Macrolide resistance in *Streptococcus pyogenes* results primarily from modification of the drug target site by methyltransferases encoded by *erm* genes, *erm(A)* and *erm(B)* or by active efflux mediated by a *mef*-encoded efflux pump. Of these, *erm(A)* is inducibly expressed (1) and generally confers low-level resistance to macrolides, whereas lincosamides and streptogramins B (MLS<sub>B</sub>), which share overlapping binding sites, remain active against *erm(A)*-harboring *S. pyogenes* (2). Conversely, *erm(B)* can be constitutively or inducibly expressed and confers high-level resistance to MLS<sub>B</sub> (2). *mef(A)* also is constitutively expressed but confers low to moderate resistance to macrolides and generally confers low-level resistance to macrolides, whereas *mef(B)* confers high-level resistance (2). In bacteria, the magnitude of which is the main parameter influencing the rate of development and stability of the resistance mechanisms and, conversely, the rate at which resistance would decrease under decreasing use of antimicrobial drugs (5). We investigated temporal changes in the molecular epidemiology of macrolide-resistant *S. pyogenes* during 1999–2009 in relation to strain fitness (i.e., ability of bacteria to survive and reproduce) and to outpatient use of MLS<sub>B</sub> and tetracycline in Belgium.

**The Study**

We screened 11,819 *S. pyogenes* isolates from patients with tonsillopharyngitis or invasive disease in Belgium during 1999–2009 for macrolide resistance. We used double-disk diffusion, MIC testing, and multiplex PCR to detect *erm* and *mef* genes and investigated their clonality by *emm* typing and by pulsed-field gel electrophoresis (6). The prevalence of macrolide-resistant *S. pyogenes* decreased from 13.5% to 3.3% during 1999–2006 and remained low from 2006 onward (Figure 1); most isolates harbored *erm(B)* (395 [46.5%]) or *mef(A)* (383 [45.1%]). We detected *erm(A)* in only 85 (10.0%) resistant strains; however, their proportions among macrolide-resistant strains increased from 1 (1.2%) of 81 in 1999 to 36 (76.6%) of 47 in 2009. *erm(A)*-harboring *S. pyogenes* isolates predominantly harbored *emm77* (50/85[5.8%]). *mef(A)* was mostly associated with *emm1*, *emm4*, and *emm12* and *erm(B)* with *emm11*, *emm22*, and *emm28* (Figure 2, Appendix, wwwnc.cdc.gov/EID/article/18/9/12-0049-F2.htm). During 1999–2009, proportions of *mef(A)*- and *erm(B)*-associated *emm* types decreased gradually, whereas those of *erm(A)*-harboring *emm77* increased steadily from 2006 onward (Figure 2). *erm(A)*-*emm77* became predominant in 2008-2009, representing 10–28 (32.2%–59.6%) of total macrolide-resistant *S. pyogenes* isolates during those 2 years (Figures 1, 2). Most (97.8%) *erm(A)*-*emm77* belonged to the same pulsed-field gel electrophoresis cluster and harbored *tet(O)*, indicating gene linkage.

Next, we used data on outpatient use of MLS<sub>B</sub> and tetracycline collected by the Belgian National Institute for Health and Disability Insurance during 1997–2008 and aggregated at the active substance level (World Health Organization Collaborating Center for Drug Statistics Methodology, www.whocc.no/atc/structure_ and_principles/) to model the data obtained for macrolide-resistant *S. pyogenes*. MLS<sub>B</sub> and tetracycline use was expressed in packages/1,000 inhabitants/day, a better proxy for prescriptions than defined daily doses in Belgium, where the number of defined daily doses per package or prescription had increased during the previous decade (7). MLS<sub>B</sub> and tetracycline use decreased from 1997 to 2004 (1.16–0.53 packages/1,000 inhabitants/day) and remained stable at this level (0.50–0.53 packages/1,000 inhabitants/day) from 2004 onward (Figure 1). Total outpatient use of antimicrobial drugs also decreased (3.75–2.4 packages/1,000 inhabitants/day) during 1997–2007, as did use of penicillins, whereas proportional use of amoxicillin--
clavulanate acid increased transiently soon after public campaigns began in Belgium (8). Yearly proportions of macrolide-resistant strains among total isolates correlated with MLS$_B$ and tetracycline use in generalized linear models with a negative binomial distribution and a log-link (GLM, PROC GENMOD, SAS Institute, Cary, NC, USA). Using an interval of 2 years, we observed a highly significant positive correlation between decreasing use of MLS$_B$ and tetracycline during 1997–2007 and decreasing levels of macrolide-resistant S. pyogenes during 1999–2009 (p<0.0001). The consistent decrease in MLS$_B$ and tetracycline use since 1997 was further accentuated by the start of public health campaigns in December 2000 that also were directed toward prescribers and successfully reduced antimicrobial drug prescribing in Belgium (Figure 1) (8). A similar trend was observed in Finland, where a nationwide increase in erythromycin use and resistant S. pyogenes led to issuance of national recommendations to reduce outpatient use of MLS$_B$; erythromycin-resistant S. pyogenes declined after 2 years of reduced MLS$_B$ use (9). Nonetheless, for S. pyogenes, these correlations are not always clear, primarily because of frequent clonal fluctuations for this organism. For instance, despite a 21% decrease in macrolide use in Slovenia, resistance doubled among noninvasive S. pyogenes isolates (10).

Notwithstanding clonal changes, the fitness costs (i.e., an organism’s decreased ability to survive and reproduce because of a genetic change, expressed as a decreased bacterial growth rate) associated with particular resistance mechanisms is another major factor governing the relation between use and resistance. Mathematical models have shown threshold levels of antimicrobial drug use below which the frequency of resistance would not increase if resistance imposes a fitness cost for the bacteria (11). We further hypothesized that the frequency of certain macrolide-resistant geno-ermm-types might differ if antimicrobial drug use remains below a certain threshold. In concordance with the models, we found a negative correlation between use of MLS$_B$ and tetracycline and proportions of erm(A)-ermm77 among macrolide-resistant S. pyogenes (p = 0.0002), and we identified 0.62 packages/1,000 inhabitants/day as the critical threshold volume of MLS$_B$ and tetracycline use below which proportions of erm(A)-ermm77 among macrolide-resistant S. pyogenes would increase significantly (p<0.0001). Next, we compared the fitness of erm(A)-ermm77 with that of 6 other major macrolide-resistant geno-ermm-types in Belgium during 1999–2009 (Figure 2). After growth-competition experiments (12), initial and final proportions of competing strains were determined by multiplex PCR to detect erm(B), erm(A), or mef(A) in 50 randomly selected colonies per plated mixture. Number of generations and relative fitness of competed pairwise strains were calculated as described (13). The inducible erm(A) in an erm77 background was more fit (67%) than most of the geno-ermm-types that predominated during the previous years of higher MLS$_B$ and tetracycline use (Table). Only the mef(A)-ermm1 and erm(B)-ermmcault et al. (14) showed that in the noninduced state, the inducible vanB gene had no effect on fitness of enterococci and might explain the low fitness cost of erm(A) carriage in erm77 strains. A predominance of erm(A)-harboring strains during 1993–2002, with 30% in an erm77 background, was also reported in Norway, a country with a low prevalence of resistance (2.7%) and antimicrobial drug use (15). Of note here is the combination of erm(A) and erm77 as geno-ermm-type because the fitness benefit (i.e., lack of fitness cost) was not as remarkable for other erm(A)-harboring erm types.
Macrolide-Resistant S. pyogenes

Table. Characteristics of macrolide-resistant Streptococcus pyogenes used in competition experiments and relative fitness* of the erm(A)-emm77 geno-emm-type against competitor strains, Belgium, 1999–2009

<table>
<thead>
<tr>
<th>Geno-emm-type</th>
<th>Macrolide MIC, mg/L</th>
<th>Relative fitness (SD)†</th>
<th>p value, †test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Erythromycin</td>
<td>Clindamycin</td>
<td>erm(A)-emm77</td>
</tr>
<tr>
<td>erm(A)-emm77</td>
<td>2</td>
<td>0.125</td>
<td>ND</td>
</tr>
<tr>
<td>erm(B)-emm28</td>
<td>&gt;512</td>
<td>&gt;512</td>
<td>1.03 (0.09)</td>
</tr>
<tr>
<td>erm(B)-emm22</td>
<td>&gt;512</td>
<td>&gt;512</td>
<td>1.27 (0.15)</td>
</tr>
<tr>
<td>erm(A)-emm11</td>
<td>&gt;512</td>
<td>256</td>
<td>2.12 (0.28)</td>
</tr>
<tr>
<td>erm(A)-emm12</td>
<td>8</td>
<td>0.125</td>
<td>1.29 (0.18)</td>
</tr>
<tr>
<td>erm(A)-emm4</td>
<td>8</td>
<td>&lt;0.03</td>
<td>1.55 (0.15)</td>
</tr>
<tr>
<td>erm(A)-emm1</td>
<td>16</td>
<td>0.5</td>
<td>1.01 (0.05)</td>
</tr>
</tbody>
</table>

*The ability of the bacteria to survive and reproduce. ND, no data.
†Average of duplicate experiments.

(data not shown). The mechanisms underlying the higher fitness benefit conferred by an emm77 versus another emm background for the erm(A) genetic element remain to be investigated and might be related to differences in basal gene expression or compensatory changes in the emm77 genome or might result from differences in the genetic element harboring erm(A) in emm77.

Conclusions

Using macrolide-resistant S. pyogenes as a marker for use of MLSb and tetracycline, we showed a decrease in use of these antimicrobial drugs, accentuated by successful public health campaigns, reflected a steady decline of macrolide-resistant S. pyogenes in Belgium. Furthermore, successfully maintaining use below a critical threshold resulted in maintenance of low-level macrolide-resistant S. pyogenes and emergence of the inducibly expressed and low-level resistant erm(A)-emm77 geno-emm-type. Maintaining antimicrobial drug use below a critical threshold might facilitate stabilization of low-level antimicrobial drug resistance and of milder resistance mechanisms with lower fitness costs.

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References


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