beta-lactamase-producing nontypeable Haemophilus influenzae fails to protect Streptococcus pneumoniae from amoxicillin during experimental acute otitis media

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Acute otitis media (AOM) is one of the most common bacterial infections in pediatric patients. The predominant pathogens causing AOM are *Streptococcus pneumoniae*, *Haemophilus influenzae*, and *Moraxella catarrhalis* (22). Of these three agents *S. pneumoniae* has the lowest spontaneous clearance rate, and it is the microorganism most often associated with severe and fatal complications of AOM (1, 18, 25). As a consequence, the antimicrobial drug used for the treatment of AOM in routine practice must have a spectrum which covers these bacteria to be efficacious.

Hitherto, amoxicillin has been the first-line therapeutic choice in several countries (10, 14). Its pharmacokinetic and pharmacodynamic profiles are attractive, but its utility is sometimes compromised by an increasing proportion of β-lactam-resistant isolates. About 14 to 65% of the nontypeable (NT) *H. influenzae* isolates from the middle ear produce β-lactamase (16, 20, 22, 24). For *M. catarrhalis* isolates the frequency is virtually 100% (20, 22, 24). Because of the high rate of β-lactamase production in these two species, the use of β-lactamase-resistant drugs such as macrolides and trimethoprim-sulfamethoxazole is often recommended (9). However, many of these antibiotics are not entirely effective as empirical treatment for AOM, especially macrolides for the treatment of infections caused by NT *H. influenzae*, and they may increase the rates of nasopharyngeal carriage of resistant organisms and promote their spread (7, 8, 28).

It has been suggested that β-lactamases not only protect the producing bacteria themselves but also frustrate the therapy of concomitant infections caused by penicillin-susceptible respiratory tract pathogens with penicillins, resulting in a sheltering effect. There is experimental evidence for such a sheltering effect for *Staphylococcus aureus* in group A beta-hemolytic streptococcal abscesses (3) and *M. catarrhalis* in pneumococcal pneumonia (21). *S. pneumoniae* and NT *H. influenzae* coexist in up to 10% of the samples of middle ear fluid (16). The activity of amoxicillin against the pneumococcus in a mixed infection could thereby be threatened.

In order to explore a possible sheltering effect for β-lactamase-producing NT *H. influenzae* in amoxicillin-treated pneumococcal AOM, a well-established rat model of AOM was used. Apart from the clinical and bacteriological outcomes, protection against reinfection, morphological changes, and expression of transforming growth factor beta (TGF-β) were also analyzed.

MATERIALS AND METHODS

**Animals and surgical procedures.** Healthy male Sprague-Dawley rats (weight, 250 to 350 g) were used. The study protocol was approved by the Ethics Committee of Lund University, and the animals were managed as described previously (31). During anesthesia induced with chloralhydrate (Apoteksbolaget, Malmö, Sweden) and after a blunt dissection of the soft tissue in the neck, approximately 50 μL of a bacterial suspension was inoculated directly into the middle ear cavity through the bony wall of the bulla. The tympanic membrane was left intact, and correct inoculation was verified with an otomicroscope.
Experimental design. A total of 78 animals were challenged with S. pneumoniae, NTHi, or a combination of both bacteria. See Table 1 for details of the experimental design. Forty-four animals were treated, while the remaining 34 animals served as controls.

To investigate if the intense inflammatory reaction induced by the mixed infection would disturb the protection against reinfection that normally develops after a primary infection, a rechallenge was performed 1 month after the initial inoculation. A total of 20 animals from groups A to C were challenged in the left, contralateral middle ear with the pneumococcal strain. At this rechallenge, four animals each (to study TGF-β gene expression). The middle ear tissues were removed unilaterally from the right ear, and the samples were immediately frozen in liquid nitrogen and stored at −70°C until analysis.

Treatment and pharmacokinetic studies. Treatment with amoxicillin (Amoxicillin; Tiba Läkemedel AB, Land, Sweden) was introduced on day 3 after the first challenge via the drinking water (250 mg/500 ml, the recommended dose for rats by veterinary standards). Water consumption was measured on a daily basis until day 8, when the antibiotic treatment was discontinued. Water consumption and serum amoxicillin concentrations were monitored more closely in two animals, for which water consumption was registered every hour for a 4-h period. Blood samples were then collected whenever an animal consumed water. The amoxicillin concentrations were measured by the agar disk diffusion method with Sarvina lutea (ATCC 9341) as the test strain, and the antibiotic levels were calculated from duplicate assays.

Morphological examination. Tissue samples were collected from two well-defined areas in the middle ear. The areas represented the fossa nasalis and the pars flaccida. After a brief rinse in buffer, the specimens were postfixed for 2 h with 1% OsO₄ in the same buffer and, after another rinse, were dehydrated in increasing concentrations of acetone and embedded in an Epon mixture (POLYBED; PolyScience Inc., Warrington, Pa.). The specimens were sectioned (thickness, 1 μm) for light microscopy and stained with toluidine blue. They were examined under a light microscope at an objective magnification of ×40. A team member who was unaware of the challenge and treatment procedures performed the examination. The degree of inflammation, with emphasis on inflammatory cells, vascular reaction, metaplasia, and epithelial proliferation, was recorded; and the following three categories were defined: no or minor changes, moderate changes, and major changes.

Reverse transcription-PCT. To detect expression of the gene for TGF-β, an anti-inflammatory cytokine which facilitates the anabolic effects of growth factors on tissue repair and whose expression is more pronounced during pneumococcal AOM than during NT H. influenzae AOM (32), mRNA was extracted from the frozen middle ear tissue samples with Dynabeads Oligo (dT)₃₀ (Dynal A.S, Oslo, Norway). After elution of the mRNA from the beads, it was reverse transcribed and amplified as described previously (32). The sequences of the primers used to detect the TGF-β gene were 5'-AGCTCCACAGAGAACTGCG-3' (sense) and 5'-TCTAGTGGACCTGC-3' (antisense). The PCR products were subjected to electrophoresis, and all samples were further analyzed in a competitive PCR assay (32).

The PCR products were quantified by using two different competitors, one for the housekeeping β-actin gene by use of primers with the sequences 5'-TGGAGAACGTATGAGCTG-3' and 5'-TCCACAGAGACTTGCGC-3' (antisense) and one for the TGF-β gene. The β-actin served as an internal control for total cell mass and mRNA recovery, and the levels of TGF-β expressed were corrected for the β-actin transcript levels in each sample.

Statistical analysis. Fisher’s exact test was used for statistical analysis of the rat model studies, and Student’s t test was used to compare the TGF-β mRNA levels between treated and untreated animals. A difference was considered statistically significant when P < 0.05.

RESULTS

Clinical findings and protective rate. All animals developed AOM after the first challenge. In 8 (10%) animals the infection progressed into a bilateral middle ear infection on day 4. Four
of these animals belonged to untreated group C with mixed infections, whereas the remaining four belonged to either treatment group B with mixed infections \( (n/1005) \) or group D with untreated pneumococcal infections \( (n/1005) \). The courses of these contralateral infections were relatively short, and they were resolved on day 7 in all but two animals. These two animals belonged to untreated pneumococcus-infected group D and exhibited opaque effusions behind the tympanic membrane on day 8. Seven animals (9%) developed severe, systemic infections and died. Four of these animals (57%) had bilateral infections. In group A, the deaths \( (n = 2) \) occurred early and before or just after the antibiotic treatment of the pneumococcal AOM had been initiated, i.e., on days 3 and 4. In group B, which consisted of animals with treated mixed infections, the animals succumbed \( (n = 2) \) on days 4 and 5, and in group C, which consisted of animals with untreated mixed infections, the animals succumbed on days 4 \( (n = 1) \) and 6 \( (n = 2) \). All seven animals were excluded from further studies.

The otomicroscopic aspects of untreated and amoxicillin-treated AOM are shown in Fig. 1. The treatment accelerated the resolution of the infection. The most rapid clearance took place in group A (treated pneumococcal infections), which was significantly faster than that observed in the groups with mixed infections, groups B (treated) and C (untreated), on treatment days 3 to 5, i.e., on days 6 to 8 postinoculation \( (P = 0.00001 \) to \( 0.02) \). On day 8, the last day of treatment, 94% of the infections in group A, 60% of the infections in group B \( (P = 0.02) \), and 45% of the infections in group C \( (P = 0.0002) \) had cleared, as determined by otomicroscopy. At no time point were there any statistically significant differences between the groups with mixed infections, groups B (treated) and C (untreated). The only group in which all animals had a normal status on day 8 was untreated group E, challenged with NT \( H. influenzae \). There was, however, no substantial difference between this group and groups B \( (P = 0.06) \) and C \( (P = 0.08) \). Opaque effusions could be observed only in animals in group B (treated mixed infections) and group D (untreated pneumococcal infections) after day 7.

The proneness to develop AOM after rechallenge of the left middle ear was similar among animals in groups A to C. The protective rate is presented in Table 2. The otomicroscopic appearance of the right tympanic membrane was also evaluated in these three groups. On day 56, the presence of white plaques in the tympanic membrane was substantial in the right ears of all animals with resolved mixed infections. The plaques extended over both the pars flaccida and the pars tensa of the tympanic membrane, and this was independent of antibiotic therapy. In animals challenged with the pneumococcal strain alone, the white plaques in the right tympanic membrane were limited to the pars tensa. After rechallenge the myringosclerotic-like changes were restricted to the vessel area of the pars tensa in the left ears of animals in all groups.

**Antibiotic and bacteriological data.** There were no differences in the levels of water consumption between the animal groups, and the treatment was well tolerated. The daily dose of amoxicillin was \( 58 \pm 9 \) mg/kg of body weight, as deduced from the level of water consumption. Serum amoxicillin concentrations were \( 4 \pm 3 \) μg/ml (range, 1.7 to 6.1 μg/ml).
The frequencies of positive middle ear fluid cultures on days 3 and 8 in the various groups are shown in Table 2. On day 3, 96% of the middle ear fluid cultures were positive, and for 56% of the animals with mixed infections, NT H. influenzae overgrew the pneumococci. The effect of amoxicillin on pneumococcal growth was significant in both animals with mixed infections and animals with pure pneumococcal infections. None of the specimens from animals in treatment groups A and B yielded growth of pneumococci on day 8, whereas the values for untreated groups C and D were 40% (P = 0.04) and 100% (P = 0.003), respectively. In contrast to the pneumococci, the β-lactamase-producing NT H. influenzae exhibited a slight tendency to persist at the infection site during treatment (Table 2, groups B and C). This tendency was not statistically significant (P = 0.08).

**Structural observations and expression of TGF-β.** The structural changes are summarized in Table 3. On day 3, the specimens were categorized into two groups. In the group with major changes, specimens exhibited a massive inflammatory response with abundant inflammatory cells (Fig. 2a). The degree of epithelial proliferation could not be determined due to the inflammatory changes. Sclerosis occurred in one specimen. On day 8, the degree of inflammation had decreased in three animals treated with amoxicillin. All but one of the specimens with mixed infections were assigned to the category with major changes, with numerous inflammatory cells still present. Gland-like formations and polyps in the fossa nasalis extended into the middle ear cavity in some specimens, and sclerosis occurred. Ciliated cells and goblet cells were increased in number and were also present in the inner epithelium of the pars flaccida. After 56 days, the middle ears of treated animals challenged with S. pneumoniae had no or minor changes (Fig. 2b) or moderate changes, whereas the specimens from the groups with mixed infections exhibited moderate changes (Fig. 2c) or major changes (Fig. 2d). The major changes were characterized by extensive alterations in the epithelium in the fossa nasalis, with several newly formed layers of epithelial cells and connective tissue and increased numbers of ciliated and secretory cells. Islands of epithelial cells were observed in subepithelial tissue, and polyps extended into the middle ear cavity. The pars flaccida was thickened, and ciliated cells were present in the inner epithelium. Three of four specimens from the animals with amoxicillin-treated mixed infections (group B) and three of five specimens from the animals with untreated mixed infections (group C) were assigned to this category.

The expression of TGF-β differed between the animal groups with mixed infections. The transcript levels were lower for animals in group B (amoxicillin treated; mean, 25.9 ± 11.1 fg) than animals in group C (untreated; mean 35.4 ± 27.5 fg), but the difference was not statistically significant (P = 0.34).

**DISCUSSION**

In vitro and in vivo studies have demonstrated the ability of β-lactamase-producing strains to protect penicillin-susceptible

### TABLE 2. Frequency of positive middle ear fluid cultures during primary infection and protective rate after rechallenge

<table>
<thead>
<tr>
<th>Animal group</th>
<th>Inoculum</th>
<th>Growth (no. of specimens with growth/total no.) on:</th>
<th>Protective rate (no. of animals protected/total no. [%])</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Day 3</td>
<td>Day 8</td>
</tr>
<tr>
<td>A</td>
<td>Pnc</td>
<td>—</td>
<td>0/10</td>
</tr>
<tr>
<td>B</td>
<td>Pnc and NTHi</td>
<td>—</td>
<td>0/11 (Pnc), 5/11 (NTHi)</td>
</tr>
<tr>
<td>C</td>
<td>Pnc and NTHi</td>
<td>16/16 (NTHi), 16/16 (Pnc)</td>
<td>4/10 (Pnc), 1/10 (NTHi)</td>
</tr>
<tr>
<td>D</td>
<td>Pnc</td>
<td>3/3</td>
<td>3/3</td>
</tr>
<tr>
<td>E</td>
<td>NTHi</td>
<td>5/6</td>
<td>2/6</td>
</tr>
</tbody>
</table>

*a Amoxicillin treated.

*b Pnc, S. pneumoniae; NTHi, NT H. influenzae.

Scanty, prior to the amoxicillin treatment, all animals in group A were included in untreated group D, and all animals in group B were included in untreated group C.

The culture results on day 3 for groups A and B can therefore be found only in groups D and C, respectively.

The frequencies of positive middle ear fluid cultures on days 3 and 8 in the various groups are shown in Table 2.

### TABLE 3. Summary of structural changes in pars flaccida and fossa nasalis in relation to time and challenge group

<table>
<thead>
<tr>
<th>Day</th>
<th>Category</th>
<th>Histological findings</th>
<th>Category assignment by challenge group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Inflammatory cells</td>
<td>Metaplasia</td>
</tr>
<tr>
<td>3 (prior to ab)</td>
<td>Moderate changes</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>Major changes</td>
<td>++++</td>
<td>++++</td>
</tr>
<tr>
<td>8</td>
<td>Moderate changes</td>
<td>+</td>
<td>++/+++</td>
</tr>
<tr>
<td></td>
<td>Major changes</td>
<td>+</td>
<td>+/+++</td>
</tr>
<tr>
<td>56</td>
<td>No or minor changes</td>
<td>0</td>
<td>0/+</td>
</tr>
<tr>
<td></td>
<td>Moderate changes</td>
<td>0/+</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>Major changes</td>
<td>+</td>
<td>++++</td>
</tr>
</tbody>
</table>

*a Abbreviations 0, no changes; +, minor changes; ++, moderate changes; ++++, extensive changes; NA, not applicable; ab, antibiotic treatment.

*b A, S. pneumoniae infection and antibiotic treatment; B, S. pneumoniae and H. influenzae infections and antibiotic treatment; C, S. pneumoniae and H. influenzae infections and antibiotic treatment. The data (n values) indicate the number of animals in the group/total number of animals.
FIG. 2. Light micrographs representing pars flaccida after challenge. (a) major changes prior to treatment on day 3; (b) no or minor changes on day 56 after treatment of pneumococcal infection, (c) moderate changes on day 56 caused by mixed infections; and (d) major changes on day 56 caused by mixed infections. Magnifications, ×336.
bacteria in localized mixed infections at various sites (3, 4, 19, 21). In contrast to that work, the present study could not demonstrate this phenomenon. Despite the presence of NT H. influenzae cells, which produced sufficient amounts of β-lactamase to protect themselves, the pneumococci were successfully eradicated from the rat middle ear by the amoxicillin treatment. These findings indicate that the degrading effect may vary with the type of β-lactamase and the microorganism producing the β-lactamase. Thus, the presence of β-lactamase-producing upper respiratory tract pathogens or commensal organisms in polymicrobial infections or in the immediate surroundings does not automatically render penicillins ineffective against otherwise susceptible bacteria. Results similar to the present results have been demonstrated in a surgical animal model by Renneberg and Walder (33) and indirectly in a clinical study by Joki-Erkkilä et al. (23).

Although H. influenzae did not frustrate the amoxicillin treatment of S. pneumoniae infections, the inadequate antibiotic coverage against this microorganism resulted in moderate to major structural changes in the middle ear mucosa. These changes did not affect the protective rate, but in the majority of the group B animals with treated mixed infections the changes were more extensive than those usually observed after untreated AOM induced by NT H. influenzae (31). The substantial myringosclerotic-like changes found in all animals with mixed infections, independent of treatment, also indicate that considerable injury to the tympanic membrane was caused by the combination of gram-positive and gram-negative bacteria. The development of white plaques in both the pars flaccida and the pars tensa in 100% of the animals has not previously been observed in this model of AOM. The fact that the first case of sclerosis was recorded on day 3 and the fact that the antibiotic treatment did not reduce the frequency of white plaques in the tympanic membrane, their distributions, or the morphological alterations to the mucosa suggest that the initial tissue injury was established early during the course of AOM and was probably established prior to the introduction of antibiotic treatment.

How the two bacterial species may interact with each other in the middle ear cavity is not known, but Elliott and coworkers (11) have shown that the relationship can be close and of a parasitic or symbiotic nature. In the present study, the overgrowth of NT H. influenzae in the middle ear tissue cultures on day 3 and the shift from early to late deaths when NT H. influenzae was added to the inoculum support the idea of a bacterial interaction or local competition. Despite a possibly competitive situation that might limit bacterial expansion to some extent, a mixed infection in the middle ear appeared to increase the strain on host tissues and defenses. Mixed infections are most common in AOM patients with treatment failure (16). To avoid long-standing mixed infections, measures in the form of tympanocentesis and a change of treatment to an antibiotic with a broader spectrum of activity should probably be taken without delay in suspected cases.

The widespread use of antibiotics for the treatment of AOM has lately led to prevalent β-lactamase production among the leading gram-negative pathogens of the middle ear, so why insist on using amoxicillin and not amoxicillin-clavulanate (AMC) as the first-line drug? Apart from differences in virulence and spontaneous recovery rates between gram-positive and gram-negative pathogens, ecological issues must be considered. The impact of AMC on the gastrointestinal flora is not negligible (15, 29), but of more concern is its effect on the nasopharyngeal flora. A wider spectrum of bacteria is eradicated by AMC than amoxicillin (5), and the competitive balance between pneumococci and commensal organisms could thereby be disturbed (17). Cultures of nasopharyngeal specimens from otitis-prone children show low numbers of alpha-hemolytic streptococci with activity that interferes with common pathogens that cause otitis (34), and significantly fewer children recently treated with amoxicillin than those treated with AMC have been shown to be prone to otitis (2). Furthermore, in the work of Joki-Erkkilä et al. (23), the presence of β-lactamase-producing M. catarrhalis, but not β-lactamase-producing H. influenzae, appeared to prevent the development of penicillin resistance among pneumococcal isolates in the nasopharynx, presumably by reducing the selection pressure. In this context, it is interesting to compare the remarkably low frequency of isolation of M. catarrhalis and the high frequency of isolation of penicillin-resistant pneumococci in Spain with the corresponding frequencies found in northern Europe and the United States (6, 9, 24).

In an era with a high prevalence of resistance among pathogens of the middle ear, the potential benefit to the individual who is treated with antibiotics must be weighed against the public health risk for the emergence of resistant microorganisms. In Scandinavia the frequency of isolation of pneumococci with reduced susceptibilities to penicillin is lower than that in most European countries (12, 26, 27), and penicillin V is still, after more than 45 years, the drug of choice for the treatment of AOM, with S. pneumoniae as the primary target. The step from treatment with penicillin V and amoxicillin to AMC might appear to be short, but it requires consideration and should probably not be taken unless it is called for.

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