with granulocyte-macrophage colony-stimulating factor or interferons (36). While IAV can trigger the expression of interferon-regulated genes in the middle ear (8), a role for complement in middle ear NET production and pneumococcal OM is inconsistent with previous reports that complement protects against the development of pneumococcal OM (38). Moreover, we have found that, in vitro, IgA is able to induce both NET formation and pneumococcal outgrowth in the absence of complement (data not shown). Thus, clearly elucidating the pathway by which antibodies induce NET formation in the middle ear remains an important area for future studies.

In this study, we used purified IgA to confirm the role of antibodies in NETs and pneumococcal outgrowth in the middle ear. However, other antibody isotypes may also be able to induce NET formation in vivo. Indeed, our preliminary data suggest that the presence of IgG (in the absence of IgA) in the middle ears of coinfected B6.µMT−/− mice is also sufficient to facilitate pneumococcal outgrowth (data not shown). Thus, the interactions between antibodies and NET-producing neutrophils may not be restricted to one antibody isotype.

The antibodies involved in the development of OM in the present study were unlikely to be specific for S. pneumoniae or IAV, as middle ear disease could be induced in B6.µMT−/− mice by the transfer of IgA, which did not bind to pneumococcal or IAV antigens. Moreover, coinfected B6 mice (which develop pneumococcal OM) did not possess pneumococcus-specific antibodies in the middle ear. It currently remains unclear if the “OM-inducing” antibodies observed in this study were natural antibodies (i.e., polyspecific, low-affinity antibodies that can be produced in the absence of apparent antigenic stimuli) (39) or high-affinity antibodies that were produced in response to nonpneumococcal antigens. The possibility also exists that these antibodies actually bind to self-antigens, as autoantibodies are known inducers of NET production (40).

It is important to note that despite the findings of this study, specific anti-pneumococcal antibodies are still likely to protect against pneumococcal OM, as has been observed in clinical trials of anti-pneumococcal conjugate vaccines (41, 42). This is due, in part, to the ability of anti-capsular antibodies to reduce nasopharyngeal colonization with the corresponding serotype strains (43, 44). Colonization is the essential first step in the development of pneumococcal OM, and an increased number of pneumococci in the nose is associated with an increased risk of OM (45, 46). Therefore, regardless of whether anti-pneumococcal antibodies are able to induce NETs in the middle ear, anti-pneumococcal antibodies are still likely to decrease the risk of OM by reducing pneumococcal colonization in the nasopharynx.

Finally, this study found that the role of “OM-inducing antibodies” in pneumococcal outgrowth was at least to some extent tissue specific, as B6.µMT−/− mice did not display reduced pneumococcal titers in the nasal cavity relative to wild-type B6 mice. However, the role of NETs in secondary pneumococcal disease may not be restricted to the middle ear. It has recently been demonstrated that mice coinfected with S. pneumoniae and influenza virus display increased pulmonary lesions and NET formation in the lung compared to mice infected with either pathogen alone, and these NETs were unable to kill S. pneumoniae (30). Therefore, determining the role of NETs, and the stimuli required for their production, in the pathogenesis of invasive pneumococcal disease (i.e., pneumococcal pneumonia, sepsis, and meningitis) remains a key area for further study.

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